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UNITED STATES DISTRICT COURT

NORTHERN DISTRICT OF CALIFORNIA

SAN FRANCISCO DIVISION

REARDEN LLC, REARDEN MOVA LLC, California limited liability companies, Plaintiffs, v. THE WALT DISNEY COMPANY, a Delaware corporation, WALT DISNEY MOTION PICTURES GROUP, INC., a California corporation, BUENA VISTA HOME ENTERTAINMENT, INC. a California corporation, MARVEL STUDIOS, LLC, a Delaware limited liability company, MANDEVILLE FILMS, INC., a California corporation, Defendants.	No. ____ **COMPLAINT FOR COPYRIGHT, PATENT, AND TRADEMARK INFRINGEMENT** **<u>DEMAND FOR JURY TRIAL</u>**

TABLE OF CONTENTS

Plaintiffs Rearden LLC and Rearden Mova LLC (collectively, "Plaintiffs"), through their attorneys and for their claims against defendants The Walt Disney Company, Walt Disney Motion Pictures Group, Inc., Buena Vista Home Entertainment, Inc., Marvel Studios, LLC (collectively, "Disney"), and Mandeville Films, Inc. (collectively, "Defendants"), allege as follows.

I. INTRODUCTION

> "There have been a lot of great CG [computer graphics] performances, but [the Beast] was a romantic hero, someone who was at the emotional center of the movie. I always said that we could get everything else in this movie right, but if we didn't get a Beast that people believed in then [the movie] wouldn't work."[1] - Bill Condon, Director, *Beauty and the Beast*

1. Disney's *Beauty and the Beast* opened on March 17, 2017 to an astonishing $170 million in North America and $350 million globally, establishing numerous new box-office records in the process. It became the top film opening of all time for a PG-rated film, both domestically *and* internationally. It was the seventh largest opening for a film of any rating in North America. And it is now the highest grossing PG-rated film of all time, earning over $500 million domestically and $1.25 billion worldwide. *Beauty and the Beast* is the tenth highest grossing movie of any rating of all time.[2]

2. The film's romantic hero, the Beast, was a CG (computer graphics) character played by actor Dan Stevens, with every human subtlety of his facial performance carried through to the animal-like CG face of the Beast by a unique Oscar-winning visual effects ("VFX") technology called MOVA Contour Reality Capture. Stevens described how MOVA Contour was used:

> The facial capture [for the Beast] was done separately using a technology called "MOVA." So, every ten days, two weeks, I'd go into a booth and spray my face with UV paint and 27 little cameras would capture the facial expressions of all the scenes we had done on previous days…they would take that information and morph it onto the Beast, his face…

and co-star Emma Watson (Belle) lauded MOVA Contour, saying:

> I'm so pleased that we did it the way we did it because when you see Beast on screen there is something so human about him… [MOVA

[1] Truitt, Brian, "Watch the crazy way 'Beauty and the Beast' turned Dan Stevens into a monster", USA Today, May 29, 2017. https://www.usatoday.com/story/life/entertainthis/2017/05/29/exclusive-video-how-dan-stevens-was-transformed-in-beauty-and-the-beast/102281138/.

[2] http://www.boxofficemojo.com/movies/?id=beautyandthebeast2017.htm.

> Contour] really captures the subtlety of Dan's facial expression and the performance that he gives…I don't think the world has seen anything like it before. I think it's really unique to our film.[3]

And Director Bill Condon went further, expressly crediting the success of the CG Beast to the unique capabilities of MOVA Contour and attributing the film's success in its entirety to MOVA Contour:

> "[The Beast] was at the emotional center of the movie, who was the romantic hero of the movie, who was going to be a CG character…and it was this new process [MOVA Contour] which—you know usually its dots like this [Condon points to his face] and then animators fill in the dots—but actually captured every pore of Dan [Stevens]'s skin and that's why so much of him, this great performance, comes through…"[4]

This view was affirmed by *Beauty and the Beast's* editor, Virginia Katz:

> "…the main concern, for me and I think for all [working on the movie], was how that the Beast was going to be visualized. I mean, if the Beast didn't work, then the film wouldn't work."[5]

3. But in all of the film industry and media accolades about the record-breaking success of *Beauty and the Beast*, and the acclaimed cutting-edge digital MOVA Contour technology that made the film's success possible, nowhere is it mentioned that the patented and copyright-protected MOVA Contour technology was stolen from its inventor and developer, Rearden LLC, and its owner Rearden Mova LLC. Nowhere is it mentioned that although Disney had previously contracted with Rearden LLC and its controlled entities on *four previous major motion pictures* to use MOVA Contour and knew of a Rearden Demand Letter[6] to one of the thieves demanding immediate return of the stolen MOVA Contour system, Disney nonetheless contracted with the thieves to use the stolen MOVA Contour system. And, nowhere is it mentioned that *after* Rearden and Rearden Mova were in widely-reported litigation against the thieves, Disney secretly used MOVA Contour in *Beauty and the Beast* throughout the litigation, and then prior to the film's release, flaunted its unauthorized use of MOVA Contour as a promotional vehicle for the film. Throughout this entire time, Disney never

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[3] Paris Press Conference, Feb 17, 2017. https://www.youtube.com/watch?v=R9mKV_gklgw&feature=youtu.be&t=12m14s and https://youtu.be/PDmNbXMTxd0?t=12m5s .

[4] Id.

[5] Romanello, Linda, Post Magazine, March 1, 2017. http://www.postmagazine.com/Publications/Post-Magazine/2017/March-1-2017/Cover-Story-Disneys-i-Beauty-and-the-Beast-I-.aspx.

[6] *Shenzhenshi, et al. v. Rearden, et al.*, NDCA Case No. 15-797, Dkt: 383, at 169.

bothered to contact its longtime MOVA Contour service provider Rearden LLC to ask any questions or to verify Disney's authorization to use the MOVA Contour system, methods, trade secrets, or trademarks that Disney knew Rearden owned.

4. And this was not the first time. Disney contracted with the same thieves previously (after receiving the Rearden Demand Letter) to use MOVA Contour in at least one other film, *Guardians of the Galaxy*, which was also highly successful. Disney falsely designated the thieves as the owners of MOVA's facial capture technologies, resulting in widespread industry confusion to the point where Disney's use of MOVA Contour in *Guardians of the Galaxy*—despite being wholly unauthorized—was the *only* movie cited by the Academy of Motion Picture Arts and Sciences when awarding "MOVA [Contour] Facial Performance Capture system" a Sci-Tech Oscar:

> "MOVA uses phosphorescent makeup applied with a sponge, strobing fluorescent lights, and an array of 32 cameras. Instead of capturing around a hundred points on the face [using conventional marker-based facial capture] MOVA creates an animated mesh with thousands of points. This offers digital recreations with all the subtle and dynamic motions performed by the actor. **You would have seen this most recently by Josh Brolin playing Thanos in the blockbuster *Guardians of the Galaxy*.**"[7]

And Disney contracted with the same thieves again to use the MOVA Contour technology for the same Thanos character in a sequence in the closing credits of *Avengers: Age of Ultron* used by defendants Disney MPG and Marvel to promote the next *Avengers* film.

5. Disney used the stolen MOVA Contour systems and methods, made derivative works, and reproduced, distributed, performed, and displayed at least *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast*, in knowing or willfully blind violation of Rearden Mova LLC's intellectual property rights. This case seeks all just and equitable copyright, patent and trademark remedies on behalf of the inventors and owners of the MOVA Contour systems and methods, plaintiffs Rearden LLC and Rearden Mova LLC.

[7] https://youtu.be/F90iv9I-Sr4 and http://oscar.go.com/news/oscar-news/150209-ampas-sci-tech-awards-2015-winners (emphasis added).

II. THE PARTIES

6. Plaintiff Rearden LLC ("Rearden") is a California limited liability company having its principal place of business at 355 Bryant Street, Suite 110, San Francisco, California 94107.

7. Plaintiff Rearden Mova LLC ("Rearden Mova") is a California limited liability company having its principal place of business at 355 Bryant Street, Suite 110, San Francisco, California 94107. Rearden MOVA is wholly owned by Rearden.

8. Defendant The Walt Disney Company ("Disney Company") is a Delaware corporation having its principal place of business at 500 S. Buena Vista Street, Burbank, California 91521.

9. Defendant Walt Disney Motion Pictures Group, Inc. ("Disney MPG") is a California corporation having its principal place of business at 500 S. Buena Vista Street, Burbank, California 91521. Disney MPG is a wholly-owned subsidiary of defendant Disney Company.

10. Defendant Buena Vista Home Entertainment, Inc., d/b/a Walt Disney Studios Home Entertainment ("Buena Vista"), is a California corporation having its principal place of business at 500 S. Buena Vista Street, Burbank, California 91521. Buena Vista is a wholly-owned subsidiary of defendant Disney Company.

11. Defendant Marvel Studios, LLC ("Marvel") is a Delaware limited liability company having a principal place of business at 500 S. Buena Vista Street, Burbank, California, 91521. Marvel is a division of Disney MPG.

12. Defendant Mandeville Films, Inc. ("Mandeville") is a California corporation having its principal place of business at 3000 West Olympic Boulevard., Building 5, Santa Monica, California 90404.

III. JURISDICTION AND VENUE

13. This Court has subject matter jurisdiction under 28 U.S.C. § 1331, federal question jurisdiction, and § 1338, patent, trademark and copyright jurisdiction.

14. This Court has personal jurisdiction over all defendants. It has general personal jurisdiction over Disney MPG, Buena Vista, and Mandeville because they are corporations organized and existing under the laws of the State of California. It has general personal jurisdiction over

Disney Company and Marvel because their principal places of business are in the State of California and they have the capacity to sue and be sued in the State of California. And this Court has specific personal jurisdiction over all defendants because they have committed acts in the State of California that give rise to all acts of infringement asserted herein.

15. Venue is proper for plaintiffs' copyright and trademark infringement claims under 28 U.S.C. § 1400(a) and 1391 (b), (c) and (d). Disney MPG and Buena Vista reproduced and distributed, and authorized the performance and display of, *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* throughout this judicial district, and created derivative works without authorization in this judicial district. All other defendants are residents of the State of California and subject to personal jurisdiction in this judicial district.

16. Venue is proper for plaintiffs' patent infringement claims against defendant Disney MPG under 28 U.S.C. §§ 1400(b) because defendant Disney MPG is a California corporation, and has sufficient minimum contacts to be subject to personal jurisdiction in this judicial district if this judicial district were a separate state.

IV. FACTUAL ALLEGATIONS

A. The MOVA Contour systems and methods

17. The technology at the core of this case includes MOVA Contour Reality Capture ("Contour" or "MOVA Contour") technology that was conceived and developed by plaintiff Rearden and is currently owned by Rearden MOVA, which is wholly owned by Rearden.

18. MOVA Contour (http://www.rearden.com/mova.html) is one of many technologies incubated and offered by Rearden (www.rearden.com), a San Francisco Bay Area company founded in 1999 by Steve Perlman as an incubator for fundamental technology, creative works, and their interplay.

19. MOVA Contour is the fourth performance motion capture technology that Rearden has used in film and video game production since its founding 18 years ago. Facial performance motion capture, as both a technology and a tool for motion picture and video game production, falls squarely within the focus of Rearden's business. Rearden practices all of its technologies and inventions, either directly or indirectly by spinning off Rearden entities to use its technologies and

inventions. Despite holding a global portfolio of hundreds of its own patents, Rearden has never been in the business of licensing third parties to practice its technologies and inventions, and it has never licensed nor sought to license any of its technologies, inventions, patents, copyrights, or trademarks. Rearden's intellectual property portfolio exists only to protect Rearden's product and services offerings, and neither Rearden nor any of its controlled entities has ever previously sued any other person or entity for patent or copyright infringement.

20. Mr. Perlman previously worked as Principal Scientist at Apple where he developed, among many other technologies, the multimedia underpinnings of the color Macintosh as well as QuickTime. He left Apple for two startups that later went public, and designed and co-founded WebTV, which was later acquired by Microsoft. Microsoft named Perlman President of a new Silicon Valley division focused on television products, which ultimately developed Microsoft's cable, satellite, IPTV and Xbox 360 systems. Perlman left Microsoft in 1999 and self-funded a technology incubator and visual effects production studio in San Francisco called Rearden, Inc. (now Rearden LLC). Rearden focused largely on developing fundamental media-related technologies whose development times (e.g. 5 to 15 years) are beyond the horizon of venture capital and corporate research and development. Perlman has operated Rearden continuously through to this day. He is a prolific inventor. Perlman is a named inventor on over 500 patents worldwide, and among his many innovations are the following:

- The underlying technology for QuickTime (the video streaming technology for iPhone, iPad, iPod and Mac and much of the multimedia technology for Apple);
- The underlying technology for many of Microsoft's video products;
- OnLive cloud gaming technology;
- MOVA Contour facial capture technology;
- Artemis pCell wireless technology; and
- A wide range of other technologies in other fields, including medical and national defense life-saving technologies, often in cooperation with the U.S. government and U.S. agencies, sometimes not publicly disclosed.

21. A major technology focus of Rearden from its 1999 founding to this day is "performance motion capture," a production technology typically used to create a 3D animated character in a movie or a video game that moves exactly like a human performer. In 2000, Rearden began offering motion capture services for movies and video games (through wholly-owned subsidiaries Rearden Studios and then MOVA LLC) using existing commercial "marker-based" motion capture systems that could capture and track body ("skeletal") motion, but there was no known technology at that time that could capture and track the subtleties of human facial motion in a realistic, life-like manner, despite an urgent need:

> "The state of the art [before Contour] was … marker-based motion capture…we looked at a number of other films at the time that were using facial marker tracking…as you can see, it gives you a pretty crappy performance… What we realized was that what we needed was the information that was going on between the markers. We needed the subtleties of the skin. We needed to see skin moving over muscle moving over bone. We needed creases and dimples and wrinkles…" [8]

Rearden set out to invent and perfect a photorealistic facial motion capture and tracking system.

22. Over the next five years, Rearden's technical team tried dozens of different approaches to solve the problem, ultimately leading to the conception and perfection of a solution to the long-felt need—a technology that precisely captures and tracks the 3D shape and motion of a human face to sub-millimeter precision, producing photorealistic results. Rearden branded the technology Contour Reality Capture, and offered it as a service. This innovative technology was recognized in the motion picture industry as revolutionary:

> "Contour's promise is enormous," [Director David] Fincher said, "The notion that the human face in all its subtleties could be mapped in real time and such density of surface information opens up so many possibilities for both two- and three-dimensional image makers and story-tellers."
>
> "I live in this environment, and I see stuff every day, so I get a little jaded," said [Digital Domain Senior VP and Executive Producer Ed] Ulbrich… "Other developments have been gradual, more evolutionary than revolutionary. Contour separates the performance from the

[8] Ulbrich, Ed, "How Benjamin Button Got His Face" TED Talk, Feb 2009. https://www.ted.com/talks/ed_ulbrich_shows_how_benjamin_button_got_his_face.

> photography. It's a substantial turning point in the business, and I think it will change how picture are made."[9]

23. MOVA Contour's technical breakthrough was introduced at the Special Interest Group on Computer Graphics and Interactive Techniques ("SIGGRAPH") Conference on July 31, 2006 to wide acclaim, including photographs of Contour's systems and methods on the front page of the *New York Times*[10], page B1 of the *Wall Street Journal*[11], and *The Hollywood Reporter*, among other publications. Mr. Perlman was invited to present MOVA Contour technologies and their practical applications in movie production to the Directors Guild of America[12]. And he was invited on many occasions to give public presentations on MOVA Contour and the development process that led to its invention, for example in a speech at Columbia University[13].

24. The following photograph[14] from an article in *The Hollywood Reporter* on the day MOVA Contour was unveiled—July 31, 2006—was directed to movie and video game industry professionals and illustrates several Contour Program output files, which are described in further detail later in this complaint:

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[9] Marlowe, Chris, "Contour mapping intricate detail: Mova revolutionizing motion-capture process with new system," The Hollywood Reporter, July 31, 2006, http://www.rearden.com/press/2006/Contour-HollywoodReporter-060731-2.pdf.

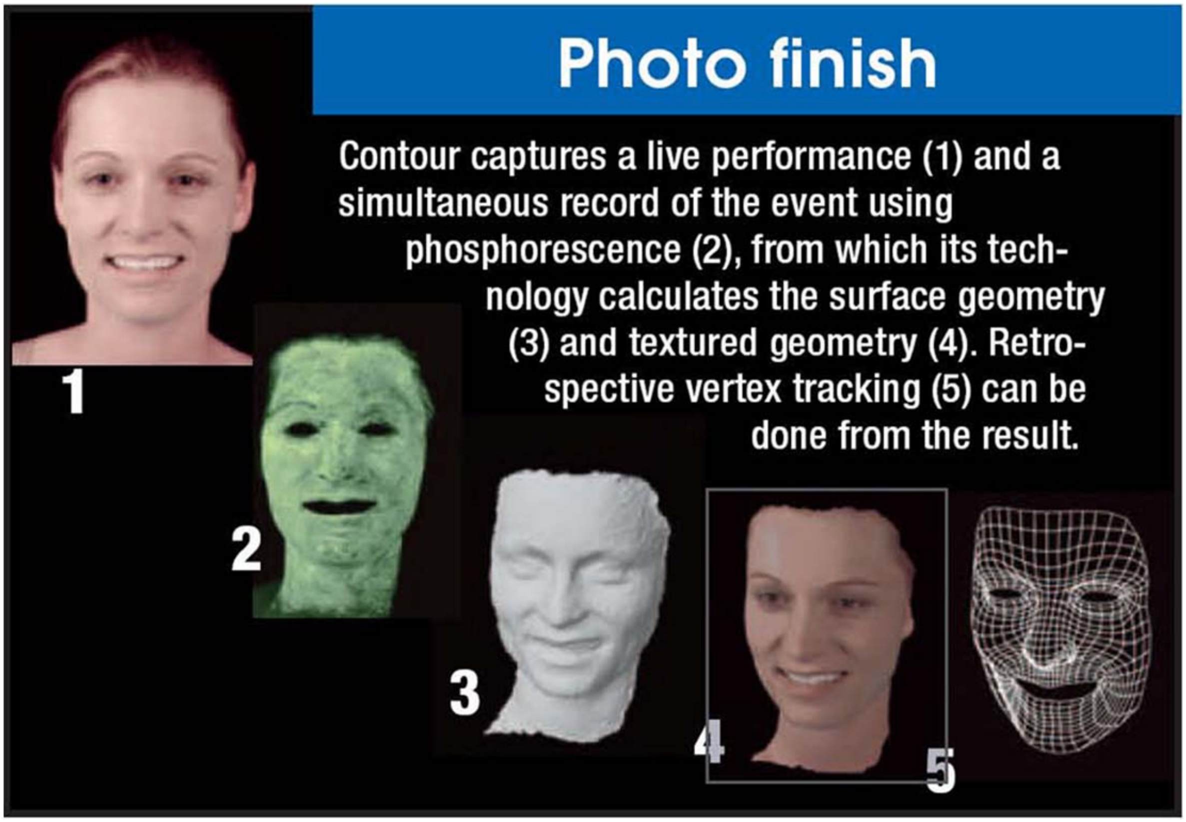
[10] Markoff, John, "Camera System Creates Sophisticated 3-D Effects", New York Times, July 31, 2006. https://nyti.ms/2uAfwGF.

[11] Wingfield, Nick, "Digital Replicas May Change Face of Films", July 31, 2006. http://on.wsj.com/2teIRbO.

[12] "'Facial Performance Capture for Photoreal Digital Characters' Presented by Steve Perlman, Founder & President, Mova", Digital Day 2007: The Future of the Future, Directors Guild of America, July 28, 2007. http://ishindler.com/articles/DGA_Digital_Day_flyer07.pdf.

[13] https://youtu.be/1QxrQnJCXKo.

[14] Marlowe, op. cit.



25. Also on July 31, 2006, the following photographs appeared in a *New York Times* article directed to a general readership audience, which illustrate an application of the phosphor-based makeup used in MOVA Contour facial motion capture methods:

Actors must cover themselves with makeup containing phosphorescent powder for Contour, a system that can create 3-D effects. Austin Hice and three Contour Program output files (this photograph appeared on the front page):[15]

An actress goes from live performance, left, to phosphorescence, to a Contour-generated image, right. Mova.com

26. Also on July 31, 2006, the following photograph appeared in a *Wall Street Journal* article directed to a general readership audience, which illustrates the same three Contour Program output files with "non-technical reader" annotations for each image (the web version of the article included a video that showed the three output files in motion):[16]

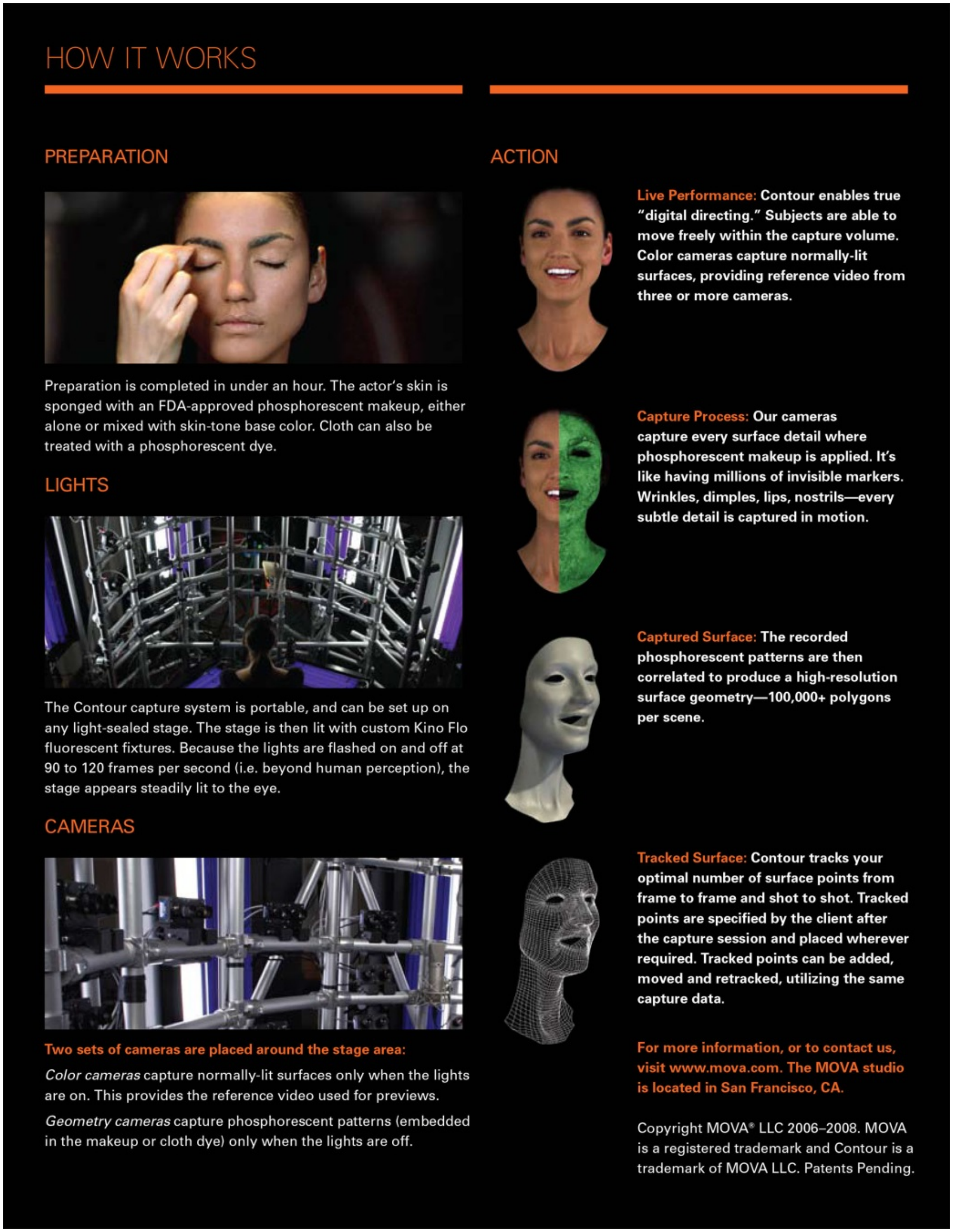
[15] Markoff, op. cit.

[16] Wingfield, op. cit.

27. In one embodiment, MOVA Contour uses an array of cameras whose shutters are synchronized to strobing white lights and ultraviolet lights ("black lights") in conjunction with phosphor-based makeup applied to the performer in random patterns, with the entire system controlled by highly-advanced and proprietary MOVA Contour software that operates the Contour system in real time to capture an actor's performance frame-by-frame, and then creates original Contour Program output files based on the performance, frame-by-frame.

28. The Contour system is controlled, and the captured camera images are processed, by several computers running copyrighted software. Some of the software operates prior to a facial capture session to prepare and calibrate the Contour system, some of the software operates in real-time during a live facial capture, and some of the software operates after the facial capture. Collectively, this Contour software is referred to herein as the "Contour Program." The Contour Program produces several types of output files, some of which are used by the Contour Program itself for further processing, and some are used for driving a CG face in a movie or video game.

29. One embodiment of the operation of the MOVA Contour system and methods, and the Contour Program is described in the following page from a MOVA Contour brochure below, distributed at computer graphics and entertainment industry conferences:



HOW IT WORKS

PREPARATION

Preparation is completed in under an hour. The actor's skin is sponged with an FDA-approved phosphorescent makeup, either alone or mixed with skin-tone base color. Cloth can also be treated with a phosphorescent dye.

LIGHTS

The Contour capture system is portable, and can be set up on any light-sealed stage. The stage is then lit with custom Kino Flo fluorescent fixtures. Because the lights are flashed on and off at 90 to 120 frames per second (i.e. beyond human perception), the stage appears steadily lit to the eye.

CAMERAS

Two sets of cameras are placed around the stage area:

Color cameras capture normally-lit surfaces only when the lights are on. This provides the reference video used for previews.

Geometry cameras capture phosphorescent patterns (embedded in the makeup or cloth dye) only when the lights are off.

ACTION

Live Performance: Contour enables true "digital directing." Subjects are able to move freely within the capture volume. Color cameras capture normally-lit surfaces, providing reference video from three or more cameras.

Capture Process: Our cameras capture every surface detail where phosphorescent makeup is applied. It's like having millions of invisible markers. Wrinkles, dimples, lips, nostrils—every subtle detail is captured in motion.

Captured Surface: The recorded phosphorescent patterns are then correlated to produce a high-resolution surface geometry—100,000+ polygons per scene.

Tracked Surface: Contour tracks your optimal number of surface points from frame to frame and shot to shot. Tracked points are specified by the client after the capture session and placed wherever required. Tracked points can be added, moved and retracked, utilizing the same capture data.

For more information, or to contact us, visit www.mova.com. The MOVA studio is located in San Francisco, CA.

Copyright MOVA® LLC 2006–2008. MOVA is a registered trademark and Contour is a trademark of MOVA LLC. Patents Pending.

30. **Preparation:** Phosphor-based makeup (various types of phosphor are supported) is applied in a random pattern on the performer's face, neck, etc.—whatever body surfaces are intended to be captured—typically using an airbrush, sponge or cotton swab.

31. **Lights:** The performer sits or stands in the arc-shaped Contour rig in a light-sealed stage. One part of the Contour Program causes white lights and black lights to be flashed so rapidly that the flashing is beyond human perception and it appears to the performer and observers that the lights are on steadily. Typically fluorescent lamps or LEDs are used.

32. **Cameras:** One part of the Contour Program causes the shutters on two pluralities of cameras, distributed around the rig, to open and close synchronously with the flashing of the lights such that:

(a) a first plurality of cameras open their shutters when the white lights are on, illuminating the natural skin color of the performer; and

(b) a second plurality of cameras open their shutters when the white lights are off and the phosphor-based makeup is emitting random patterns of light (typically in green or blue).

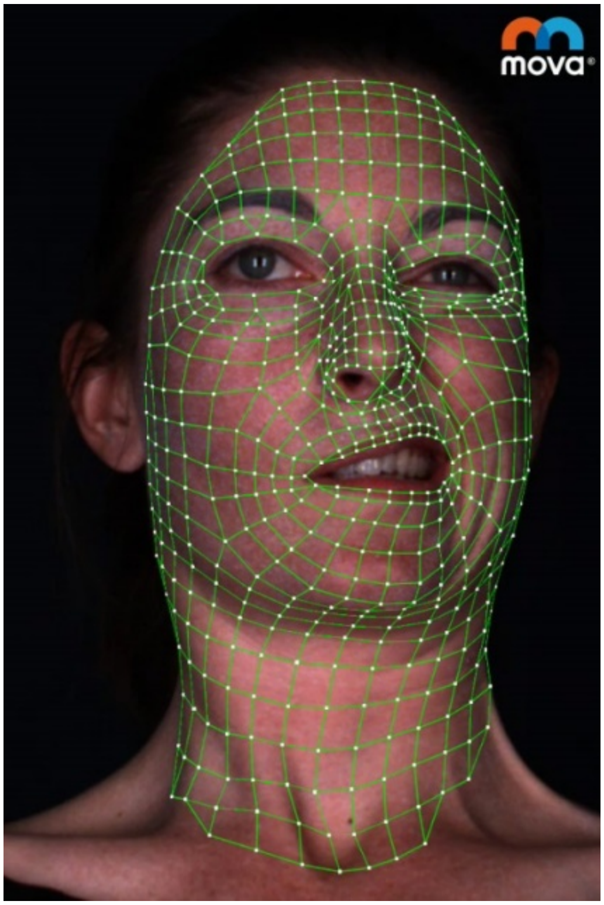
33. **Action:** The performer provides her or his facial performance while one part of the Contour Program causes the output of each of the plurality of cameras to be recorded onto storage devices. The output files of the two pluralities of cameras are illustrated in each half of the face in the "Capture Process" section of the brochure reproduced above.

(a) the output of the first plurality of cameras is called herein the "**Skin Texture**" and it looks like normal skin and facial features of the performer from multiple angles, largely without visible makeup, and

(b) the output of the second plurality of cameras is called herein the "**Makeup Pattern**" and it looks like a random pattern of green or blue largely without showing the skin or other facial features (e.g. eyes or mouth) of the performer.

34. The Contour Program uses the Makeup Pattern output files to compute a high-resolution 3D surface that moves in the shape of the skin of the performer with sub-millimeter precision. This output file is called herein the "**Captured Surface**" and, rendered on a display, it looks like a 3D bust of the performer's skin in motion. A still frame of a Captured Surface is shown in the "Captured Surface" section of the brochure reproduced above.

35. The Contour Program also uses the Makeup Pattern output files to compute a high-resolution 3D mesh that tracks 3D points on the skin of the performer as the skin moves from frame-to-frame. This output file is called herein the "**Tracking Mesh**" and, rendered on a display, it looks like a 3D mesh that exactly follows the movement, stretching and wrinkling, etc., of the skin as the performer moves her or his face. A still frame of a Tracking Mesh is shown in the "Tracked Surface" section of the brochure reproduced above. The Tracking Mesh tracks the subtleties of the performer's facial motion with sub-millimeter precision. For example, if the performer's expression causes the cheeks to bulge out from a smile, the 3D points on the mesh tracking the cheek will bulge out in exactly the same 3D shape. If the forehead furrows into wrinkles, then the 3D points on the mesh tracking the forehead will furrow into wrinkles in exactly the same 3D shape. The Tracking Mesh can be configured to be at any resolution, whether thousands or even millions of 3D points, depending on the level of tracking detail required by the project. An example of a Tracking Mesh tracking skin deformation from an extreme expression is shown here:



36. The Contour output files specified above can be used for many different applications. Often they are used for "retargeting" the performer's face onto another 3D model of a face, either a real face (e.g. when Rupert Grint (Ron Weasley) transforms into the face of Daniel Radcliffe (Harry Potter) in *Harry Potter and the Deathly Hallows, Part I*), or a fictional face (e.g. Mark Ruffalo's face transforms into the Hulk's superhero face in *The Avengers*, Brad Pitt's 44-year-old face retargeted to an 87 year-old version of his face in *The Curious Case of Benjamin Button*), or Jeff Bridge's face retargeted in *TRON: Legacy* (2010) to his 28 year-younger face as it appeared in *TRON* (1982).

37. When the retargeting is from a first performer's real face to the real face of a second performer, then each performer's face is captured by the Contour system, with output files created by the Contour Program for each performer. The Captured Surface, Tracking Mesh, and Skin Texture output files can be used in the construction of a 3D model of the face of the second performer, and then the Tracking Mesh of the first performer is used to control the 3D model of the second performer's face. The result is a 3D model of the face of the second performer that is controlled by the motion of the first performer's face. For example, the photograph below shows a man (the "second performer") captured by Contour. The 3D model of a CG head (center) was generated from the Contour Program output files, including the Makeup Pattern (left) and Tracking Mesh (right):

The photograph below shows the performance of the woman ("the first performer") in the brochure reproduced above (showing her Skin Texture (left) and Tracking Mesh (right) Contour output files) retargeted to the man's CG head in the above photo by retargeting the 3D points on her Tracking Mesh to the 3D model of the man's CG head. As you can see in her Live Performance (showing the Skin Texture output file, below left), her facial expression causes the man's CG head to track her facial expression. Contour's Tracking Mesh is so precise that a high degree of realism is maintained, even though the man's CG face and head have a very different shape and size than hers, and he is male and she is female. In fact, Contour output files capture the woman's performance with such fidelity that observers of the animation have commented that despite the fact that the man's CG face clearly has a male *shape*, the *motion* appears to be that of a female face. The video of this and other Contour examples is available on Rearden's home page (www.rearden.com, click on the MOVA logo and click on the video), or directly (www.rearden.com/mova.php or https://vimeo.com/86130623):

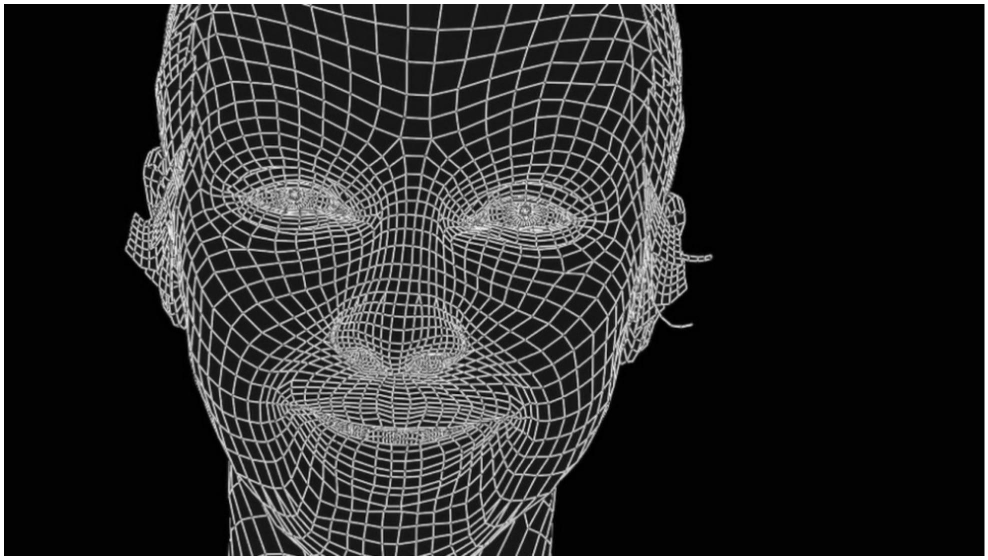
38. A similar retargeting process can be performed with a fictional head. For example, the two photographs below are of a performer whose face was captured in the Contour system showing the Skin Texture output file on the left and how she appeared to the naked eye (or a conventional camera), showing the Makeup Pattern combined with Skin Texture on the right:

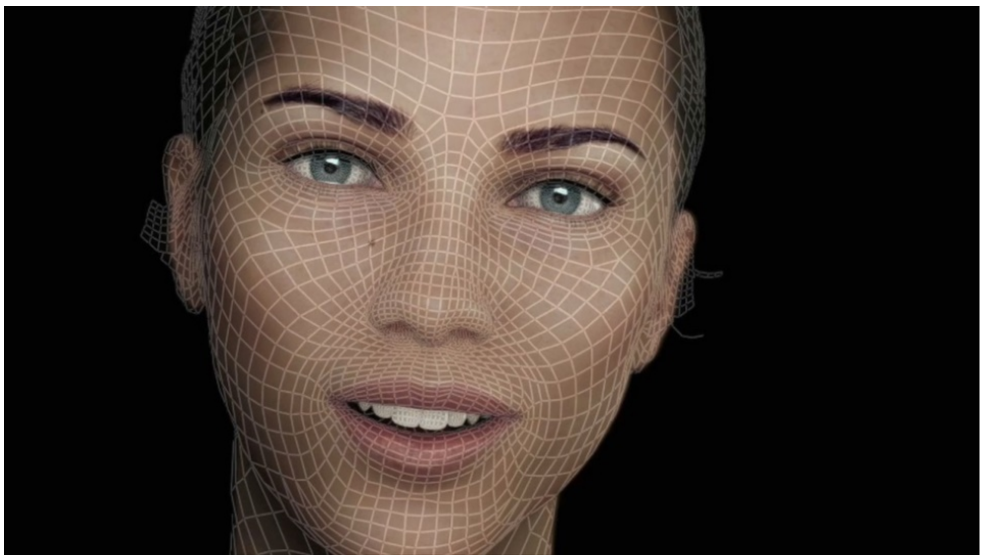
39. The photograph below shows several views of a CG model of the head of a video game character that was created by an artist:

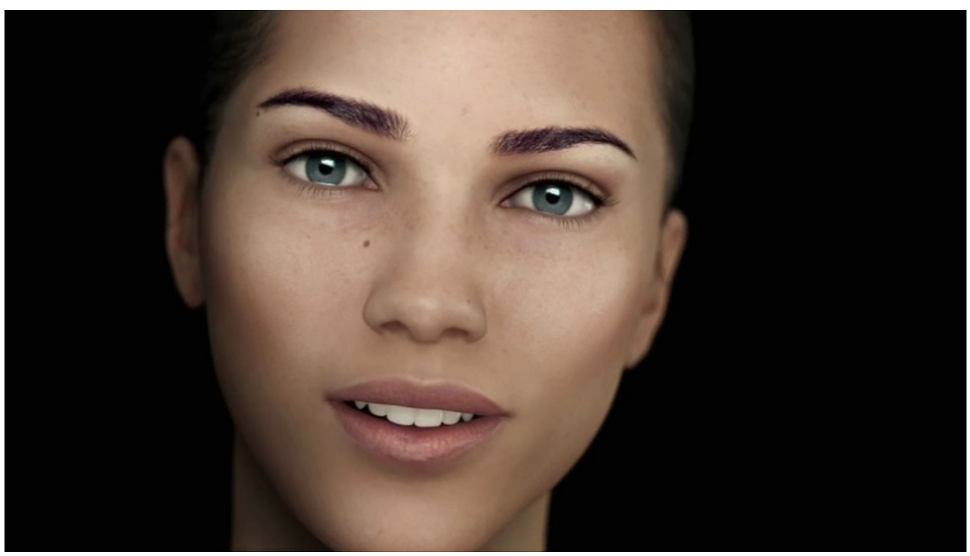
Although the head looks almost photoreal (it was only a test, not a polished CG model) when it is in a neutral pose and immobile, if the face were animated—whether through hand-drawn animation or prior art motion capture techniques—any photorealism would be lost because the human eye and brain are precisely attuned to notice any unnatural imperfection in facial motion. But, by using the Contour system and methods and the Contour Program, every subtle motion of the human face is captured with sub-millimeter precision, producing output files that retain that precision and can be retargeted to any fictional CG head, bringing it to life.

40. The photographs below show the above video game character's head in two expressions retargeted from the Tracking Mesh generated by the Contour Program from the Contour facial capture of the above actress. Although the photorealism of the motion cannot be seen in static photographs, the motion is realistic and life-like, despite the fact that the performer's face is a very different shape than that of the CG head. Even in a static image, however, one can see how the expressionless CG model tracked the good-natured expression of the actress:

41. A 3D "wireframe" (a mesh of 3D points) of the retargeted CG Character's head is shown below, separately and overlaid upon the rendered image, and then the final rendered image:







42. In summary, the MOVA Contour Program does substantially all of the work in the process of precisely transforming the facial performance of a live performer, capturing the most subtle of facial motions with sub-millimeter precision to drive with realism the life-like motion of faces of CG characters that appear in a finished movie, video game, or other production, or utilized for other applications. The process begins by airbrushing or otherwise applying a random pattern of phosphor-based makeup on a performer, having the performer sit or stand in the arc-shaped Contour rig surrounded by an array of white lights and black lights and two pluralities of cameras, with the lights flashed rapidly and synchronized with the camera shutters as Skin Textures and Makeup Patterns are captured by the Contour Program. The Contour Program then processes the Makeup Pattern to capture thousands or even millions of 3D points as the performer's face moves, producing precise Captured Surface and Tracking Mesh files. Thus, the Contour Program produces output files that include the following:

- **Skin Texture**, showing the normal skin and facial features of the performer from multiple angles, largely without visible makeup
- **Makeup pattern**, showing the random pattern of makeup on the performer from multiple angles, largely without visible skin or facial features
- **Captured Surface**, a high-resolution moving 3D surface in the shape of the performer's skin as the performer's face moves
- **Tracking Mesh**, a high-resolution 3D mesh that exactly tracks the movement, stretching, wrinkling, etc. as the performer moves their face.

The Tracking Mesh can then be retargeted to a CG face, driving that CG face with photorealistic and natural motion, thereby precisely preserving every subtlety of human expression by the performer in the final movie, video game, or other production.

43. Within days after the Mova Contour Program, system and methods were unveiled at SIGGRAPH in 2006, tests and production began on one of the first movies utilizing MOVA Contour, *The Curious Case of Benjamin Button.* The movie was released in 2008. The photorealistic reverse-aging of Brad Pitt's face from an 87-year-old man backwards to his then-age of 44, and then

further backwards to a younger age, was widely lauded as a visual effects ("VFX") milestone, the first ever photorealistic CG face, winning an Academy Award for Best Visual Effects for the team at the VFX production company, Digital Domain, which had hired Rearden to operate the MOVA Contour system to capture Brad Pitt's face and generate Contour Program output files for the film.

44. In a widely-viewed TED (Technology, Entertainment, Design) Talk entitled, "How Benjamin Button Got His Face," Ed Ulbrich, Digital Domain's Senior VP and Executive Producer (subsequently the CEO of successor Digital Domain 3.0, Inc.), confirmed that *The Curious Case of Benjamin Button* would have been "impossible" to make but for MOVA Contour's system and methods and the unprecedented facial capture precision and subtlety of the MOVA Contour Program's output files. Ulbrich stated in the talk:

> "We first got involved in *The* [*Curious Case of Benjamin Button*] project in the early 90s.... We took a lot of meetings and we seriously considered it. But at the time, we had to throw in the towel. **It was deemed impossible**. **It was beyond the technology of the day to depict a man aging backward**... The project came back to us a decade later.... **we came across a remarkable technology called Contour**… creating a surface capture as opposed to a marker capture…**This was when we had our 'Aha!' This was the breakthrough**…we could put Brad [Pitt] in this [Contour] device, and use this Contour process, and we could stipple on this phosphorescent makeup and put him under the black lights, and we could, in fact, scan him in real time… effectively, we ended up with a [Contour Program output file] 3D database of everything Brad Pitt's face is capable of doing…we could transpose the [Contour Program output file] data of Brad at [then-aged] 44 onto [a 3D model of] Brad at 87. So now, we had a 3D database of everything Brad Pitt's face can do at age 87, in his 70s and in his 60s."[17]

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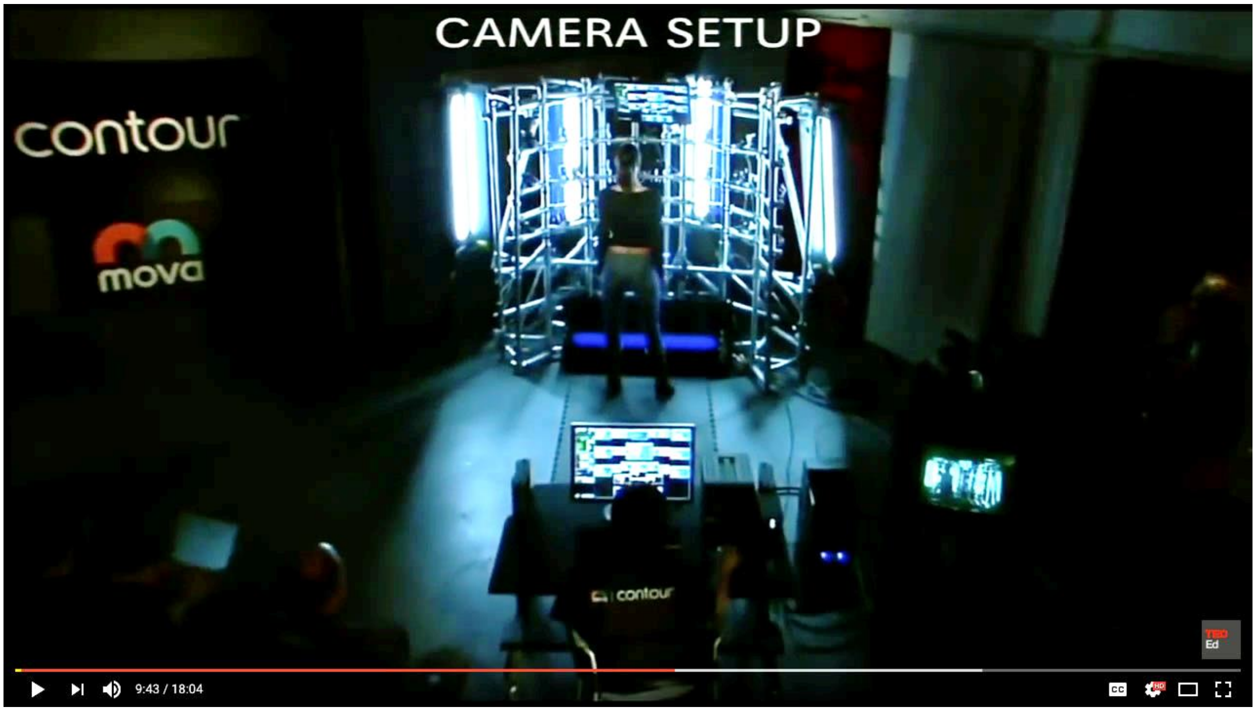
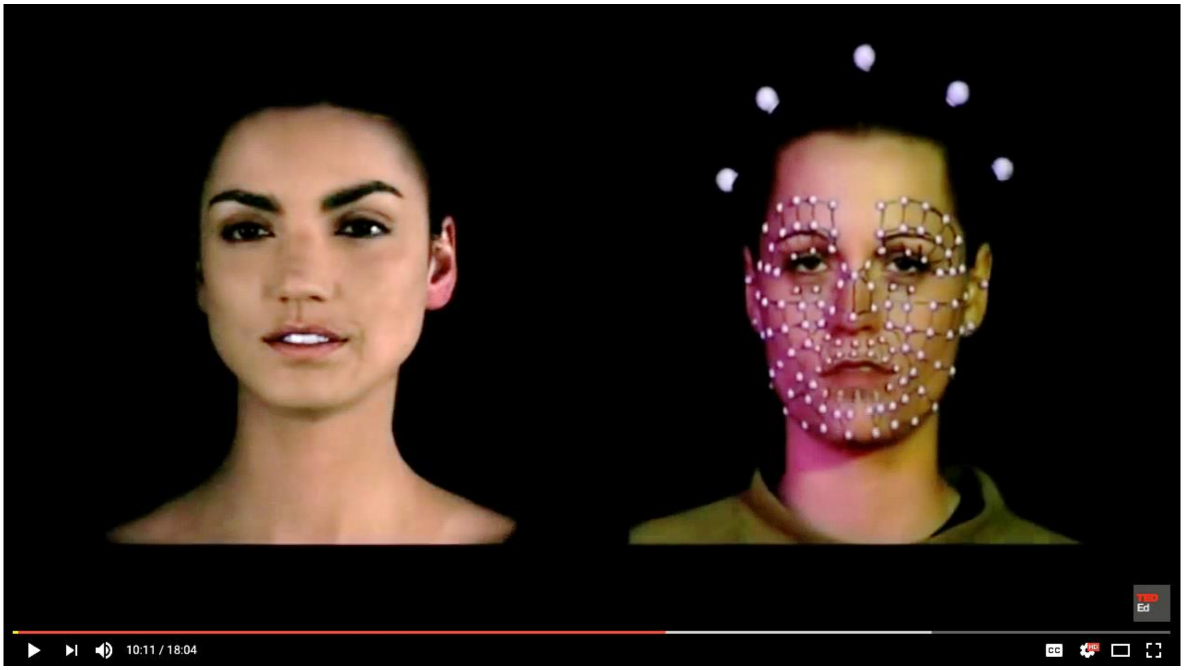
[17] Ulbrich, op. cit. (emphasis added).

45. In the TED Talk, Ulbrich showed details of the MOVA Contour system and methods, Contour Program output files, and how the CG face of Benjamin Button in the final movie was derived from the Contour Program output files. The following paragraphs describe still frames from the TED talk (labeled by "Minutes:Seconds" from the start of the video).

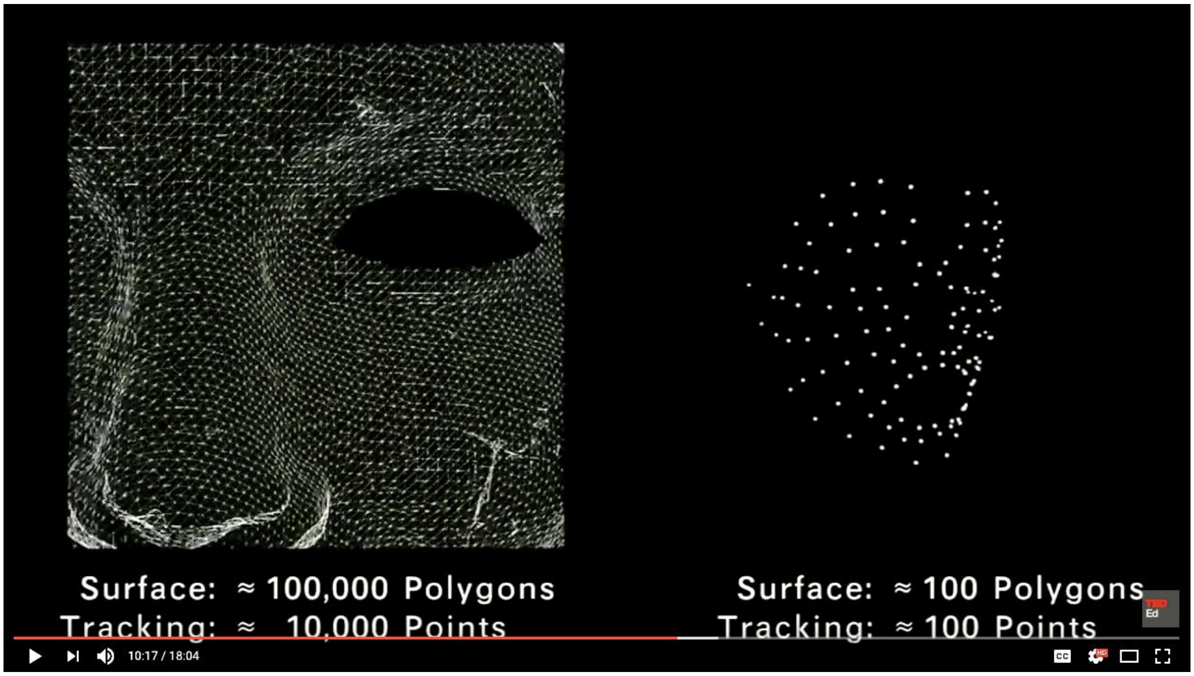
46. **9:43:** The branded MOVA Contour "rig", a semicircle of two pluralities of cameras with synchronized white lights and black lights surrounding a performer, with MOVA staff operating the Contour system:



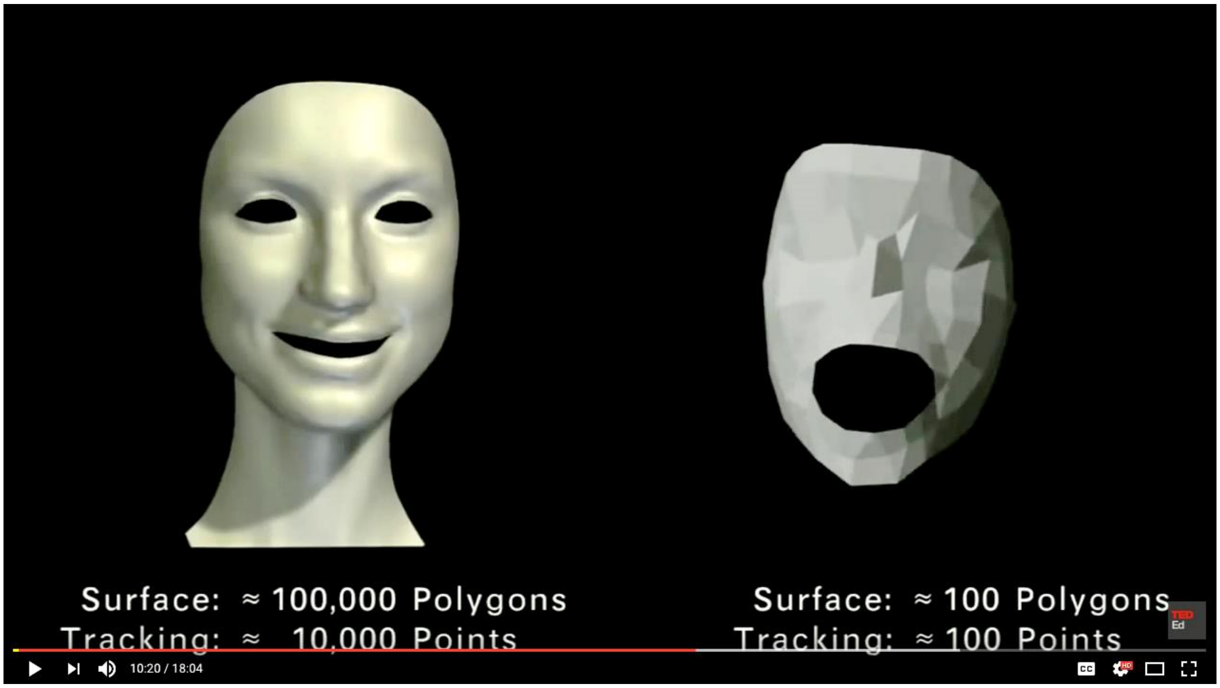
47. **10:11:** On the left, Contour Program **Skin Texture** output file, showing the performer's natural skin color and facial features. On the right, a performer with conventional motion capture markers on her face:



48. **10:17:** On the left, Contour Program **Tracking Mesh** output file, showing hundreds of thousands of 3D points, the Tracking Mesh resolution is so high that the points can only be seen by zooming in. In contrast, conventional marker-based resolution is shown on the right:



49. **10:20:** On the left Contour Program **Captured Surface** output file, showing high-resolution surface geometry. In contrast, marker-based facial capture surface geometry on the right:

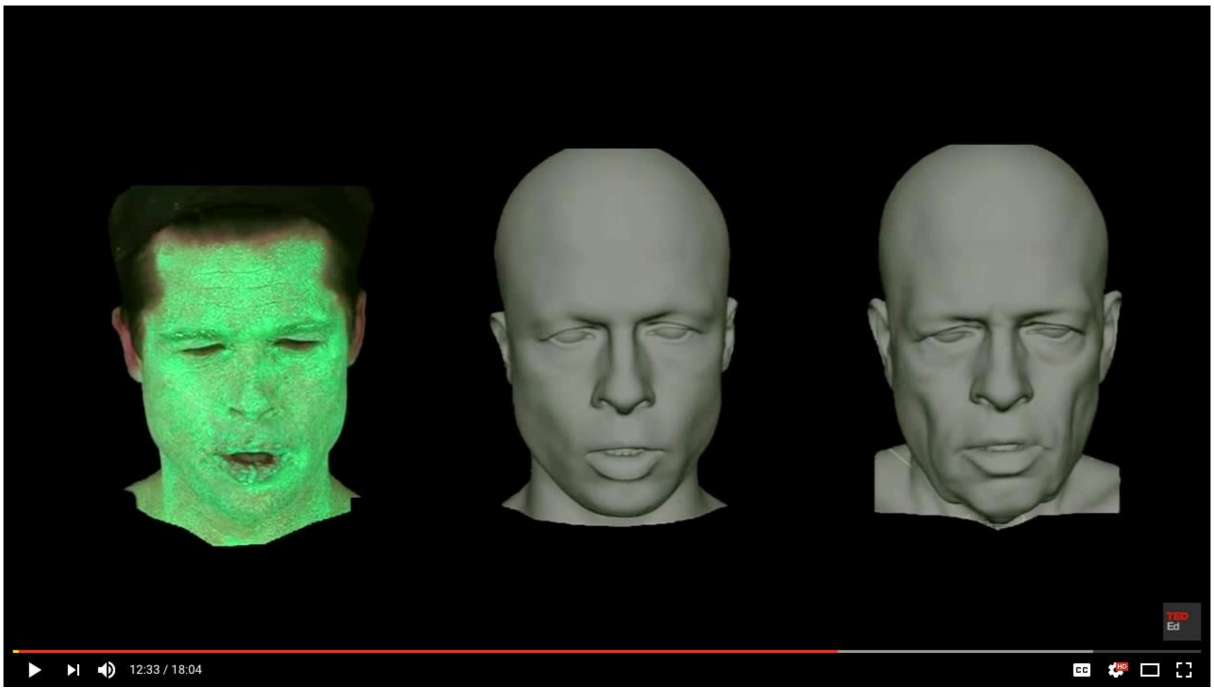


50. **10:39:** Contour Program **Makeup Pattern** output files, showing random patterns of phosphor-based makeup. Each of the four Contour facial captures of Mr. Pitt was a separate motion facial performance used for a different facial expression of Benjamin Button. The Contour Program created high-resolution **Captured Surface** and **Tracking Mesh** output files from each of these:

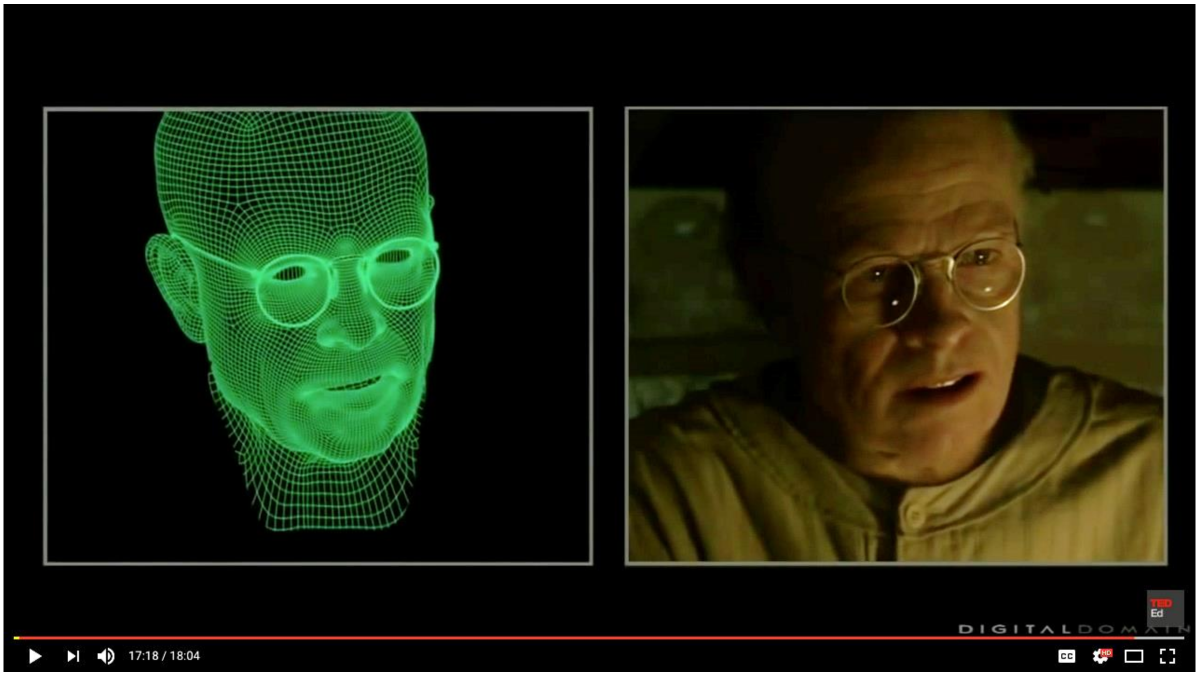
51. **10:49:** Contour Program **Makeup Pattern** output files, showing how many Contour output files were used. Each of the Contour facial captures was a separate motion facial performance of Mr. Pitt used for a different facial expressions of Benjamin Button. The Contour Program created high-resolution **Captured Surface** and **Tracking Mesh** output files from each of these, creating a database of Capture Surface and Tracking Mesh Contour output files:

52. **12:33:** Contour Program **Makeup Pattern** output file (left), **Captured Surface** output file (middle), retargeted **Captured Surface** and **Tracking Mesh** output files to a derivative fictional aged head (right), are shown below. The 3D points of the Contour **Tracking Mesh** output file of Mr. Pitt's actual face were retargeted to corresponding 3D points on the fictional "maquette" (i.e. hand-made 3D bust) of Mr. Pitt at age 87. As a simple example, the 3D point on the right corner of Mr. Pitt's actual mouth could correspond to the 3D point on the right corner of the 3D maquette's mouth. As Mr. Pitt's smile widens during the Contour capture session, moving the tracked 3D point on the corner of his mouth outward, the retargeted 3D point on the maquette's mouth would move proportionately outward causing the 87-year-old smile to widen. As described by Mr. Ulbrich: "[Left:] This is Brad doing one of the [character expression] poses. [Middle:] And here's the resulting [**Captured Surface** output file] data that comes from that, the model that comes from that. [Right:]

Retargeting is the process of transposing that [**Captured Surface** and **Tracking Mesh** output file] data onto another model. And because the life cast, or the bust—the maquette—of Benjamin was made from Brad, we could transpose the [**Captured Surface** and **Tracking Mesh** output file] data of Brad at 44 [years] onto Brad at 87[years]. Effectively, we ended up with a [**Captured Surface** and **Tracking Mesh** output file] 3D database of everything Brad Pitt's face is capable of doing…we could transpose the [**Captured Surface** and **Tracking Mesh** output file] data of Brad at [then-aged] 44 onto [a 3D maquette of] Brad at 87. So now, we had a 3D database of everything Brad Pitt's face can do at age 87, in his 70s and in his 60s":



53. **17:18:** On the left is 87-year-old fictional head maquette Tracking Mesh retargeted from, and derivative of, a Contour Program **Tracking Mesh** output file, with a pair of glasses added in as a prop. The final derivative face is shown on the right after various steps such as texturing and lighting that is applied to the maquette. The resulting derivative face is integrated into the live-action footage of the final scene, producing the final derivative work:

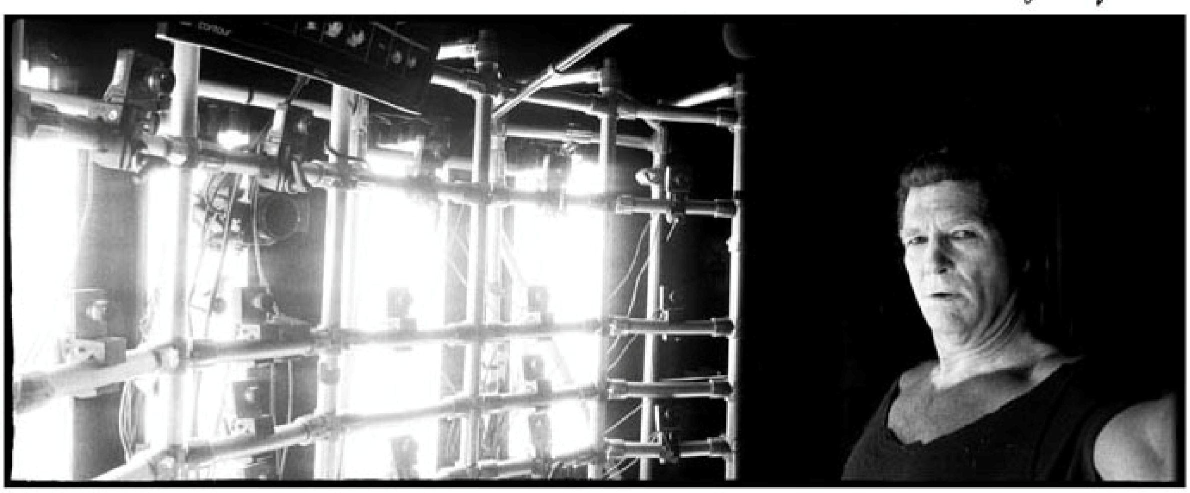


54. The photorealistic reverse-aging derived from the MOVA Contour system, methods and output files received wide acclaim when *The Curious Case of Benjamin Button* was released in December of 2008. But even before the movie's release, word of the unprecedented CG face realism achieved by MOVA Contour was spreading through the VFX industry. In July of 2008, defendant Disney hired MOVA for another reverse-aging movie, *TRON: Legacy,* the sequel to Disney's 1982 *TRON.* MOVA Contour was used in a similar manner as in *Benjamin Button* to reverse-age the face of Jeff Bridges, the star of *TRON* and *TRON: Legacy*, to look as he did in 1982. Mr. Bridges published his experience of using MOVA Contour through wide-angle black-and-white photography and hand-written notations, below:[18]

[18] http://www.jeffbridges.com/tron_book/tron_book_08.html.

. . . and Ready . . .

. . . . to be digitized

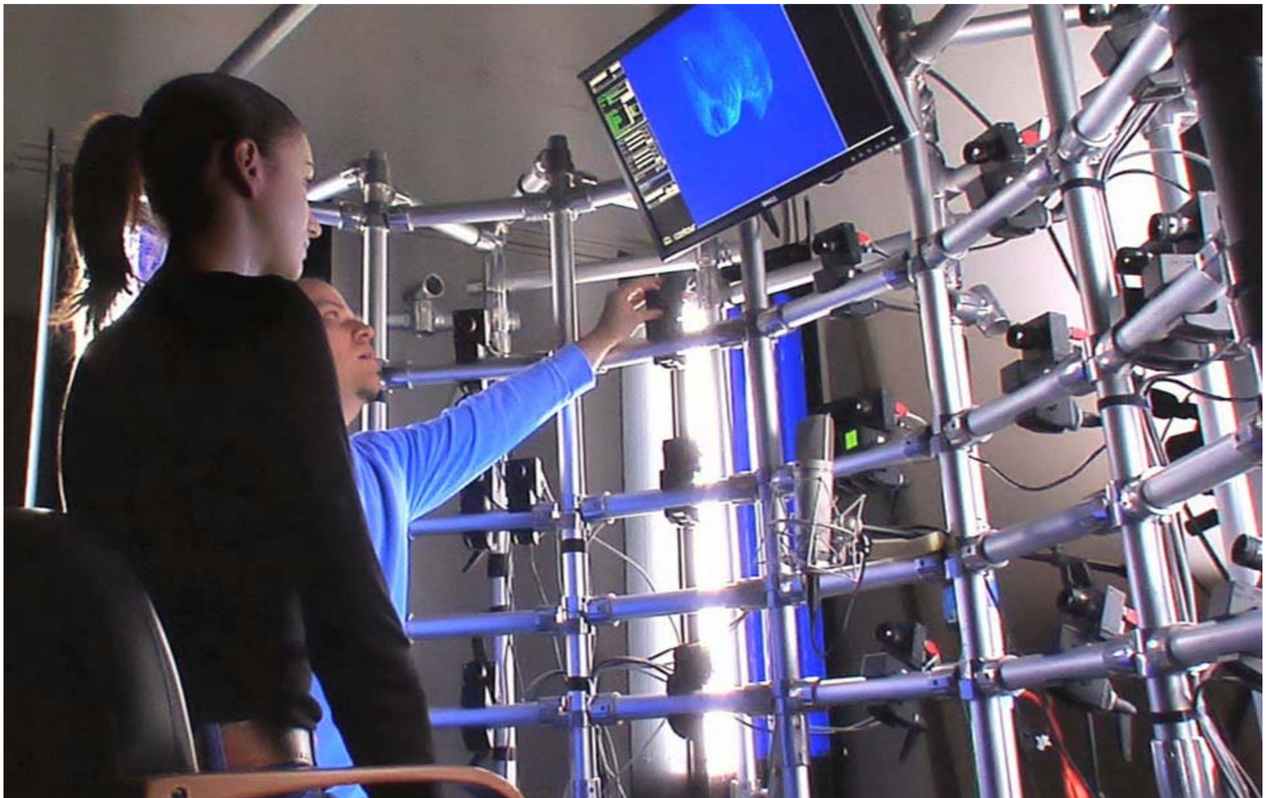


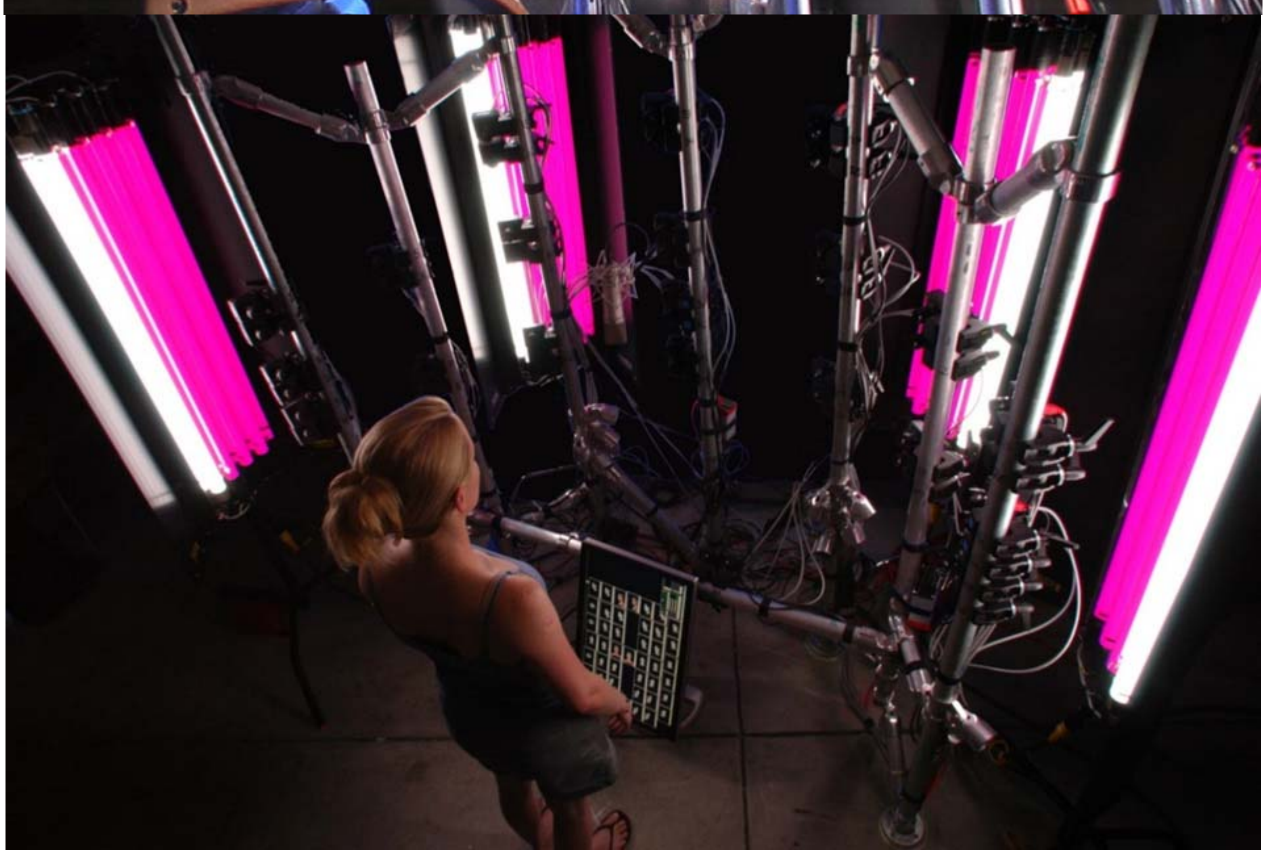
Mova Technology came up with this rig . . .

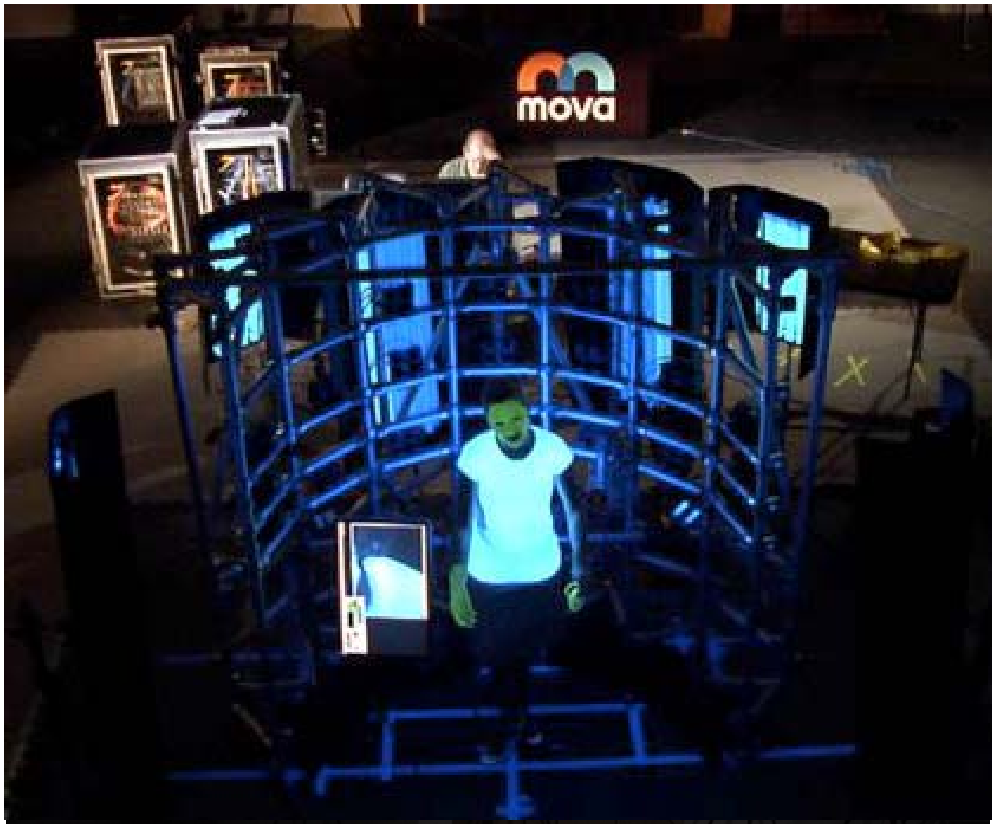
55. In addition to transforming an actor's age, the same process can be used for many other VFX purposes, such as transforming an actor's face into a creature (e.g. the Hulk in defendant Disney's *The Avengers*), or mapping one character's face onto another's (e.g. Rupert Grint (Ron Weasley) was transformed into Daniel Radcliffe (Harry Potter) in *Harry Potter and the Deathly Hallows, Part I*).

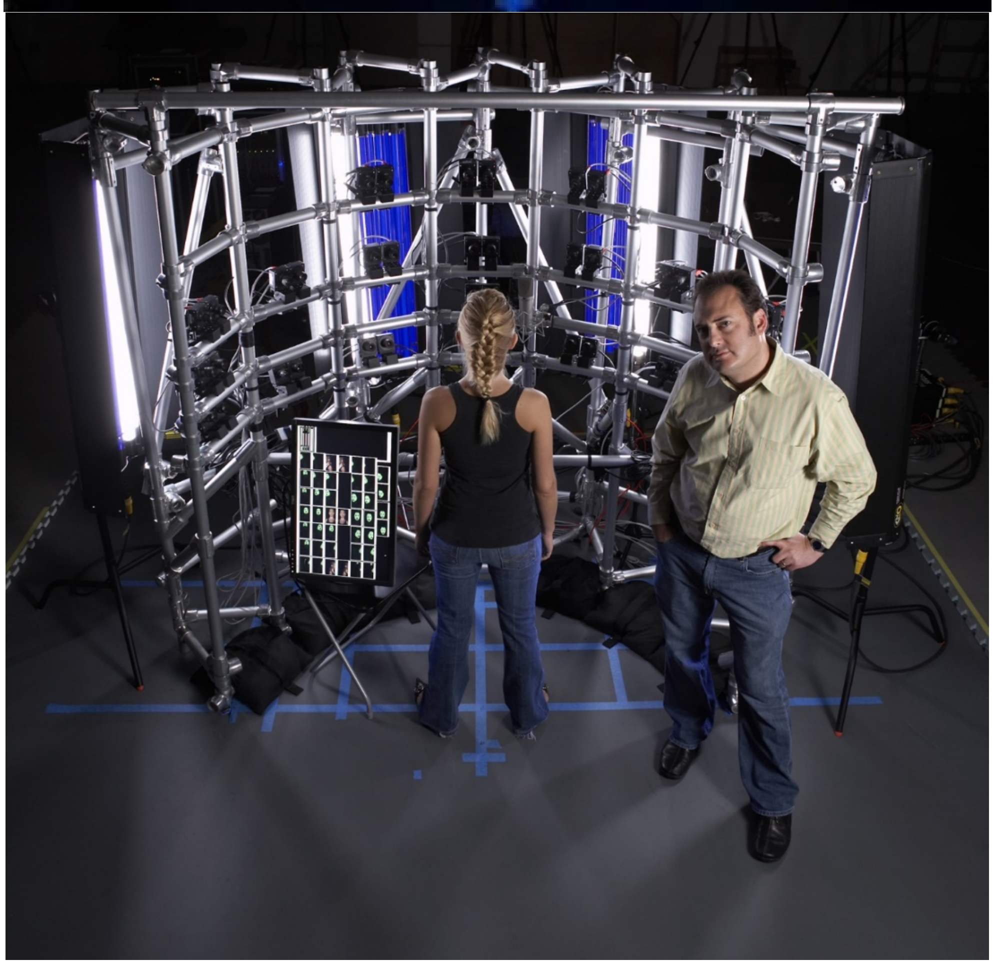
56. The following four photographs show the arc-shaped Contour rig, two pluralities of synchronized cameras, white light and black light sources, computers running the Contour Programs, and actors wearing the phosphor-based makeup of the MOVA Contour systems and methods, used lawfully by defendants and operated by Rearden and Rearden-controlled entities in *TRON: Legacy*

(2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012) (Mr. Perlman appears at the right in the last photograph):

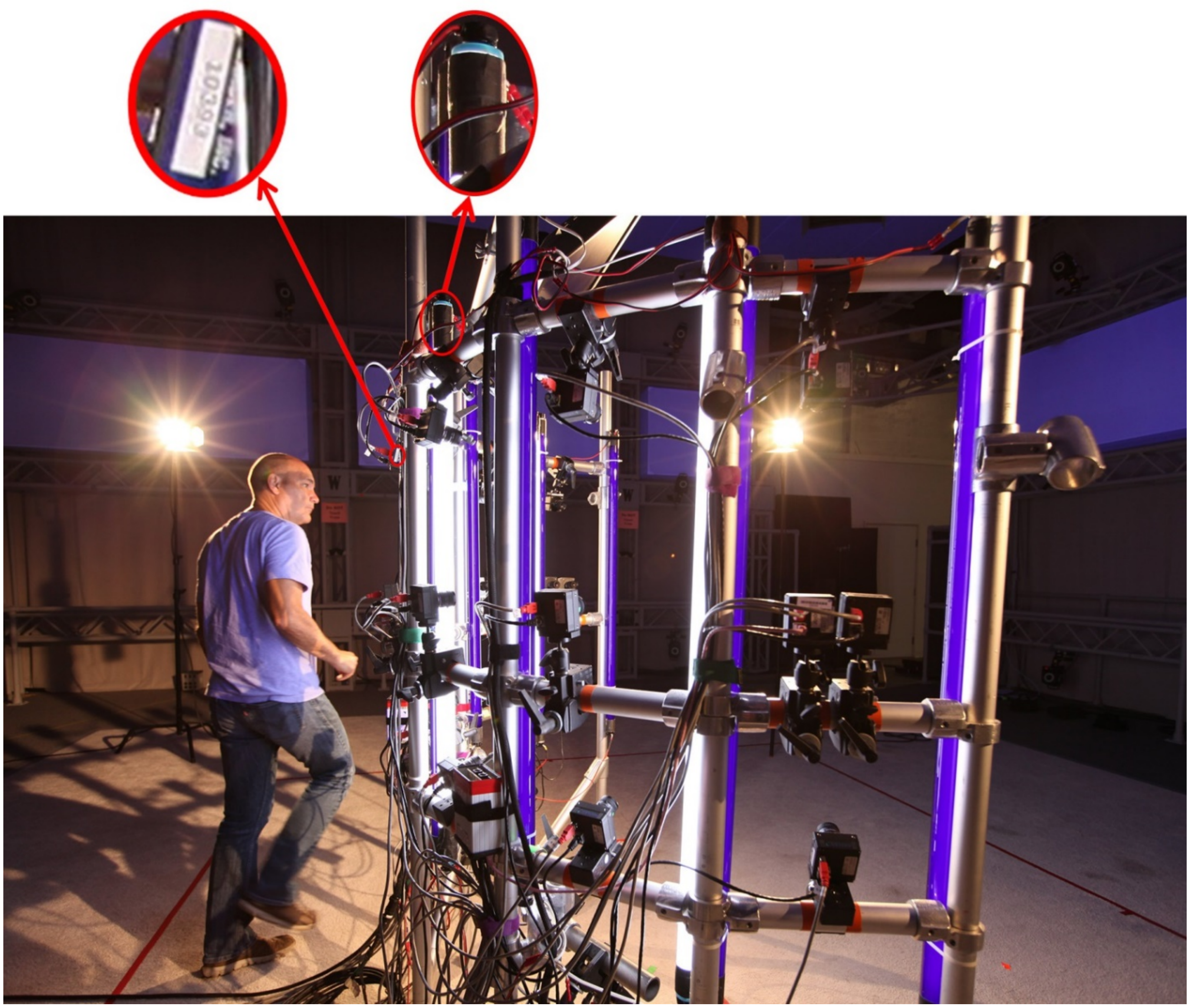





mova



57. And the following photograph released by Digital Domain shows the stolen MOVA Contour rig that was operated by the thieves and used unlawfully by defendants in at least *Guardians of the Galaxy* and *Beauty and the Beast*. Close inspection of the photo shown in the left inset, shows the thieves neglected to remove a Rearden, Inc. Asset Tag on one of the stolen cameras (Rearden, Inc. is Rearden LLC's predecessor in interest). Rearden Asset #10393 is a Basler 102f Camera, Serial # 20606024, purchased on October 1, 2006 and stolen in 2013. Also, numerous tell-tale details specific to Contour's operation are visible in the stolen Contour rig photograph (e.g. the right inset shows black tape is wrapped around the end of a fluorescent lamp tube to prevent light spillage from the glowing electrode, a Contour-specific technique taught in Rearden's US Patent 7,567,293 at 19:66-20:15), confirming that the thieves used the identical Rearden system and methods:



58. The Contour system has no "operating manual." It is a hand-built system, the operation of which is known only by Rearden's MOVA team who invented it and Rearden's MOVA employees and contractors who have been trained to use it under strict confidentiality obligations. It was not intended to be an end-user system and must be used carefully with knowledge of its operation for it to function correctly and safely. Defendants were able to use the Contour system only because they had engaged former Rearden employees to operate Rearden's Contour system using Rearden trade secrets without authorization.

B. The MOVA Contour intellectual property

59. The MOVA Contour computer program is the subject of United States Copyright Registration No. TXu001977151, a copy of which is attached hereto as Exhibit 1. Plaintiff Rearden Mova is the owner of Copyright Registration No. TXu001977151. The MOVA Contour Program runs on computers that are part of the MOVA Contour physical apparatus.

60. The MOVA Contour methods and systems are the subject of issued United States Patent Nos. 7,605,861 (the "'861 Patent"), 8,659,668 (the "'668 Patent"), 7,548,272 (the "'272 Patent"), 7,567,293 (the "'293 Patent"), and 8,207,963 (the "'963 Patent") (copies are attached as Exhibits 2, 3, 4, 5 and 6), as well as numerous United States pending patent applications, and international patents and patent applications. Plaintiff Rearden Mova is the exclusive owner of the '861, '668, '272, '293, and '963 patents, as well as all other domestic patent applications and all international patents and patent applications drawn to the MOVA Contour systems and methods. The Mova Contour physical apparatus and methods are embodiments of the claims of the '861, '668, '272, '293 and '963 patents.

61. MOVA® and Contour® are the subject of United States Trademark Registration Nos. U.S. Registration No. 3,843,152 and U.S. Registration No. 3,628,974, respectively. Copies of these registrations are attached hereto as Exhibits 7 and 8.

62. The MOVA Contour systems and methods include know-how, confidential information that derives independent economic value, both actual and potential, from not being generally known to the public or other persons who can obtain economic value from its disclosure and use. The MOVA Contour confidential information includes, without limitation:

- the source code and object code used in operating the MOVA Contour physical assets;
- many specific functionally-designed mechanisms, such as determining when part of the face is obstructed from the view of certain cameras and seamlessly filling in those parts of the face with views from other cameras;
- certain of the processes used along with the MOVA Contour physical assets, such as the timing configurations for the Mova system;
- sequencing the steps of calibration, aperture adjustment and focus adjustment of the Mova cameras;
- specific phosphor-based makeup formulations;
- techniques for applying makeup to performers being captured;
- specific electrical set up safety measures of the MOVA Contour rig;
- specific electrical modification of fluorescent light ballasts so as to operate safely;
- specific performer medical considerations, such as, in the case of performers receiving Botox treatments for facial wrinkles, scheduling shoots in specific intervals relative to their treatments to maintain natural skin motion;
- specific instructions to performers on how to perform in such a way to keep their faces within the capture volume;
- specific instructions to performers for specialized moves, such as singing, or bending the head downward and upward, with the face going out of and then back into view of the cameras; and
- information regarding MOVA's prior customer relationships and business terms.

63. Rearden and Rearden Mova have protected this confidential information by, *inter alia*, maintaining email, documents, source and object code, and other software in secure locations; controlling access to these locations; and by including confidentiality provisions in its agreements with all of its employees and contractors who have ever had access to any source code, object code other software, electrical set up, proprietary electrical circuit designs, timing systems, interconnects, makeup formulations, phosphor research, results of proprietary tests, etc. The following confidentiality provisions of a Rearden employment agreement (Rearden referenced as "the

Company"), for example, are representative of those in all other Rearden employment and contractor agreements:

- "At all times, both during my employment by the Company and after its termination, I will keep in confidence and trust and will not use or disclose any Proprietary Information or anything relating to it without the prior written consent of an officer of the Company..."
- "I agree that during my employment by the Company I will not remove any Company Documents and Materials from the business premises of the Company or deliver any Company Documents and Materials to any person or entity outside the Company, except as I am required to do in connection with performing the duties of my employment. I further agree that, immediately upon the termination of my employment by me or by the Company for any reason ... I will return all Company Documents and Materials, apparatus, equipment and other physical property, or any reproduction of such property ..."

64. The MOVA Contour confidential information constitutes trade secrets as that term is defined in the California Uniform Trade Secrets Act ("CUTSA") at sections 3426 to 3426.11 of the California Civil Code, and the Defense of Trade Secrets Act at 18 U.S.C. § 1832(b), *et seq*.

65. The "MOVA Assets" at issue herein include the MOVA Contour technology, and related hardware and software, source code, domestic and international patents and patent applications, domestic and international trademarks, copyrights, trade secrets, domain names, business records, and various related physical goods (the "MOVA Assets").

C. Rearden's use of the MOVA Contour system and methods in fifteen major motion pictures and industry acclaim

66. Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by Paramount Pictures for "*The Curious Case of Benjamin Button*" (2008) and *Transformers: Dark of the Moon* (2011).

67. Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by Universal Studios in *The Incredible Hulk* (2008) and *Snow White and the Huntsman* (2012).

68. Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by 20th Century Fox in *Percy Jackson and the Olympians: The Lightning Thief* (2010).

69. Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by Sony Pictures in *The Amazing Spider-Man* (2012).

70. Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by Warner Brothers Studios in *Harry Potter and the Deathly Hallows*, Part 1 (2010) and Part 2 (2011), *Green Lantern* (2011), *Jack the Giant Slayer* (2013), and *Gravity* (2013).

71. And Rearden and/or its controlled affiliates operated the MOVA Contour system for, and authorized used of its system, methods and Contour Program output files by defendants Disney Company and Disney MPG in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012) (including defendant Marvel).

72. In each of the above fifteen films, the motion picture studios performed a routine intellectual property due diligence prior to contracting with Rearden for use of the MOVA Contour systems and methods, in part to verify that Rearden and/or Rearden-controlled affiliates owned the MOVA Contour Assets and technology and had the right to use them for the benefit of the studios.

73. Rearden and/or Rearden-controlled affiliates have built considerable good will in the MOVA Contour Assets and technology. Rearden and/or Rearden-controlled affiliates used the MOVA Contour systems and methods in the fifteen major motion pictures identified above, which collectively grossed roughly $9.5 billion in global box office. Five of these movies are in the top-25 highest-grossing movies since 2008 (when the first Contour movie was released), including the number one highest grossing movie in each of 2011 and 2012[19]. The MOVA Contour system and methods and the Contour Program output files have been the subject of numerous motion picture

[19] www.boxofficemojo.com.

industry press articles in which movie industry luminaries like director David Fincher have lauded the MOVA Contour technology:

> "Contour's promise is enormous," Fincher said. "The notion that the human face in all its subtleties could be mapped in real time and with such density of surface information opens up so many possibilities for both two- and three-dimensional image makers and storytellers."[20]

The MOVA Contour system and methods and the Contour Program output files have been the subject of an invited presentation by Steve Perlman to the Director's Guild of America[21], and they were identified as a "breakthrough" in the aforementioned TED talk[22]. MOVA Contour facial capture's improvements over prior facial performance capture technologies have been acclaimed by major motion picture actors, producers, directors, and top VFX professionals, including Ed Ulbrich in his TED Talk description of MOVA Contour and how it was essential in the creation of *The Curious Case of Benjamin Button*.[23]. And on February 9, 2015, the Academy of Motion Picture Arts and Sciences awarded the Scientific and Technical Award to the MOVA [Contour] facial performance capture system.[24]

D. Transfer of the MOVA Assets to OnLive, Inc., OL2, Inc., and Rearden Mova

74. The MOVA Contour systems and methods, along with video game streaming technology, was spun out of Rearden in 2007 into OnLive, Inc., a corporation controlled by Rearden. OnLive, Inc. thereafter owned all of the MOVA Assets, both Contour and other motion capture technology.

75. On August 17, 2012, OnLive, Inc. assigned all of its assets, including the MOVA Assets, to OL2, Inc. as part of an assignment for the benefit of creditors ("ABC"). On information and belief, OL2, Inc. was primarily focused on the video gaming unit of OnLive, Inc., and was not interested in offering any MOVA Contour movie production services.

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[20] Marlowe, July 31, 2006, op. cit.

[21] Directors Guild of America, July 28, 2007, op. cit.

[22] Op. cit.

[23] Ulbrich, Op. cit.

[24] http://oscar.go.com/news/oscar-news/150209-ampas-sci-tech-awards-2015-winners

76. In October of 2012, Rearden learned that OL2, Inc. was interested in selling the MOVA Assets, and ultimately decided to reacquire them. Rearden formed a wholly-owned subsidiary, MO2 LLC, as a vehicle to acquire the MOVA Assets from OL2, Inc.

77. Rearden's CEO Perlman tasked his employee Greg LaSalle with management of MO2 LLC. LaSalle had worked with Rearden from 1999 to 2007, and between 2007 and August 17, 2012 worked for OnLive, Inc. LaSalle was rehired by Rearden LLC on August 20, 2012.

78. On February 11, 2013, OL2, Inc. transferred the MOVA Assets to MO2 LLC through a Membership Interest and Asset Purchase and Sale Agreement. MO2 LLC is wholly owned by Rearden.

79. On April 19, 2013, MO2 LLC transferred the MOVA Assets to another wholly-owned Rearden company, Rearden Mova LLC.

80. On September 18, 2014, Rearden recorded patent assignments for the MOVA Asset patents, reflecting the assignment from OL2, Inc. LLC to MO2 LLC made in the Membership Interest and Asset Purchase and Sale Agreement.

81. Rearden also recorded patent assignments for the MOVA Asset patents, reflecting the assignment from MO2 LLC to Rearden Mova on April 19, 2013. However, the execution dates of the online forms were incorrectly filled in with the recordation dates of September18, 2014 (and in one case, September 8, 2014). As soon as it became aware of the errors, Rearden corrected the erroneous execution dates to the correct date: April 19, 2013.

E. Shenzhenshi's transparently false ownership claims

82. Unknown to Rearden, starting in October 2012, then Rearden employee LaSalle was in negotiation with a company called Digital Domain 3.0, Inc. ("DD3"), then a People's Republic of China and India-owned Delaware Corporation doing business in Venice Beach, California under "DD3" or "Digital Domain" business names. DD3 is a successor company to prior Digital Domain companies that Rearden, OnLive, Inc., and LaSalle (on behalf of Rearden and OnLive, Inc.) had worked with previously in movie productions making authorized use of the MOVA technology identified above. DD3 is currently wholly-owned by Digital Domain Holdings Ltd. ("DDHL"), a Hong Kong exchange-listed Bermuda corporation with its principal place of business in Hong Kong.

83. On February 20, 2015, Shenzhenshi Haitiecheng Science and Technology Co., Ltd. ("Shenzhenshi"), allegedly another People's Republic of China corporation with its purported principal place of business in Shenzhen, China, filed a declaratory judgment action against Rearden and various other Rearden entities in this judicial district, Case No. 3:15-cv-00797-JST, alleging that it had acquired the MOVA Assets by assignment from MO2 LLC on May 8, 2013. Shenzhenshi further alleged that it had granted an exclusive license to the MOVA Assets to DD3.

84. But as set forth above, MO2 LLC did not own the MOVA Assets on May 8, 2013, so it could not have assigned them to Shenzhenshi on that date. Rather, MO2 LLC had previously assigned the MOVA Assets to Rearden Mova LLC on April 19, 2013. Further, on May 8, 2013 LaSalle was not a Rearden employee, and as an employee or not, LaSalle never had authority to sell the MO2 LLC Assets to anyone (and certainly not for his personal enrichment). Nor could Shenzhenshi have granted a license of the MOVA Assets to Digital Domain because it never owned the MOVA Assets. Shenzhenshi, DD3 and LaSalle knew that the MO2-Shenzhenshi transaction was a ruse. LaSalle wrote to his attorneys, "[DD3] are going to actually acquire the Mova assets through one of their Chinese companies [Shenzhenshi]. I believe this is so it would be nearly impossible for Steve [Perlman] to go after them….They will indemnify me against any claims brought by Rearden and Steve Perlman." [25]

85. The day after the Court granted Rearden permission to file counterclaims, a company called Virtue Global Holdings, Ltd., a British Virgin Islands corporation, suddenly appeared in the Shenzhenshi case represented by Shenzhenshi's counsel. Shenzhenshi absconded from the litigation. Months later Virtue Global Holdings alleged that Shenzhenshi had assigned the MOVA Assets to Virtue Global Holdings on December 17, 2015. But again, as set forth above, Shenzhenshi never owned the MOVA Assets and therefore could not have assigned them to Virtue Global Holdings.

86. Rearden asserted counterclaims for declaratory relief against Shenzhenshi and Virtue Global Holdings affirming Rearden's ownership of the MOVA Assets, and for patent, trademark,

[25] *Shenzhenshi, et al. v. Rearden, et al.,* NDCA Case No. 15-797, HEYL001594.

and copyright infringement, misappropriation of trade secrets, fraudulent transfer, and other causes of action, against Shenzhenshi and Virtue Global Holdings.

87. The MOVA Asset ownership and fraudulent transfer claims were bifurcated and tried in December, 2016. A ruling is pending.

F. Defendants' unauthorized use of the MOVA Assets and Technologies

88. Once LaSalle was hired by DD3 in or about May, 2013, DD3 took possession of the MOVA Contour physical apparatus for Shenzhenshi. On information and belief, LaSalle had access to the secure storage facility where the physical MOVA Contour apparatus was kept, and assisted DD3 in taking unauthorized possession of the patented MOVA Contour apparatus and copies of the copyrighted Contour Program.

89. Thereafter, DD3 began secretly offering MOVA Contour facial performance capture services and Contour Program output files to motion picture studios and production companies, including defendants. The system used by DD3 is the very *same system* developed and constructed by Rearden and stolen by DD3 from the secure storage facility, which includes commercial embodiments of the system claims in the MOVA patents. And the statements by *Beauty and the Beast* co-stars Stevens and Watson, and Director Condon, confirm that DD3 performed the very *same methods* that are the commercial embodiments of the method claims of the MOVA patents.[26]

90. But even before Shenzhenshi allegedly acquired the MOVA Assets from LaSalle, and before DD3 began secretly offering MOVA Contour facial performance capture services and output files, Disney MPG and DD3 were in negotiations with LaSalle to acquire the MOVA Assets in March 2013. On March 27, 2013, Rearden wrote LaSalle a demand letter (the "Rearden Demand Letter") asserting that Rearden owned the MOVA Assets, that LaSalle had taken them illegally, and that Rearden would take legal action if necessary.[27] LaSalle notified Disney MPG that he had received the Rearden Demand Letter and as a result, Disney MPG "dropped out" of the running to acquire the MOVA Assets.[28] Only DD3 remained, but after receiving the Rearden Demand Letter, it

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[26] Paris Press Conference, Feb 17, 2017. Op. cit.

[27] *Shenzhenshi, et al. v. Rearden, et al.,* NDCA Case No. 15-797, HEYL000306-HEYL000307.

[28] *Shenzhenshi, et al. v. Rearden, et al.,* NDCA Case No.15-797, Dkt: 383, p. 169, op. cit.

also declined to acquire the MOVA Assets itself, and instead had its shadowy foreign affiliate (of unknown relationship) Shenzhenshi acquire the MOVA Assets and license them back to DD3 "…so it would be nearly impossible for Steve [Perlman] to go after them."[29]

91. Despite the fact that defendant Disney MPG was sufficiently concerned about the Rearden Demand Letter to drop out of acquiring the MOVA Assets, despite the fact that it knew that MOVA Asset ownership was claimed by Rearden (the company they had hired for MOVA Contour services on four previous movies), and it knew Rearden had asserted that LaSalle had stolen the MOVA Assets in the Demand Letter, defendant Disney MPG nonetheless secretly contracted, either directly or through entities subject to its supervision and control, for and used the MOVA Assets on at least two of their largest motion pictures *without ever contacting Rearden.*

1. *Guardians of the Galaxy*

92. *Guardians of the Galaxy* is a motion picture produced by defendant Marvel subject to the supervision and control of defendant Disney MPG. At all material times, defendants Disney MPG and Marvel were dominated and controlled by defendant Disney Company.

93. On information and belief, between February, 2013 and July, 2014, Disney MPG, either directly or through an entity subject to its supervision and control, contracted with DD3 to provide facial performance capture services and output files made with the patented MOVA Contour systems and methods and the copyrighted Contour Program and output files, including at least the performance of actor Josh Brolin as the character Thanos in *Guardians of the Galaxy*. DD3 provided such facial performance capture services subject to the terms of its contract with, and subject to the supervision and control of, defendant Disney MPG. Disney MPG incorporated the output files of the patented MOVA Contour systems and methods and the copyrighted Contour Program and output files into derivative works that were reproduced, distributed, displayed and performed in *Guardians of the Galaxy* without authorization. The following photograph was used by Disney MPG to promote the use of the MOVA Contour facial motion capture technology in the film, followed by a close-up of the Thanos character's face that is derivative of MOVA Contour Program output files:

[29] *Shenzhenshi, et al. v. Rearden, et al.,* NDCA Case No.15-79717, HEYL001594, op. cit.

94. Defendant Disney MPG knew or should have known that the patented MOVA Contour systems and methods and copyrighted Contour Program and output files were owned by Rearden and/or other Rearden-controlled entities due to several factors:

- Disney MPG had been notified of the Rearden Demand Letter, which accused then Rearden employee LaSalle of stealing the MOVA Assets. Upon conducting due diligence, Disney MPG had dropped out of the running to acquire the MOVA Assets from LaSalle.[30]

[30] *Shenzhenshi, et al. v. Rearden, et al.*, NDCA Case No. 15-797, Dkt: 383, p. 169, op. cit.

- Disney MPG had previously contracted with Rearden and/or its controlled entities to provide authorized facial performance capture services and Contour Program output files for use in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012) (including defendant Marvel), all high-value movies.

95. Neither Rearden nor Rearden Mova were aware or authorized use of the patented MOVA Contour systems and methods and copyrighted Contour Program and output files by DD3, defendant Marvel, defendant Disney MPG, or any other party in *Guardians of the Galaxy*. Nor, were Rearden or Rearden Mova aware of—let alone authorize—any reproduction, distribution, performance, or display of the copyrighted Contour Program's output files or the creation of derivative works based upon those output files, by DD3, defendant Marvel, defendant Disney MPG, or any other party in *Guardians of the Galaxy*. At no time did DD3, defendant Marvel, defendant Disney MPG, or any other party, negotiate or come to an agreement on financial terms in which Rearden would authorize MOVA Contour services to be used in *Guardians of the Galaxy*.

96. Defendant Disney MPG released *Guardians of the Galaxy* in domestic theaters on July 21, 2014. To date, the film has grossed over $333 million at the box office in the United States and $773 million globally.[31] It was the third highest-grossing film released in 2014, both domestically and worldwide.[32]

97. Defendant Buena Vista released *Guardians of the Galaxy* on DVD and Blu-ray, and via digital distribution such as download and streaming services in the United States on or about December 9, 2014. DVD and Blu-ray sales in the United States exceeded $131 million. Buena Vista also authorized distribution of *Guardians of the Galaxy* across a wide range of other distribution means, such as on airplanes, in hotels, through cable and satellite television services, *etc*.

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[31] http://www.boxofficemojo.com/movies/?id=marvel2014a.htm.

[32] http://www.boxofficemojo.com/yearly/chart/?yr=2014, http://www.boxofficemojo.com/alltime/world/.

2. *Avengers: Age of Ultron*

98. *Avengers: Age of Ultron* is a motion picture produced by defendant Marvel subject to the supervision and control of defendant Disney MPG. At all material times, defendants Disney MPG and Marvel were dominated and controlled by defendant Disney Company.

99. On information and belief, between May 2013 and April 2015, Disney MPG, either directly or though an entity subject to its supervision and conrol, contracted with DD3 to provide facial performance capture services and output files made with the patented MOVA Contour systems and methods and the copyrighted Contour Program and output files, including at least a reprisal of the Thanos character. DD3 provided such facial performance capture services and output files subject to the terms of its contract with, and subject to the supervision and control of, defendant Disney MPG. Disney MPG incorporated the output files of the patented MOVA Contour systems and methods and the copyrighted Contour Program into a derivative work, the same Thanos character from *Guardians of the Galaxy*, appearing in the closing credits of *Avengers: Age of Ultron*:

100. Defendant Disney MPG knew or should have known that the patented MOVA Contour systems and methods and copyrighted Contour Program and output files were owned by Rearden and/or other Rearden-controlled entities due to several factors:

- Disney MPG had been notified of the Rearden Demand Letter, which accused then Rearden employee LaSalle of stealing the MOVA Assets. Upon conducting due diligence, Disney MPG had dropped out of the running to acquire the MOVA Assets from LaSalle. [33]
- Disney MPG had previously contracted with Rearden and/or its controlled entities to provide authorized facial performance capture services and Contour Program output files for use in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012) (including defendant Marvel), all high-value movies.

90. On information and belief, before contracting with DD3, Disney MPG performed an intellectual property due diligence in part to confirm DD3's right to provide facial performance capture services and digital output made using the patented MOVA Contour system and methods and copyrighted ContourPprogram. Based upon its due diligence, Disney MPG knew or should have known that DD3 did not have the right to offer or provide facial performance capture services and output files made using the patented MOVA Contour system and copyrighted Contour Program.

101. Neither Rearden nor Rearden Mova were aware or authorized use of the patented MOVA Contour systems and methods and copyrighted Contour Program and output files by DD3, defendant Marvel, defendant Disney MPG, or any other party in *Avengers: Age of Ultron*. Nor, were Rearden or Rearden Mova aware of—let alone authorize—any reproduction, distribution, performance, or display of the copyrighted Contour Program's output files or the creation of derivative works based upon those output files, by DD3, defendant Marvel, defendant Disney MPG, or any other party in *Avengers: Age of Ultron*. At no time did DD3, defendant Marvel, defendant Disney MPG, or any other party, negotiate or come to an agreement on financial terms in which Rearden would authorize MOVA Contour services to be used in *Avengers: Age of Ultron*.

102. Defendant Disney MPG released *Avengers: Age of Ultron* in domestic theaters on or about April 13, 2015. The film has grossed over $459 million at the box office in the United States, and over $1.4 billion worldwide.

[33] *Shenzhenshi, et al. v. Rearden, et al.*, NDCA Case No. 15-797, Dkt: 383, p. 169, op. cit.

103. Defendant Buena Vista released *Avengers: Age of Ultron* on DVD and Blu-ray, and by digital distribution such as download and streaming services on or about October 2, 2015. DVD and Blu-ray sales in the United States exceed $79 million. Buena Vista also distributed *Avengers: Age of Ultron* across a wide range of other distribution means, such as on airplanes, in hotels, through cable and satellite television services, etc.

3. *Beauty and the Beast*

104. *Beauty and the Beast* is a motion picture produced by defendant Disney MPG and defendant Mandeville Films, subject to the supervision and control of defendant Disney MPG. At all material times, Disney MPG was dominated and controlled by defendant Disney Company.

105. On information and belief, between February 2013 and March 2017, Disney MPG, either directly or through an agent, contracted with DD3 to provide facial performance capture services and products made using the patented MOVA Contour system and methods, and copyrighted Contour Program and output files. Including, at least the performance of actor Dan Stevens as the Beast character. DD3 provided such facial performance capture services and Contour Program output files subject to the terms of its contract and subject to the supervision and control of defendant Disney MPG. Disney MPG incorporated the Contour Program output files of the patented MOVA Contour systems and methods and copyrighted Contour Program into derivative works that were reproduced, distributed, displayed and performed in *Beauty and the Beast*, without authorization.

106. Defendant Disney MPG knew or should have known that the patented MOVA Contour physical apparatus and copyrighted Contour Program and output files were owned by Rearden and/or other Rearden-controlled entities because:

- Disney MPG was notified of the Rearden Demand Letter, which accused Rearden employee LaSalle of stealing the MOVA Assets. Upon conducting due diligence, Disney MPG dropped out of the running to acquire the MOVA Assets from LaSalle.[34]

[34] *Shenzhenshi, et al. v. Rearden, et al.*, NDCA Case No.15-797, Dkt: 383, p. 169, op. cit.

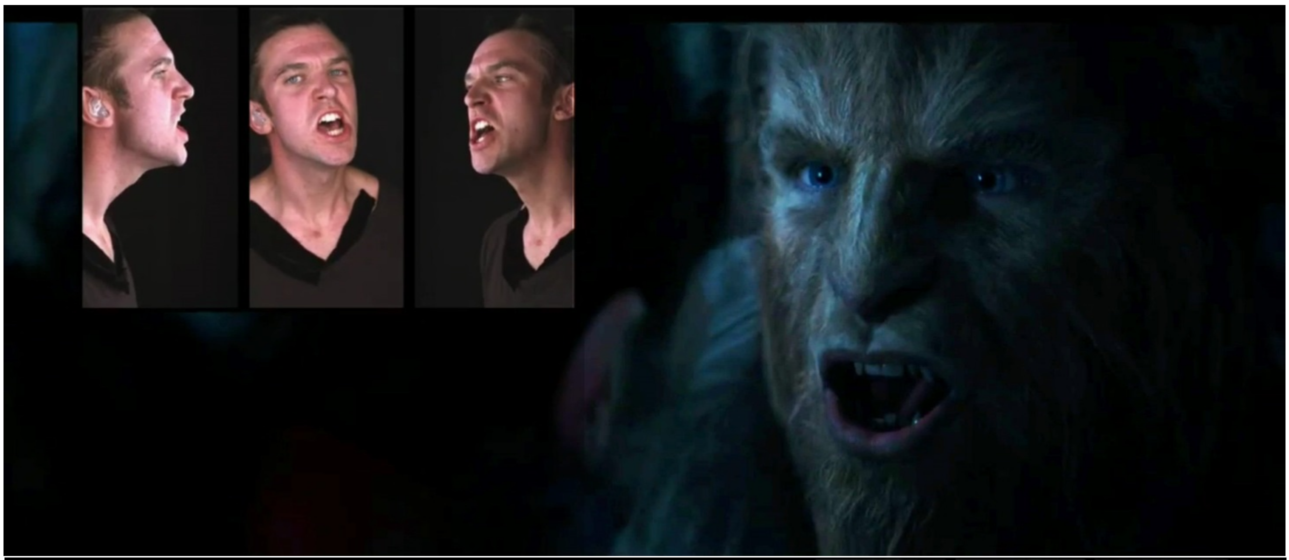
- Disney MPG had previously contracted with Rearden and/or its controlled entities to provide authorized facial performance capture services and Contour Program output files for use in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012) (including defendant Marvel), all high-value movies.

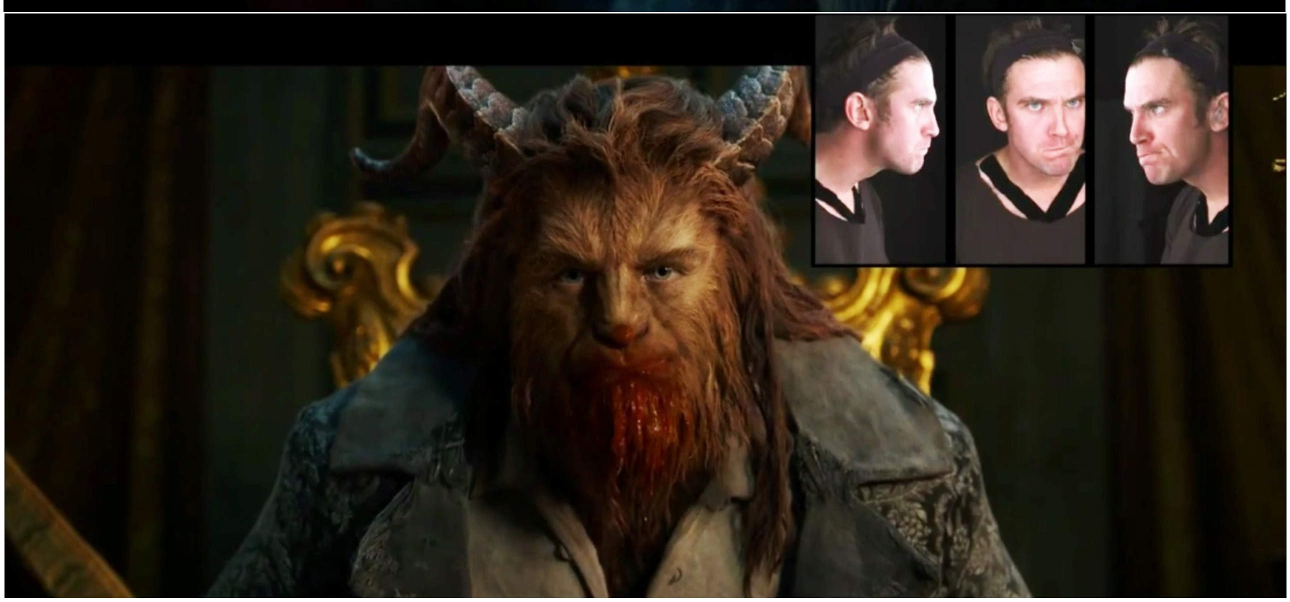
107. Neither Rearden nor Rearden Mova were aware of—let alone authorized use of—the patented MOVA Contour system and methods, and copyrighted MOVA Contour Program and output files, by DD3, defendant Mandeville Films, defendant Disney MPG, or any other party in *Beauty and the Beast*. Nor, were Rearden or Rearden Mova aware or authorize any reproduction, distribution, performance or display of the copyrighted Contour Program's output files or the creation of derivative works based upon those output files by DD3, defendant Marvel, defendant Disney MPG, or any other party in *Beauty and the Beast*. At no time did DD3, defendant Mandeville Films, defendant Disney MPG, or any other party negotiate or come to agreement on financial terms in which Rearden would authorize MOVA Contour servicesto be used in *Beauty and the Beast*.

108. The photograph below is a still from a video clip in the "Beauty of a Tale" featurette, distributed with versions of the *Beauty and the Beast* Blu-ray and through other digital distribution, that shows three views of Beast actor Dan Stevens in the stolen MOVA Contour rig. A clapperboard in front of his face shows that a facial performance is about to begin. The middle image shows the clapperboard from the front with Mr. Stevens' forehead visible behind it, the left image shows a side view from left of Mr. Stevens' face and the left side of the clapperboard, and the right image shows a side view from the right of Mr. Stevens' face and part of the right side of the clapperboard:

Mr. Stevens' face had phosphor-based makeup applied to it, which made his face appear to human observers or conventional cameras as having a blue glow. The reason Mr. Stevens' face appears in these three images in its natural skin color, without blue glow, is because these images are not from conventional cameras. They are Contour Program Skin Texture output files. But for the MOVA Contour system and methods and the copyrighted Contour Program, it would not be possible to capture and record Mr. Stevens's natural skin color.

109. The two photographs below are stills from a video clip in the "Beauty of a Tale" featurette that shows three Skin Texture output files from MOVA Contour systems and methods and the copyrighted Contour Program. As detailed in the previous paragraph, to human observers and conventional cameras, Mr. Stevens' natural skin color would not be visible, but rather he would appear as having a blue glow covering his entire face and surrounding skin areas:





110. The derivative CG image of the Beast above is a retargeting of MOVA Contour Tracking Mesh output files. The Captured Surface and Skin Texture output files were likely also used. For example, the Skin Texture could be used to locate Mr. Stevens's "eyelines" (the direction his eyes are looking), the look of his eyes and the look of his teeth and tongue when his mouth is

open. The Makeup Pattern and other Contour Program output files may have also been used. For example, Contour Program output files include frame timing files used to synchronize Mr. Stevens's utterances (e.g. dialog lines and roars) with his facial motion. These images are examples of retargeting to a CG 3D model. A CG 3D model of the Beast's face and head was created and, but for the retargeting from the Contour Program output files, would be immobile and expressionless. But the Contour output files retargeted to the CG 3D model brought the Beast's face to life, retaining the expressiveness, subtlety, and humanity of Mr. Stevens's performance in the CG 3D model.

111. The photograph below is a still from the "Beauty of a Tale" featurette that shows in the lower left Mr. Stevens performing on set in a scene, and the upper left image shows the Skin Texture output file of Mr. Stevens re-performing the facial motions of the same scene in the stolen MOVA Contour rig. On the right, the CG 3D model of the Beast is shown separately from the body. As described previously, the Tracking Mesh output file, and likely other Contour Program output files, retargeted to the 3D model of the Beast's face, bring the CG 3D model of the Beast to life, while retaining the expressiveness, subtlety and humanity of Mr. Stevens's performance:

112. The *still* images of video clips in the prior three photographs do not convey the extraordinary results achieved *in motion*, showing the expressiveness, subtlety and humanity achieved from the MOVA Contour system and methods and the copyrighted Contour Program output files. The video clip sources for the above stills can be found in the "Beauty of a Tale"

promotional video Disney provided to USA Today, which can be viewed here: https://www.usatoday.com/story/life/entertainthis/2017/05/29/exclusive-video-how-dan-stevens-was-transformed-in-beauty-and-the-beast/102281138/

113. Defendant Disney MPG released *Beauty and the Beast* in domestic theaters on or about March 17, 2017. The film has grossed over $500 million at the box office in the United States, and over $1.25 billion globally[35].

114. Defendant Buena Vista released *Beauty and the Beast* on DVD and Blu-ray, and via digital distribution such as download and streaming services on or about June 6, 2017. Many of the DVD, Blu-ray and digitally distributed versions of *Beauty and the Beast* included the Bonus Featurette entitled "A Beauty of a Tale" that showed how the MOVA Contour system was used in the creation of the Beast, including Contour Program output files. Disney also distributed "Beauty of a Tale" showing how MOVA Contour was used, including Contour Program output files as a promotion for the DVD, Blu-ray, and digital distribution release on USA Today's website, where it is publicly available for streaming over the Internet.[36] Disney has earned over $5 million on DVD, Blu-ray, and digital distribution as of the date of this complaint. Buena Vista also distributed *Beauty and the Beast* across a wide range of other distribution means, such as on airplanes, in hotels, through cable and satellite television services, *etc.*

FIRST CAUSE OF ACTION:
COPYRIGHT INFRINGEMENT
(DEFENDANTS DISNEY COMPANY, DISNEY MPG, AND MARVEL)

115. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

116. At all material times, Plaintiff Rearden Mova was and is the owner of United States Copyright Registration No. TXu001977151for the MOVA Contour computer program ("Contour Program").

117. The authors of the Contour Program created programming that performs several operations. Some of the Contour Program controls the Contour apparatus, including processing

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[35] http://www.boxofficemojo.com/movies/?id=beautyandthebeast2017.htm.

[36] Truitt, op. cit.

images from the two pluralities of Contour cameras. Some of the Contour Program operates prior to a facial capture session to prepare and calibrate the Contour system, some of the Contour Program operates in real-time during a live facial capture, and some of the Contour Program operates after the facial capture. The Contour Program produces several types of output files, some of which are used by the Contour Program itself for further processing, and some of which are used for driving a CG face in a movie or video game. The Contour Program output files include:

(a) the output of the first plurality of cameras called herein the "**Skin Texture**". Displayed, this output file looks like normal skin and facial features of the performer from multiple angles, largely without visible makeup.

(b) the output of the second plurality of cameras called herein the "**Makeup Pattern**". Displayed, this output file looks like a random pattern of green or blue largely without showing the performer's skin or other facial features (e.g. eyes or mouth).

(c) the Contour Program uses the Makeup Pattern output files to compute a high-resolution 3D surface that moves in the shape of the performer's skin with sub-millimeter precision. This output file is called herein the "**Captured Surface**" and, rendered on a display, it looks like a 3D bust of the performer's skin in motion.

(d) the Contour Program uses the Makeup Pattern output files to compute a high-resolution 3D mesh that tracks 3D points on the skin of the performer, as the skin moves from frame-to-frame. This output file is called herein the "**Tracking Mesh**" and, rendered on a display, it looks like a 3D mesh that exactly follows the movement, stretching and wrinkling the skin as the performer moves their face. The Tracking Mesh tracks the subtleties of the performer's facial motion with sub-millimeter precision.

(e) the Contour Program produces other output files associated with the facial motion capture session, for example, timing files that can be used to synchronize an audio recording of the performer with facial capture of the performer.

All of Contour Program output files, including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, were fixed in a tangible medium of expression when their embodiments were stored in non-volatile computer memory and/or media such as CD, CD-R, DVD or Blu-ray disks from which they may be perceived, reproduced, or otherwise communicated for a period of more than transitory duration.

118. The Contour Program performs substantially all of the operations required to produce the Contour Program output files, including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files. Given identical facial motion capture inputs, the Contour Program will produce identical output files. Accordingly, the authors of the Contour Program are the authors of the Contour Program output files, and these output files are subject to the copyright in the Contour Program owned by Rearden Mova.

119. It follows that at all material times Plaintiff Rearden Mova owned the exclusive right to reproduce, distribute copies of, perform, and display the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files; to make derivative works based upon Contour Program Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files; and to reproduce, distribute, perform, and display the derivative works.

120. At all material times, defendant Disney Company dominated and controlled defendants Disney MPG, Buena Vista, and Marvel, and had a substantial and continuing connection with them with respect to the infringing acts alleged herein.

121. At all material times, defendant Disney MPG had the right and ability to supervise and control the infringing conduct alleged herein, including but not limited to all infringing acts of DD3 and defendant Marvel, and had an obvious and direct financial interest in the exploitation of Rearden Mova's copyrighted works.

122. Defendant Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to defendant Marvel, contracted with DD3 to produce Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files, using the MOVA Contour facial motion capture system and methods and the MOVA Contour Program for Disney MPG's financial benefit in the production of the feature films *Guardians of the Galaxy* and *Avengers: Age of Ultron*.

123. Defendant Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Marvel, prepared at least

one CG character whose face was derived from some or all of the Contour Program output files including the Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, for insertion into its motion pictures, including but not limited to the character of Thanos in *Guardians of the Galaxy* and *Avengers: Age of Ultron.* These CG characters were and are original “audiovisual works” within the meaning of 17 U.S.C. § 101, which were fixed in a tangible medium of expression when their embodiments were stored in non-volatile computer memory and/or media such as CD, CD-R, DVD or Blu-ray disks from which they may be perceived, reproduced, or otherwise communicated for a period of more than transitory duration. The CG characters incorporate some or all Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files in their entireties, and the MOVA output files are wholly and indivisibly merged in the derivative CG characters.

124. Consequently, the CG characters prepared by Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Marvel, which were derivative of Contour Program output files including some or all of the Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, constitute “derivative works” as that term is defined in 17 U.S.C. § 101 prepared in violation of Rearden Mova’s exclusive rights under 17 U.S.C. § 106 (2).

125. On information and belief, while preparing derivative works based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, for the feature films *Guardians of the Galaxy* and *Avengers: Age of Ultron*, Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Marvel, reproduced, distributed, performed. and/or displayed copies of some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, in violation of Rearden Mova’s exclusive rights under 17 U.S.C. § 106 (1), (3), (4) and (5).

126. Disney MPG reproduced the finished *Guardians of the Galaxy* and *Avengers: Age of Ultron* films containing CG character derivative works prepared based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh

output files, and distributed the film on hard drives, by digital satellite transmission, and/or via other media for performance and display in motion picture theaters throughout the United States in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106(1), (3), (4) and (5).

127. Buena Vista reproduced the finished *Guardians of the Galaxy* and *Avengers: Age of Ultron* films containing derivative works prepared based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, and distributed the film on DVDs and Blu-rays for performance and display by consumers throughout the United States in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106(1), (3), (4) and (5).

128. None of Defendants Disney Company, Disney MPG, and Buena Vista, nor any other entities with which they acted in concert and subject to their supervision or control, including but not limited to DD3 and/or defendant Marvel, sought or received authorization from Rearden Mova to use any of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files to prepare derivative works to be used in the feature films *Guardians of the Galaxy* and *Avengers: Age of Ultron*, or to reproduce, distribute, perform or display such derivative works.

129. The acts of infringement by Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Marvel were, and are, willful, intentional, purposeful and knowing, in that Disney MPG, either alone or in concert with entities subject to its supervision and control, including but not limited to DD3 and/or Marvel, at all material times had actual knowledge that the copyright in the Contour Program has been, and is, owned by Rearden Mova as successor-in-interest to its original author and claimant, or was in reckless disregard of or willful blindness to Rearden Mova's copyright, and has acted, and continues to act, in knowing disregard of and indifference to the rights of Rearden Mova.

130. Defendants Disney Company, Disney MPG, Buena Vista, and Marvel are liable for each act of direct and actively induced copyright infringement alleged above because they had actual knowledge of the acts of infringement, personally and actively directed and participated in such acts of infringement, and financially benefitted from such acts of infringement.

131. Rearden Mova has been harmed as the direct and proximate result of the foregoing acts of copyright infringement, including both financial and irreparable harm that has no adequate remedy at law. Plaintiffs are entitled to injunctive relief, actual damages, profits of the infringer(s), and all such other remedies as may be available under the Copyright Act.

SECOND CAUSE OF ACTION:
COPYRIGHT INFRINGEMENT
(DEFENDANTS DISNEY COMPANY, DISNEY MPG,
BUENA VISTA, AND MANDEVILLE)

132. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

133. At all material times, Plaintiff Rearden Mova was and is the owner of United States Copyright Registration No. TXu001977151 for the MOVA Contour computer program ("Contour Program").

134. The authors of the Contour Program created programming that performs several operations. Some of the Contour Program controls the Contour apparatus, including processing images from the two pluralities of Contour cameras. Some of the Contour Program operates prior to a facial capture session to prepare and calibrate the Contour system, some of the Contour Program operates in real-time during a live facial capture, and some of the Contour Program operates after the facial capture. The Contour Program produces several types of output files, some of which are used by the Contour Program itself for further processing, and some of which are used for driving a CG face in a movie or video game. The Contour Program output files include:

(a) the output of the first plurality of cameras called herein the "**Skin Texture**". Displayed, this output file looks like normal skin and facial features of the performer from multiple angles, largely without visible makeup.

(b) the output of the second plurality of cameras called herein the "**Makeup Pattern**". Displayed, this output file looks like a random pattern of green or blue largely without showing the performer's skin or other facial features (e.g. eyes or mouth).

(c) the Contour Program uses the Makeup Pattern output files to compute a high-resolution 3D surface that moves in the shape of the performer's skin with sub-millimeter precision. This output file is called herein the "**Captured Surface**" and, rendered on a display, it looks like a 3D bust of the performer's skin in motion.

(d) the Contour Program uses the Makeup Pattern output files to compute a high-resolution 3D mesh that tracks 3D points on the skin of the performer, as the skin moves from frame-to-frame. This output file is called herein the "**Tracking Mesh**" and, rendered on a display, it looks like a 3D mesh that exactly follows the movement, stretching and wrinkling the skin as the performer moves their face. The Tracking Mesh tracks the subtleties of the performer's facial motion with sub-millimeter precision.

(e) the Contour Program produces other output files associated with the facial motion capture session, for example, timing files that can be used to synchronize an audio recording of the performer with facial capture of the performer.

All of Contour Program output files, including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, were fixed in a tangible medium of expression when their embodiments were stored in non-volatile computer memory and/or media such as CD, CD-R, DVD or Blu-ray disks from which they may be perceived, reproduced, or otherwise communicated for a period of more than transitory duration.

135. The Contour Program performs substantially all of the operations required to produce the Contour Program output files, including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files. Given identical facial motion capture inputs, the Contour Program will produce identical output files. Accordingly, the authors of the Contour Program are the authors Contour Program output files, and these output files are subject to copyright in the Contour Program owned by Rearden Mova.

136. It follows that at all material times Plaintiff Rearden Mova owned the exclusive right to reproduce, distribute copies of, perform, and display the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files; to make derivative works based upon Contour Program Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files; and to reproduce, distribute, perform, and display the derivative works.

137. At all material times, defendant Disney Company dominated and controlled defendants Disney MPG, Buena Vista, and had a substantial and continuing connection with them with respect to the infringing acts alleged herein.

138. At all material times, defendant Disney MPG had the right and ability to supervise and control the infringing conduct alleged herein, including but not limited to all infringing acts of DD3 and/or defendant Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden Mova's copyrighted works.

139. Defendant Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to defendant Mandeville, contracted with DD3 to produce Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files, using the MOVA Contour facial motion capture system and methods and the MOVA Contour Program for Disney MPG's financial benefit in the production of the feature film *Beauty and the Beast*.

140. Defendant Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Mandeville, prepared at least one CG character whose face was derived from some or all of the Contour Program output files including the Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, for insertion into its motion pictures, including but not limited to the character the Beast in *Beauty and the Beast*. These CG characters were and are original "audiovisual works" within the meaning of 17 U.S.C. § 101, which were fixed in a tangible medium of expression when their embodiments were stored in non-volatile computer memory and/or media such as CD, CD-R, DVD or Blu-ray disks from which they may be perceived, reproduced, or otherwise communicated for a period of more than transitory duration. The CG characters incorporate some or all Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files in their entireties, and the MOVA works are wholly and indivisibly merged in the CG characters.

141. Consequently, the CG characters prepared by Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Mandeville, based on Contour Program output files including some or all of the Skin

Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, constitute "derivative works" as that term is defined in 17 U.S.C. § 101 prepared in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106 (2).

142. On information and belief, while preparing derivative works based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface, and Tracking Mesh output files, for the feature film *Beauty and the Beast*, Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and defendant Mandeville, reproduced, distributed, performed, and/or displayed copies of some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files, in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106 (1), (3), (4) and (5).

143. Disney MPG reproduced the finished *Beauty and the Beast* film containing derivative works prepared based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files, and distributed the film on hard drives, by digital satellite transmission, and/or via other media for performance and display in motion picture theaters throughout the United States in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106(1), (3), (4) and (5).

144. Buena Vista reproduced the finished *Beauty and the Beast* film containing derivative works prepared based on some or all of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files, and distributed the film on DVDs and Blu-rays for performance and display by consumers throughout the United States in violation of Rearden Mova's exclusive rights under 17 U.S.C. § 106(1), (3), (4) and (5).

145. None of Defendants Disney Company, Disney MPG, and Buena Vista, nor any other entities with which they acted in concert and subject to their supervision or control, including but not limited to DD3 and/or defendant Mandeville, sought or received authorization from Rearden Mova to use any of the Contour Program output files including Skin Texture, Makeup Pattern, Captured Surface and Tracking Mesh output files to prepare derivative works to be used in the feature film *Beauty and the Beast*, or to reproduce, distribute, perform or display such derivative works.

146. The acts of infringement by Disney MPG, either alone or in concert with an entity subject to its supervision and control, including but not limited to DD3 and/or defendant Mandeville were, and are, willful, intentional, purposeful and knowing, in that Disney MPG, either alone or in concert with entities subject to its supervision and control, including but not limited to DD3 and/or defendant Mandeville, at all material times had actual knowledge that the copyright in the Contour Program has been, and is, owned by Rearden Mova as successor-in-interest to its original author and claimant, or was in reckless disregard of or willful blindness to Rearden Mova's copyrights, and has acted, and continues to act, in knowing disregard of and indifference to the rights of Rearden Mova.

147. Defendants Disney Company, Disney MPG, Buena Vista, and Mandeville are liable for each act of direct and actively induced copyright infringement alleged above because they had actual knowledge of the acts of infringement, personally and actively directed and participated in such acts of infringement, and financially benefitted from such acts of infringement.

148. Rearden Mova has been harmed as the direct and proximate result of the foregoing acts of copyright infringement, including both financial and irreparable harm that has no adequate remedy at law. Plaintiffs are entitled to injunctive relief, actual damages, profits of the infringer(s), and all such other remedies as may be available under the Copyright Act.

THIRD CAUSE OF ACTION:
INFRINGEMENT OF U.S. PATENT NO. 7,605,861
(DEFENDANT DISNEY MPG)

149. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

150. Plaintiff Rearden Mova LLC is the owner by assignment of U.S. Patent No. 7,605,861 (the '861 Patent), entitled "Apparatus and Method for Performing Motion Capture Using Shutter Synchronization," issued on October 20, 2009.

151. The '861 Patent generally teaches a system and methods of performing motion capture using shutter synchronization and/or using phosphor-based paint. For example, a method for mixing phosphor-based makeup with a makeup base, applying the mixture on surface regions of a motion capture subject, strobing a light source on and off, and strobing camera shutters synchronously with the strobing light source to perform motion capture.

152. The MOVA Contour facial motion capture apparatus and methods, which were conceived and developed by Rearden, and taken, offered and used by DD3, are commercial embodiments of the systems and methods claimed in the ’861 Patent.

153. By way of example, and not limitation, claim 1 of the ’861 Patent recites the following limitations:

> A method comprising:
>
> applying phosphorescent paint to regions of a performer’s face and/or body;
>
> strobing a light source on and off, the light source charging the phosphorescent paint when on; and
>
> strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the phosphorescent paint (“glow frames”) as the performer moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

154. The MOVA Contour facial motion capture method includes a step in which phosphor-based paint is applied to regions of a performer’s face.

155. The MOVA Contour facial motion capture method has white and black light sources. The white light source is alternately strobed on and off, charging the phosphorescent paint when on.

156. The MOVA Contour facial motion capture technology includes a step in which cameras with shutters controlled by computers and the MOVA Contour computer program, which open and close synchronously (strobing). The shutters open when the white light sources are off and the black light sources are on, thereby capturing sequences of images of the phosphorescent paint (“glow frames”) as the performer changes facial expressions during a performance.

157. At all material times, defendant Disney MPG had the right and ability to supervise the infringing conduct alleged herein, including but not limited to the infringing acts of defendants Marvel and Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden Mova’s patented works.

158. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion

capture system and methods for facial motion capture in *Guardians of the Galaxy* and *Avengers: Age of Ultron* without authorization. On information and belief, the contract provided for a financial payment to DD3.

159. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Beauty and the Beast* without authorization. On information and belief, the contract provided for a financial payment to DD3.

160. Each instance of DD3's unauthorized use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control, constitutes an act of direct infringement of one or more claims of the '861 Patent.

161. At all material times, Disney MPG had actual knowledge of, or was willfully blind to, the '861 Patent because it had performed an intellectual property due diligence with Rearden and worked with Rearden to use the MOVA Contour facial motion capture system for facial motion capture in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012). Based upon its intellectual property due diligence, Disney MPG had actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '861 Patent.

162. And on information and belief, Disney MPG had actual knowledge of, or was willfully blind to, the '861 Patent because it had performed an intellectual property due diligence with DD3 prior to contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in *Guardians of the Galaxy* (2014), *Avengers: Age of Ultron* (2015), and *Beauty and the Beast* (2017). A competent intellectual property due diligence would have included an examination of the public record of assignments and/or attorney of record of the '861 Patent, which would have revealed that DD3 did not have a license from any entity that could have owned the MOVA Contour facial motion capture system.

163. Disney MPG's actual knowledge of the '861 Patent, actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '861 Patent, and knowledge of or willful blindness to DD3's lack of authorization from any entity that could have owned the MOVA Contour facial motion capture system, confirm Disney MPG's specific intent to induce DD3 to infringe the '861 Patent by contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization.

164. Consequently, Disney MPG actively induced each instance of DD3's use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control. Disney MPG's active inducement of direct infringement by DD3 constitutes acts of infringement of the '861 Patent under 35 U.S.C. § 271(b).

165. Defendant Disney MPG is liable to Plaintiffs for damages adequate to compensate for Disney MPG's direct and actively-induced infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs' invention by Disney MPG under 35 U.S.C. § 284.

166. In addition, defendant Disney MPG's direct and actively-induced infringements have caused Plaintiffs irreparable harm that is not compensable by monetary damages, and therefore Plaintiffs are entitled to injunctive relief under 35 U.S.C. § 283.

167. Disney MPG's direct and actively-induced infringements constitute willful, egregious misconduct, and consequently Plaintiffs are entitled to a discretionary increase of their damages award up to three times the amount found or assessed, costs, and attorney's fees under 35 U.S.C. § 284.

168. Finally, based on the foregoing facts, Plaintiffs request that this Court declare this an exceptional case, and award Plaintiffs their costs and attorney's fees under 35 U.S.C. § 285.

FOURTH CAUSE OF ACTION:
INFRINGEMENT OF U.S. PATENT 7,567,293
(DEFENDANT DISNEY MPG)

169. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

170. Plaintiff Rearden Mova LLC is the owner by assignment of the U.S. Patent 7,567,293 (the ’293 Patent), entitled “System and Method for Performing Motion Capture by Strobing a Fluorescent Lamp,” issued on July 28, 2009.

171. The ’293 Patent teaches systems and methods for performing motion capture using fluorescent lamps. For example, capturing motion by generating synchronization signals, strobing fluorescent lamps in response to the synchronization signals to charge phosphorescent makeup or dye, and strobing camera shutters synchronously with the lamps or light source.

172. The MOVA Contour facial motion capture apparatus and methods, which were conceived and developed by Rearden, and taken, offered and used by DD3, are commercial embodiments of the systems and methods claimed in the ’293 Patent.

173. By way of example, and not limitation, claim 1 of the ’293 Patent recites the following limitations:

> A system comprising:
>
> a synchronization signal generator to generate one or more synchronization signals;
>
> one or more fluorescent lamps configured to strobe on and off responsive to a first one of the one or more synchronization signals, the fluorescent lamps illuminating makeup, markers, paint or dye applied to a subject for a motion capture session; and
>
> a first plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture sequences of images of the makeup, markers, paint or dye as the subject moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

174. The MOVA Contour facial motion capture system includes a synchronization signal generator to generate synchronization signals.

175. The MOVA Contour facial motion capture system includes florescent lamps configured to strobe on and off responsive to the synchronization signals. The florescent lamps illuminate makeup, markers, paint or dye applied to the subject for a motion capture session.

176. The MOVA Contour facial motion capture system has cameras with shutters that are controlled by the MOVA Contour Program. The shutters are strobed continuously with the strobing of the fluorescent lamps to capture sequences of images of the makeup, markers, paint or dye as the subject moves or changes facial expressions during a performance.

177. The MOVA Contour computer program signals the cameras to open their shutters when the white fluorescent light source is off and close their shutters when the white fluorescent light source is on.

178. At all material times, defendant Disney MPG had the right and ability to supervise the infringing conduct alleged herein, including but not limited to the infringing acts of defendants Marvel and Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden's patented works.

179. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Guardians of the Galaxy* and *Avengers: Age of Ultron* without authorization. On information and belief, the contract provided for a financial payment to DD3.

180. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Beauty and the Beast* without authorization. On information and belief, the contract provided for a financial payment to DD3.

181. Each instance of DD3's unauthorized use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy, Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control, constitutes an act of direct infringement of one or more claims of the '293 Patent.

182. At all material times, Disney MPG had actual knowledge of, or was willfully blind to, the ’293 Patent because it had performed an intellectual property due diligence with Rearden and worked with Rearden to use the MOVA Contour facial motion capture system for facial motion capture in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012). Based upon its intellectual property due diligence, Disney MPG had actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the ’293 Patent.

183. And on information and belief, Disney MPG had actual knowledge of, or was willfully blind to, the ’293 Patent because it had performed an intellectual property due diligence with DD3 prior to contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in *Guardians of the Galaxy* (2014), *Avengers: Age of Ultron* (2015), and *Beauty and the Beast* (2017). A competent intellectual property due diligence would have included an examination of the public record of assignments of the ’293 Patent, which would have revealed that DD3 did not have authorization from any entity that could have owned the MOVA Contour facial motion capture system.

184. Disney MPG’s actual knowledge of the ’293 Patent, actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the ’293 Patent, and knowledge of or willful blindness to DD3’s lack of a license from any entity that could have owned the MOVA Contour facial motion capture system, confirm Disney MPG’s specific intent to induce DD3 to infringe the ’293 Patent by contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization.

185. Consequently, Disney MPG actively induced each instance of DD3’s use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization in the performance of its contract with Disney MPG, or with entities subject to Disney MPG’s supervision and control. Disney MPG’s active inducement of direct infringement by DD3 constitutes acts of infringement of the ’293 Patent under 35 U.S.C. § 271(b).

186. Defendant Disney MPG is liable to Plaintiffs for damages adequate to compensate for Disney MPG's direct and actively-induced infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs' invention by Disney MPG under 35 U.S.C. § 284.

187. In addition, defendant Disney MPG's direct and actively-induced infringements have caused Plaintiffs irreparable harm that is not compensable by monetary damages, and therefore Plaintiffs are entitled to injunctive relief under 35 U.S.C. § 283.

188. Disney MPG's direct and actively-induced infringements constitute willful, egregious misconduct, and consequently Plaintiffs are entitled to a discretionary increase of their damages award up to three times the amount found or assessed, costs, and attorney's fees under 35 U.S.C. § 284.

189. Finally, based on the foregoing facts, Plaintiffs request that this Court declare this an exceptional case, and award Plaintiffs their costs and attorney's fees under 35 U.S.C. § 285.

FIFTH CAUSE OF ACTION:
INFRINGEMENT OF U.S. PATENT NO. 7,548,272
(DEFENDANT DISNEY MPG)

190. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

191. Plaintiff Rearden Mova LLC is the owner by assignment of U.S. Patent No. 7,548,272 (the '272 Patent), entitled "System and Method for Performing Motion Capture Using Phosphor Application Techniques," issued on June 16, 2009.

192. The '272 Patent teaches an improved apparatus and method for performing motion capture using phosphor application techniques. For example, a method for mixing phosphorescent makeup with a makeup base, applying the mixture on surface regions of a motion capture subject, strobing light source on and off, and strobing camera shutters synchronously with the strobing light source to perform motion capture.

193. The MOVA Contour facial motion capture apparatus and methods, which were conceived and developed by Rearden, and taken, offered and used by DD3, are commercial embodiments of the systems and methods claimed in the '272 Patent.

194. By way of example, and not limitation, claim 1 of the ’272 Patent recites the following limitations:

> A method for performing motion capture comprising:
>
> mixing phosphor with makeup to create a phosphor-makeup mixture;
>
> applying the phosphor-makeup mixture to surface regions of a motion capture subject;
>
> strobing a light source on and off, the light source charging phosphor within the phosphor-makeup mixture when on; and
>
> strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the phosphor-makeup mixture as the subject moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

195. The MOVA Contour facial motion capture method includes a step in which phosphor is mixed with makeup to create a phosphor-makeup mixture.

196. The MOVA Contour facial motion capture method includes a step in which the phosphor-makeup mixture is applied to surface regions of the motion capture subject.

197. The MOVA Contour facial motion capture technology includes a step in which a light source is strobed on and off, the light source charging phosphor within the phosphor-makeup mixture when on.

198. The MOVA Contour facial motion capture technology includes a step in which cameras with shutters are controlled by computers and the MOVA Contour Program, which opens the shutters when the white light source is off (leaving only the black light source on) which capture sequences of images of the phosphor-makeup mixture as the subject moves or changes facial expressions during a performance, and the shutters are closed when the white light source is on.

199. At all material times, defendant Disney MPG had the right and ability to supervise the infringing conduct alleged herein, including but not limited to the infringing acts of defendants Marvel and Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden’s patented works.

200. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Guardians of the Galaxy* and *Avengers: Age of Ultron* without authorization. On information and belief, the contract provided for a financial payment to DD3.

201. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Beauty and the Beast* without authorization. On information and belief, the contract provided for a financial payment to DD3.

202. Each instance of DD3's unauthorized use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control, constitutes an act of direct infringement of one or more claims of the '272 Patent.

203. At all material times, Disney MPG had actual knowledge of, or was willfully blind to, the '272 Patent because it had performed an intellectual property due diligence with Rearden and worked with Rearden to use the MOVA Contour facial motion capture system for facial motion capture in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012). Based upon its intellectual property due diligence, Disney MPG had actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '272 Patent.

204. And on information and belief, Disney MPG had actual knowledge of, or was willfully blind to, the '272 Patent because it had performed an intellectual property due diligence with DD3 prior to contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in *Guardians of the Galaxy* (2014), *Avengers: Age of Ultron* (2015), and *Beauty and the Beast* (2017). A competent intellectual property due diligence would have included an examination of the public record of assignments of the '272 Patent, which would have revealed

that DD3 did not have a license from any entity that could have owned the MOVA Contour facial motion capture system.

205. Disney MPG's actual knowledge of the '272 Patent, actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '272 Patent, and knowledge of or willful blindness to DD3's lack of authorization from any entity that could have owned the MOVA Contour facial motion capture system, confirm Disney MPG's specific intent to induce DD3 to infringe the '272 Patent by contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization.

206. Consequently, Disney MPG actively induced each instance of DD3's use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization in the performance of its contract with Disney MPG. Disney MPG's active inducement of direct infringement by DD3 constitutes acts of infringement of the '272 Patent under 35 U.S.C. § 271(b).

207. Defendant Disney MPG is liable to Plaintiffs for damages adequate to compensate for Disney MPG's direct and actively-induced infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs' invention by Disney MPG under 35 U.S.C. § 284.

208. In addition, defendant Disney MPG's direct and actively-induced infringements have caused Plaintiffs irreparable harm that is not compensable by monetary damages, and Plaintiffs therefore are entitled to injunctive relief under 35 U.S.C. § 283.

209. Disney MPG's direct and actively-induced infringements constitutes willful, egregious misconduct, and consequently Plaintiffs are entitled to a discretionary increase of their damages award up to three times the amount found or assessed, costs, and attorney's fees under 35 U.S.C. § 284.

210. Finally, based on the foregoing facts, Plaintiffs request that this Court declare this an exceptional case, and award Plaintiffs their costs and attorney's fees under 35 U.S.C. § 285.

SIXTH CAUSE OF ACTION:
INFRINGEMENT OF U.S. PATENT NO. 8,659,668
(DEFENDANT DISNEY MPG)

211. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

212. Plaintiff Rearden Mova LLC is the owner by assignment of U.S. Patent No. 8,659,668 (the ’668 Patent), entitled “Apparatus and Method for Performing Motion Capture Using a Random Pattern on Capture Surfaces,” issued on February 25, 2014.

213. The ’668 Patent claims methods for applying a random pattern to specified regions of an object, tracking the movement of the random pattern, and generating motion data representing the movement of the object.

214. The MOVA Contour facial motion capture apparatus and methods, which were conceived and developed by Rearden, and taken, offered and used by DD3, are commercial embodiments of the systems and methods claimed in the ’668 Patent.

215. By way of example, and not limitation, claim 1 of the ’668 Patent recites the following limitations:

> A method comprising:
>
> applying a random pattern of material to specified regions of a performer’s face, body and/or clothing;
>
> capturing sequences of images of the random pattern with a first plurality of cameras as the performer moves and/or changes facial expressions during a motion capture session;
>
> correlating the random pattern across two or more images captured from two or more different cameras to create a 3-dimensional surface of the specified regions of the performer’s face, body, and/or clothing;
>
> generating motion data representing the movement of the 3-dimensional surface across the sequence of images;
>
> strobing a light source on and off, the light source charging the random pattern when on; and
>
> strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture the sequences of images of the random pattern (“glow frames”) as the performer moves or changes facial expressions during a performance, wherein the shutters of the first plurality of cameras are open when the light source is off and the shutters are closed when the light source is on.

216. The MOVA Contour facial motion capture method includes a step of applying a random pattern of material, a phosphor-makeup mixture, to regions of a performer's face.

217. The MOVA Contour facial motion capture method includes a step of capturing sequences of images of the random patterns with cameras as the subject moves and changes facial expressions.

218. The MOVA Contour facial motion capture method includes a step of processing by a computer programmed with the MOVA Contour computer program, to correlate the random pattern across images captured by cameras to create a 3-dimensional surface of the performer's face.

219. The MOVA Contour facial motion capture method includes a step of processing by a computer programmed with the MOVA Contour Program to generate motion data representing movement of the three dimensional surface across the sequence of images.

220. The MOVA Contour facial motion capture method includes a step of strobing white florescent light sources on and off, where the white light sources charge the random pattern of phosphor in the phosphor-makeup mixture.

221. The MOVA Contour facial motion capture method includes a step of strobing the shutters of cameras controlled by the MOVA Contour computer program. The shutters are strobed synchronously with the strobing of the light source to capture sequences of images of the random pattern of phosphor in the phosphor-makeup mixture as the performer moves or changes facial expressions during a performance. The shutters are open when the white light source is off, and closed when the light source is on.

222. At all material times, defendant Disney MPG had the right and ability to supervise the infringing conduct alleged herein, including but not limited to the infringing acts of defendants Marvel and Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden's patented works.

223. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Guardians of the Galaxy* and *Avengers: Age*

of Ultron without authorization. On information and belief, the contract provided for a financial payment to DD3.

224. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Beauty and the Beast* without authorization. On information and belief, the contract provided for a financial payment to DD3.

225. Each instance of DD3's unauthorized use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control, constitutes an act of direct infringement of one or more claims of the '668 Patent.

226. At all material times, Disney MPG had actual knowledge of, or was willfully blind to, the '668 Patent because it had performed an intellectual property due diligence with Rearden and worked with Rearden to use the MOVA Contour facial motion capture system for facial motion capture in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012). Based upon its intellectual property due diligence, Disney MPG had actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '668 Patent.

227. And on information and belief, Disney MPG had actual knowledge of, or was willfully blind to, the '668 Patent because it had performed an intellectual property due diligence with DD3 prior to contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in *Guardians of the Galaxy* (2014), *Avengers: Age of Ultron* (2015), and *Beauty and the Beast* (2017). A competent intellectual property due diligence would have included an examination of the public record of assignments of the '668 Patent, which would have revealed that DD3 did not have a license from any entity that could have owned the MOVA Contour facial motion capture system.

228. Disney MPG's actual knowledge of the '668 Patent, actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the

claims of the ’668 Patent, and knowledge of or willful blindness to DD3’s lack of authorization from any entity that could have owned the MOVA Contour facial motion capture system, confirm Disney MPG’s specific intent to induce DD3 to infringe the ’668 Patent by contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization.

229. Consequently, Disney MPG actively induced each instance of DD3’s use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization in the performance of its contract with Disney MPG, or with entities subject to Disney MPG’s supervision and control. Disney MPG’s active inducement of direct infringement by DD3 constitutes acts of infringement of the ’668 Patent under 35 U.S.C. § 271(b).

230. Defendant Disney MPG is liable to Plaintiffs for damages adequate to compensate for Disney MPG’s direct and actively-induced infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs’ invention by Disney MPG under 35 U.S.C. § 284.

231. In addition, defendant Disney MPG’s direct and actively-induced infringements have caused Plaintiffs irreparable harm that is not compensable by monetary damages, and therefore Plaintiffs are entitled to injunctive relief under 35 U.S.C. § 283.

232. Disney MPG’s direct and actively-induced infringements constitute willful, egregious misconduct, and consequently Plaintiffs are entitled to a discretionary increase of their damages award up to three times the amount found or assessed, costs, and attorney’s fees under 35 U.S.C. § 284.

233. Finally, based on the foregoing facts, Plaintiffs request that this Court declare this an exceptional case, and award Plaintiffs their costs and attorney’s fees under 35 U.S.C. § 285.

SEVENTH CAUSE OF ACTION:
INFRINGEMENT OF U.S. PATENT NO. 8,207,963
(DEFENDANT DISNEY MPG)

234. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

235. Plaintiff Rearden Mova LLC is the owner by assignment of U.S. Patent No. 8,207,963 (the ’963 Patent), entitled “System and Method for Performance Motion Capture and Image Reconstruction,” issued on June 26, 2012.

236. The ’963 Patent claims methods for establishing a reference frame and tracking many vertices from frame to frame through the captured sequence.

237. The MOVA Contour facial motion capture apparatus and methods, which were conceived and developed by Rearden, and taken, offered and used by DD3, are commercial embodiments of the systems and methods claimed in the ’963 Patent.

238. By way of example, and not limitation, claim 1 of the ’963 Patent recites the following limitations:

> 1. A computer-implemented system for performing motion capture of a subject comprising:
>
> a plurality of cameras for capturing a sequence of image frames of the subject over a period of time, each frame having a plurality of vertices defining a captured surface of the subject;
>
> a computing system for processing the sequence of image frames, the computing system having a memory for storing program code and a processor for processing the program code to perform the operations of:
>
> establishing a reference frame having one or more of the plurality of vertices and specifying a location for each of the vertices;
>
> performing frame-to-frame tracking to identify locations of vertices within an N'th frame based on locations of vertices within an (N-1)'th frame or an earlier frame;
>
> performing reference-to-frame tracking to identify locations of vertices within the N'th frame based on the locations of vertices in the reference frame to counter potential drift between the frames;
>
> storing the locations of vertices for use in subsequent reconstruction of the motion of the subject; and performing the frame-to-frame and reference-to-frame tracking again using a different set of parameters, the parameters defining a search area for the vertices of each frame wherein multiple correlation passes are performed with the different sets of parameters;
>
> and wherein for passes after the first, the search area is shrunk by using an estimate of the position of a vertex based on the position of nearby vertices that were successfully tracked in the previous passes.

239. The MOVA Contour facial motion capture method includes a step of using a plurality of cameras for capturing a sequence of image frames of the subject over a period of time, each frame having a plurality of vertices defining a captured surface of the subject.

240. The MOVA Contour facial motion capture method includes a step of using a computing system for processing the sequence of image frames, the computing system having a memory for storing program code and a processor for processing the program code to perform the operations of:

(a) establishing a reference frame having one or more of the plurality of vertices and specifying a location for each of the vertices;

(b) performing frame-to-frame tracking to identify locations of vertices within an N'th frame based on locations of vertices within an (N-1)'th frame or an earlier frame;

(c) performing reference-to-frame tracking to identify locations of vertices within the N'th frame based on the locations of vertices in the reference frame to counter potential drift between the frames;

(d) storing the locations of vertices for use in subsequent reconstruction of the motion of the subject; and performing the frame-to-frame and reference-to-frame tracking again using a different set of parameters, the parameters defining a search area for the vertices of each frame wherein multiple correlation passes are performed with the different sets of parameters; and

(e) wherein the search area is shrunk by using an estimate of the position of a vertex based on the position of nearby vertices that were successfully tracked in the previous passes.

241. At all material times, defendant Disney MPG had the right and ability to supervise the infringing conduct alleged herein, including but not limited to the infringing acts of defendants Marvel and Mandeville, and had an obvious and direct financial interest in the exploitation of Rearden's patented works.

242. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Guardians of the Galaxy* and *Avengers: Age*

of Ultron without authorization. On information and belief, the contract provided for a financial payment to DD3.

243. Defendant Disney MPG, acting either alone or through entities subject to its supervision and control, contracted with DD3 to use the patented MOVA Contour facial motion capture system and methods for facial motion capture in *Beauty and the Beast* without authorization. On information and belief, the contract provided for a financial payment to DD3.

244. Each instance of DD3's unauthorized use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in the performance of its contract with Disney MPG, or with entities subject to Disney MPG's supervision and control, constitutes an act of direct infringement of one or more claims of the '963 Patent.

245. At all material times, Disney MPG had actual knowledge of, or was willfully blind to, the '963 Patent because it had performed an intellectual property due diligence with Rearden and worked with Rearden to use the MOVA Contour facial motion capture system for facial motion capture in *TRON: Legacy* (2010), *Pirates of the Caribbean: On Stranger Tides* (2011), *John Carter* (2012), and *The Avengers* (2012). Based upon its intellectual property due diligence, Disney MPG had actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the claims of the '963 Patent.

246. And on information and belief, Disney MPG had actual knowledge of, or was willfully blind to, the '963 Patent because it had performed an intellectual property due diligence with DD3 prior to contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in *Guardians of the Galaxy* (2014), *Avengers: Age of Ultron* (2015), and *Beauty and the Beast* (2017). A competent intellectual property due diligence would have included an examination of the public record of assignments of the '963 Patent, which would have revealed that DD3 did not have a license from any entity that could have owned the MOVA Contour facial motion capture system.

247. Disney MPG's actual knowledge of the '963 Patent, actual knowledge that Rearden regarded the MOVA Contour facial motion capture system and methods to be embodiments of the

claims of the ’963 Patent, and knowledge of or willful blindness to DD3’s lack of authorization from any entity that could have owned the MOVA Contour facial motion capture system, confirm Disney MPG’s specific intent to induce DD3 to infringe the ’963 Patent by contracting with DD3 to use the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization.

248. Consequently, Disney MPG actively induced each instance of DD3’s use of the MOVA Contour facial motion capture system for facial motion capture in the *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures without authorization in the performance of its contract with Disney MPG, or with entities subject to Disney MPG’s supervision and control. Disney MPG’s active inducement of direct infringement by DD3 constitutes acts of infringement of the ’963 Patent under 35 U.S.C. § 271(b).

249. Defendant Disney MPG is liable to Plaintiffs for damages adequate to compensate for Disney MPG’s direct and actively-induced infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs’ invention by Disney MPG under 35 U.S.C. § 284.

250. In addition, defendant Disney MPG’s direct and actively-induced infringements have caused Plaintiffs irreparable harm that is not compensable by monetary damages, and therefore Plaintiffs are entitled to injunctive relief under 35 U.S.C. § 283.

251. Disney MPG’s direct and actively-induced infringements constitute willful, egregious misconduct, and consequently Plaintiffs are entitled to a discretionary increase of their damages award up to three times the amount found or assessed, costs, and attorney’s fees under 35 U.S.C. § 284.

252. Finally, based on the foregoing facts, Plaintiffs request that this Court declare this an exceptional case, and award Plaintiffs their costs and attorney’s fees under 35 U.S.C. § 285.

EIGHTH CAUSE OF ACTION:
TRADEMARK INFRINGEMENT
(DEFENDANTS DISNEY COMPANY, DISNEY MPG AND BUENA VISTA)

253. Plaintiffs reallege and incorporate each and every allegation contained in the paragraphs above with the same force and effect as if said allegations were fully set forth herein.

254. At all material times, plaintiff Rearden Mova was the owner of U.S. Registration No. 3,843,152 for the MOVA service mark.

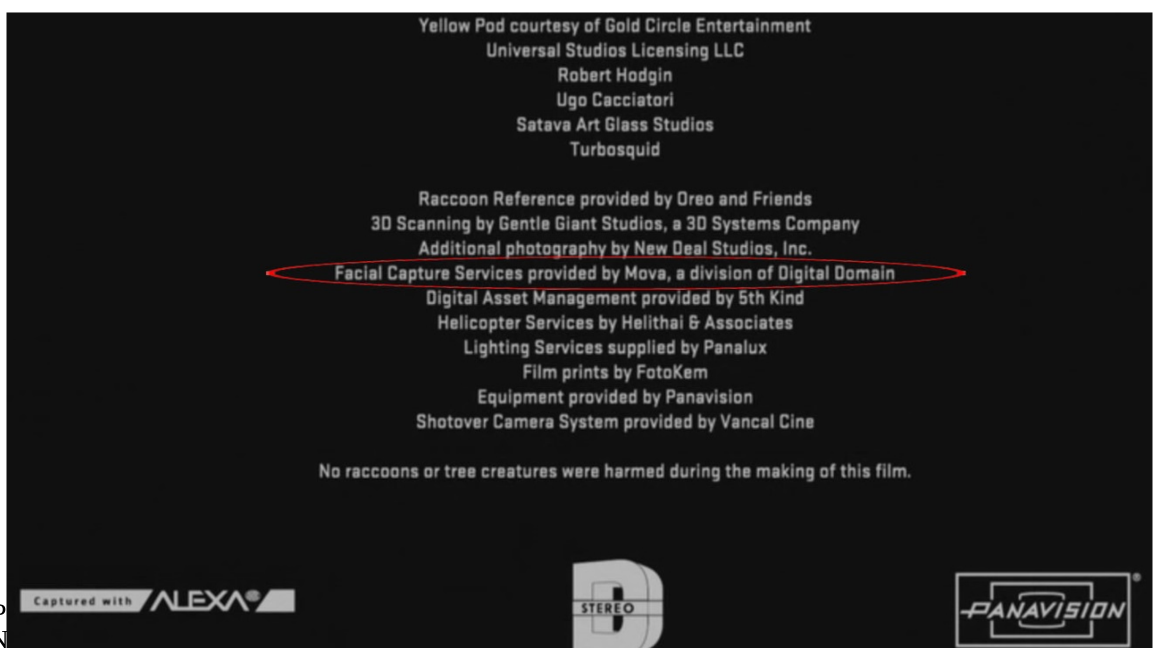
255. MOVA is an arbitrary or at least fanciful mark that is inherently distinctive.

256. Since at least 2006, Rearden Mova and its predecessors in interest have used the MOVA service mark in connection with the marketing, promotion, and sales of facial performance capture services and output files to the motion picture and video game industry, including major motion picture studios and VFX studios.

257. Through the marketing, promotion, and sales efforts of Rearden Mova and its predecessors in interest from 2005 through the present, and through the widespread publicity of and industry acclaim for the MOVA Contour facial performance capture technology and services offered by Rearden, Rearden Mova's MOVA service mark has acquired secondary meaning indicating that Rearden is the exclusive origin of the MOVA Contour facial performance capture technology and services.

258. At all material times, defendant Disney Company dominated and controlled defendants Disney MPG and Buena Vista.

259. Without authorization, Disney MPG and Buena Vista used Rearden Mova's MOVA service mark in commerce in the credits on their *Guardians of the Galaxy* film, stating that "Facial motion capture services were provided by Mova, a division of Digital Domain," as shown below:



260. Without authorization, Disney MPG and Buena Vista used Rearden's MOVA service mark in commerce in their *Beauty of the Beast* featurette in connection with commercial advertising and promotion of their *Beauty and the Beast* film

261. Without authorization, Disney MPG, acting either directly or through entities subject to its supervision and control, used Rearden's MOVA service mark in commerce in connection with commercial advertising and promotion of its *Guardians of the Galaxy* and *Beauty and the Beast* films, including press releases, press conferences, and other advertising and promotional activities.

262. Disney MPG and Buena Vista's unauthorized use of Rearden Mova's MOVA service mark on the credits for their *Guardians of the Galaxy* and *Beauty and the Beast* films is a use of a word or term that is likely to cause confusion, mistake or deception as to the affiliation, connection, or association of Disney with Rearden, and/or as to the origin, sponsorship of approval of the facial motion capture services used in the *Guardians of the Galaxy* and *Beauty and the Beast* films by Rearden because the MOVA service mark is exclusively associated with Rearden and its MOVA Contour facial motion capture services.

263. Disney MPG and Buena Vista's unauthorized use of Rearden Mova's MOVA service mark on the credits for their *Guardians of the Galaxy* and *Beauty and the Beast* films is a misleading description or representation of fact that is likely to cause confusion, mistake or deception as to the affiliation, connection, or association of Disney with Rearden, and/or as to the origin, sponsorship of approval of the facial motion capture services used in the *Guardians of the Galaxy* and *Beauty and the Beast* films by Rearden because the MOVA service mark is exclusively associated with Rearden and its MOVA Contour facial motion capture services.

264. Unauthorized use of Rearden Mova's MOVA service mark by Disney MPG, acting either directly or through entities subject to its supervision and control, including but not limited to defendants Marvel and Mandeville, in commerce in connection with commercial advertising and promotion of its *Guardians of the Galaxy* and *Beauty and the Beast* films, including press releases, press conferences, and other advertising and promotional activities, constitutes a use of a word or term and a misleading description or representation of fact that is likely to cause confusion, mistake

or deception as to the characteristics and qualities of the facial motion capture services in the films because the MOVA service mark is exclusively associated with Rearden and its MOVA Contour facial motion capture services.

265. Rearden Mova is, and is likely to continue to be, damaged by Disney MPG and Buena Vista's unauthorized use of its Rearden MOVA service mark.

266. Disney MPG and Buena Vista's unauthorized use of Rearden Mova's MOVA service mark in commerce was with actual knowledge or willful disregard of Rearden Mova's service mark, with intent to cause confusion, mistake or deception.

267. Defendants Disney Company, Disney MPG, and Buena Vista are liable to Plaintiffs for each and every act of trademark infringement alleged herein.

268. Plaintiffs are entitled to an award of its actual damages, disgorgement of defendants' profits, and costs and attorney's fees.

269. Furthermore, Plaintiffs have suffered irreparable harm that is not compensable by monetary damages, and is therefore entitled to injunctive and other equitable relief.

PRAYER FOR RELIEF

Wherefore, Plaintiffs request the following relied:

A. Enter preliminary and/or permanent injunctions as follows:

1. Pursuant to 17 U.S.C. § 502, enter an injunction prohibiting defendants from reproducing, distributing, performing or displaying, or authorizing the same, the *Guardians of the Galaxy*, *Avengers: Age of Ultron,* and *Beauty and the Beast* motion pictures in any medium without authorization of Plaintiffs.

2. Pursuant to 35 U.S.C. § 283, enter an injunction prohibiting defendant Disney MPG from using the patented MOVA Contour facial motion capture system and methods without authorization of Plaintiffs.

3. Pursuant to 15 U.S.C. § 1116, enter an injunction prohibiting defendants from using any of Plaintiffs' trademarks and service marks, and prohibiting distribution of the *Guardians of the Galaxy* and *Beauty and the Beast* motion pictures in any medium bearing any of Plaintiffs' trademarks and service marks without authorization of Plaintiffs.

B. Pursuant to 17 U.S.C. § 503 and/or 15 U.S.C. § 1118, order the impoundment and destruction of all infringing copies of *Guardians of the Galaxy*, *Avengers: Age of Ultron*, and *Beauty and the Beast* motion pictures in any medium.

C. Award financial damages compensation as follows:

1. Pursuant to 17 U.S.C. § 504, award Plaintiffs (a) actual damages; and (b) any additional profits of defendants that are attributable to the copyright infringements alleged herein and are not taken into account in computing the actual damages.

2. Pursuant to 35 U.S.C. § 284, award Plaintiffs damages adequate to compensate for defendant Disney MPG's patent infringements, in an amount to be proved at trial but in no event less than a reasonable royalty for the use made of Plaintiffs' invention by defendant Disney MPG.

3. Pursuant to 17 U.S.C. § 1117, award Plaintiffs (a) defendants' profits; (b) damages sustained by Plaintiffs in an amount to be proved at trial; and (c) the costs of this action.

D. Willful Infringement.

1. Pursuant to 35 U.S.C. § 284, enter a finding that defendant Disney MPG's patent infringements as alleged herein were willful, egregious misconduct, and order a discretionary increase of Plaintiffs' damages award up to three times the amount found or assessed, costs, and attorney's fees.

2. Pursuant to 17 U.S.C. § 1117, enter a finding that defendants' trademark infringements as alleged herein were willful, in reckless disregard, or in willful blindness to Plaintiffs' copyright and trademark rights, and order enhanced damages, costs, and attorney's fees.

E. Award Plaintiffs their costs and attorney's fees as follows:

1. Pursuant to 17 U.S.C. § 505, award full costs and a reasonable attorney's fee to Plaintiffs.

2. Pursuant to 35 U.S.C. § 285, enter a finding that Disney MPG's patent infringements as alleged herein, present an exceptional case, and award Plaintiffs their costs and attorney's fees with respect to their patent infringement claims.

3. Pursuant to 15 U.S.C. § 1117, enter a finding that Defendants' trademark infringements as alleged herein present an exceptional case, and award Plaintiffs their costs and attorney's fees with respect to their patent infringement claims.

F. Grant such other and further relief as the Court deems just and equitable.

DEMAND FOR JURY TRIAL

Pursuant to Fed. R. Civ. P. 38(b), plaintiff demands trial by jury of all issues so triable under the law.

DATED: July 17, 2017 HAGENS BERMAN SOBOL SHAPIRO LLP

By */s/ Rio S. Pierce*
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Rearden LLC and Rearden Mova LLC

Exhibit 1

Certificate of Registration

This Certificate issued under the seal of the Copyright Office in accordance with title 17, *United States Code*, attests that registration has been made for the work identified below. The information on this certificate has been made a part of the Copyright Office records.

United States Register of Copyrights and Director

Registration Number
TXu 1-977-151
Effective Date of Registration:
February 11, 2016

Title

Title of Work: MOVA Contour

Completion/Publication

Year of Completion: 2009

Author

- **Author:** OnLive, Inc.
  Author Created: computer program
  Work made for hire: Yes
  Citizen of: United States

Copyright Claimant

Copyright Claimant: Rearden Mova LLC
355 Bryant Street, Suite 110, San Francisco, CA, 94107, United States
Transfer statement: By written agreement

Rights and Permissions

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Certification

Name: Jonathan Kirsch
Date: February 11, 2016
Applicant's Tracking Number: 2347.3.4

Correspondence: Yes

0000TXU0019771510202

Exhibit 2

US007605861B2

(12) **United States Patent**
LaSalle et al.

(10) **Patent No.: US 7,605,861 B2**
(45) **Date of Patent: *Oct. 20, 2009**

(54) **APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING SHUTTER SYNCHRONIZATION**

(75) Inventors: **Greg LaSalle**, San Francisco, CA (US); **Roger Van der Laan**, Los Altos, CA (US); **Stephen G. Periman**, Palo Alto, CA (US); **John Speck**, Sunnyvale, CA (US); **Timothy S. Cotter**, Sunnyvale, CA (US); **Kenneth A. Pearce**, San Francisco, CA (US)

(73) Assignee: **OnLive, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 576 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **11/077,628**

(22) Filed: **Mar. 10, 2005**

(65) **Prior Publication Data**

US 2006/0203096 A1 Sep. 14, 2006

(51) **Int. Cl.**

H04N 5/222	(2006.01)
H04N 9/04	(2006.01)
H04N 5/228	(2006.01)
H04N 5/225	(2006.01)
H04N 5/262	(2006.01)

(52) **U.S. Cl.** **348/371**; 348/208.14; 348/370; 348/207.99; 348/218.1; 348/239

(58) **Field of Classification Search** 348/169–172, 348/218.1, 208.14, 162, 207.99, 239, 370–371
See application file for complete search history.

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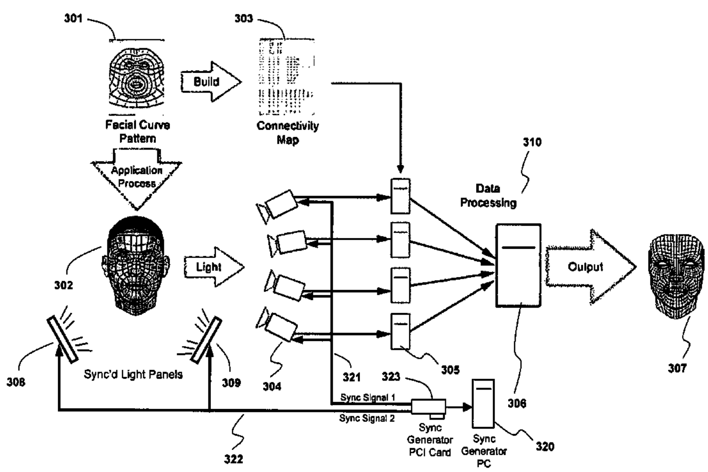
Primary Examiner—David L Ometz
Assistant Examiner—Richard M Bemben
(74) *Attorney, Agent, or Firm*—Blakely, Sokoloff, Taylor & Zafman LLP

(57) **ABSTRACT**

A method is described comprising: applying phosphorescent paint to specified regions of a performer's face and/or body; strobing a light source on and off, the light source charging the phosphorescent paint when on; and strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture images of the phosphorescent paint, wherein the shutters are open when the light source is off and the shutters are closed when the light source is open.

52 Claims, 11 Drawing Sheets



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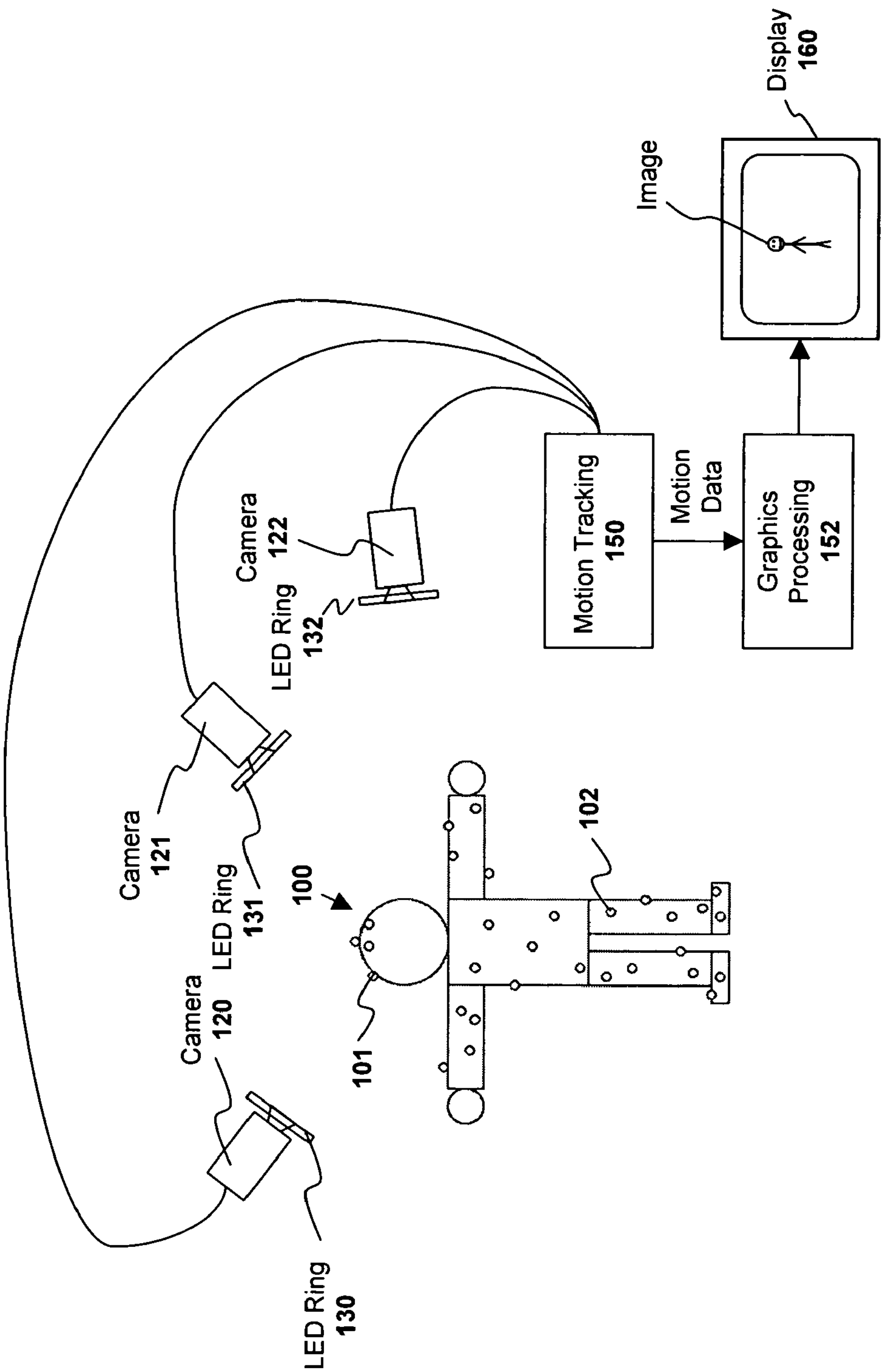


Fig. 1
(prior art)

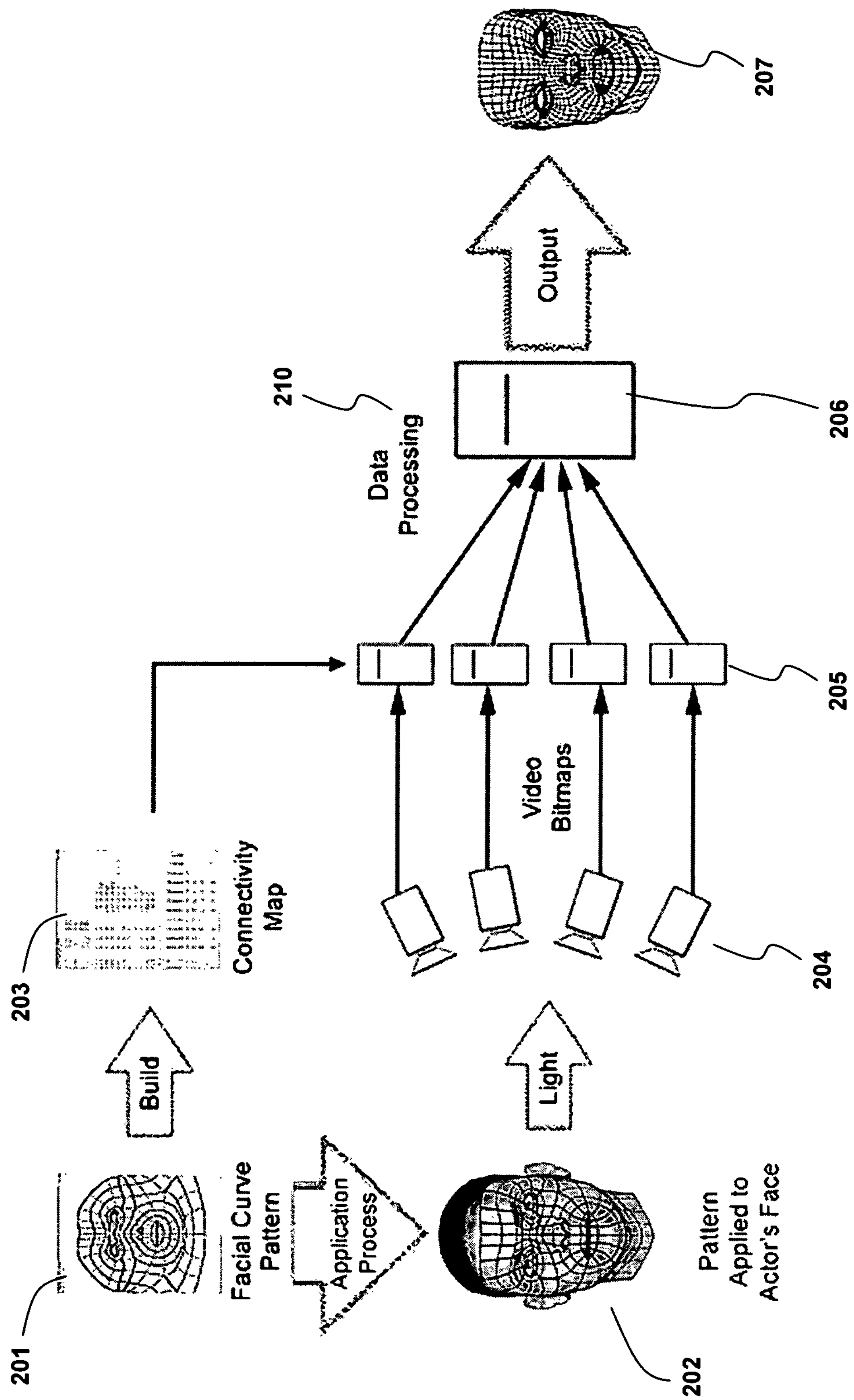

201
Facial Curve Pattern
Build
203
Connectivity Map
Application Process
Light
202
Pattern Applied to Actor's Face
204
Video Bitmaps
205
Data Processing
210
206
Output
207

Fig. 2

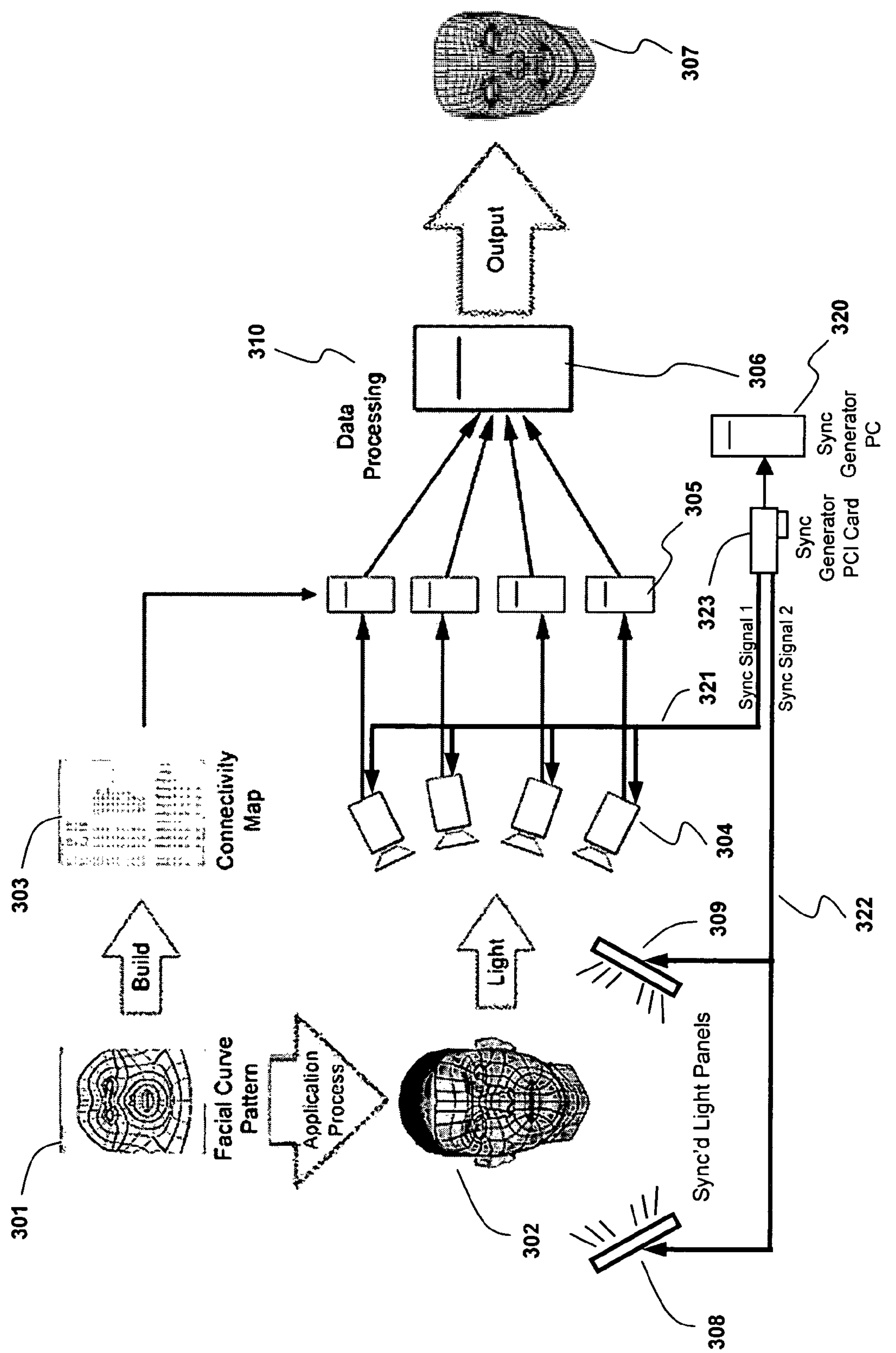
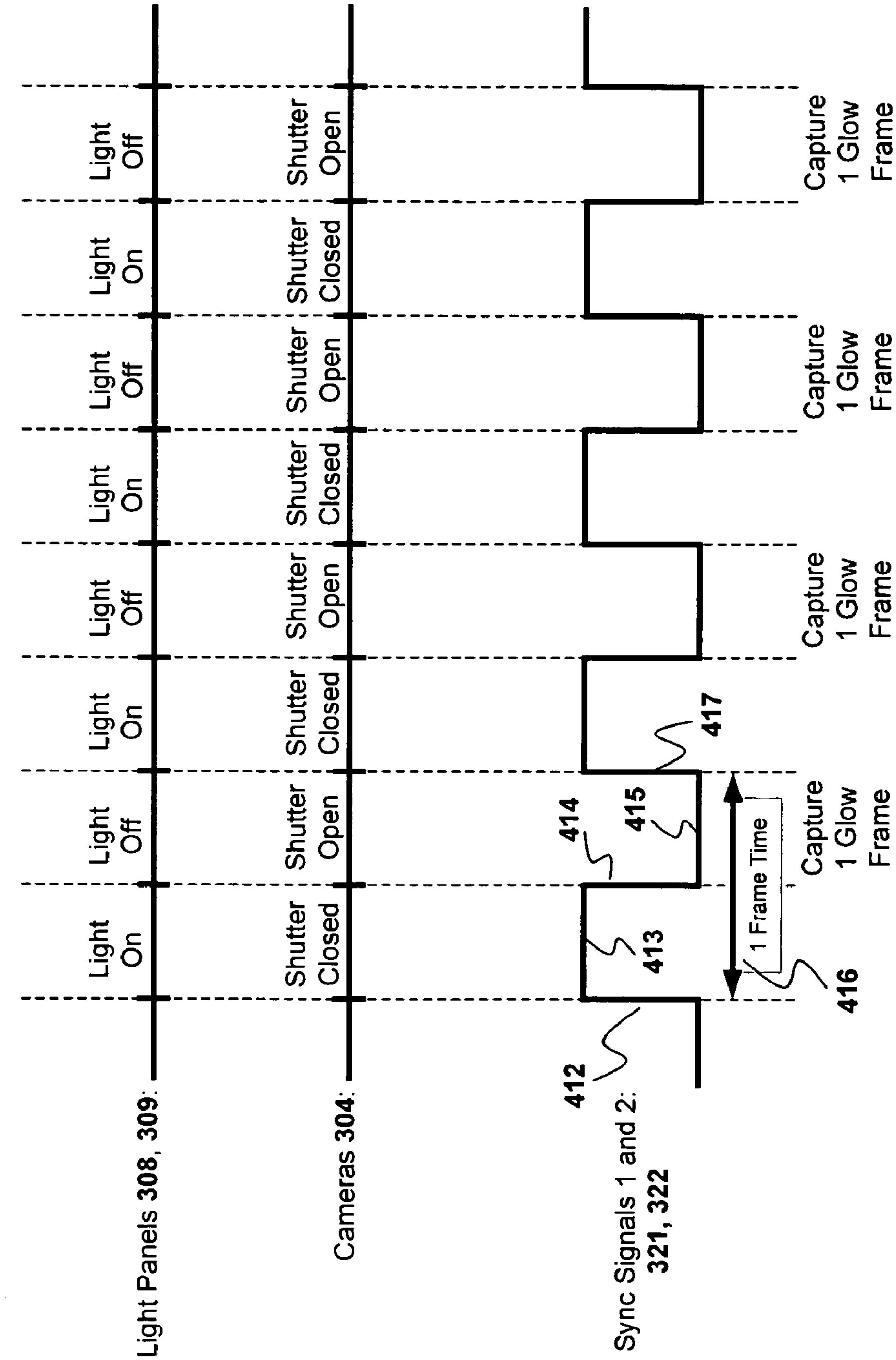

301
Facial Curve Pattern
Application Process
Build
303
Connectivity Map
Light
302
Sync'd Light Panels
308
309
304
322
321
Sync Signal 1
Sync Signal 2
323
Sync Generator PCI Card
305
Sync Generator PC
320
Data Processing
310
306
Output
307

Fig. 3



Light Panels 308, 309:
Cameras 304:
Sync Signals 1 and 2: 321, 322
Light On
Light Off
Shutter Closed
Shutter Open
Capture 1 Glow Frame
1 Frame Time
412
413
414
415
416
417

Fig. 4

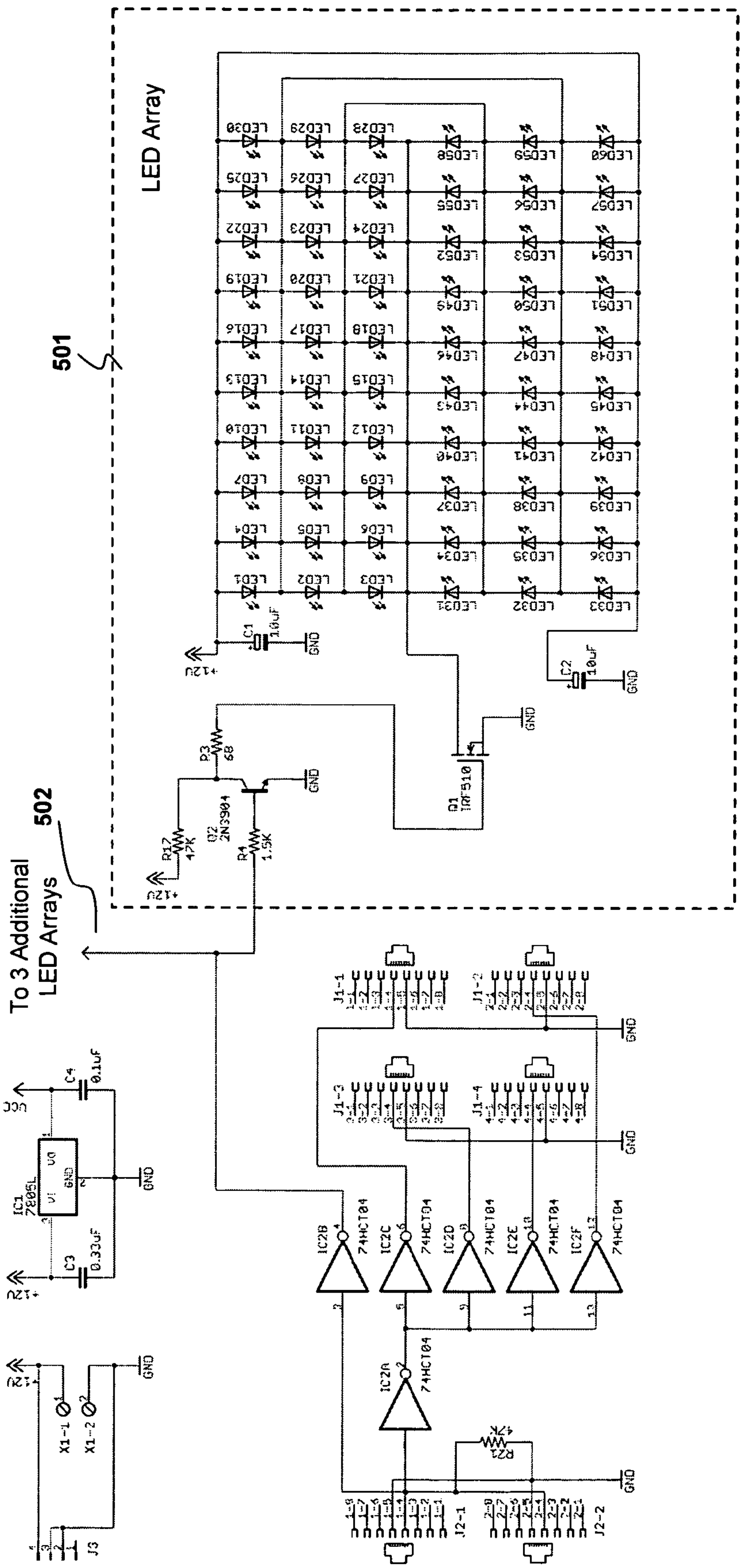


Fig. 5

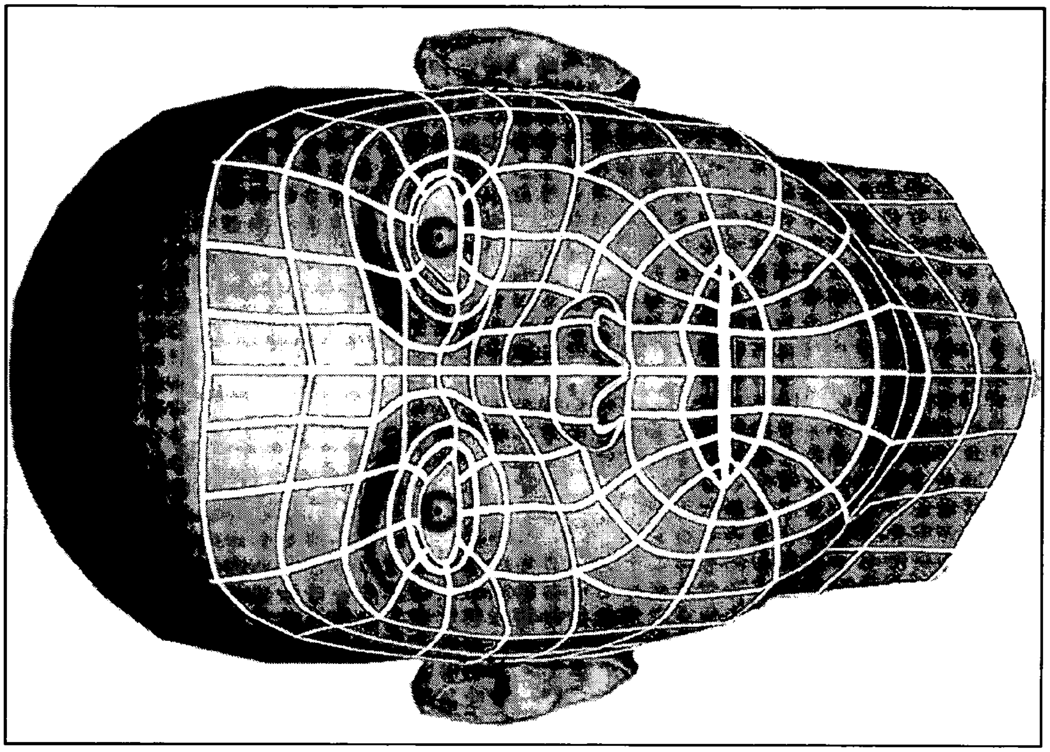


Fig. 6a

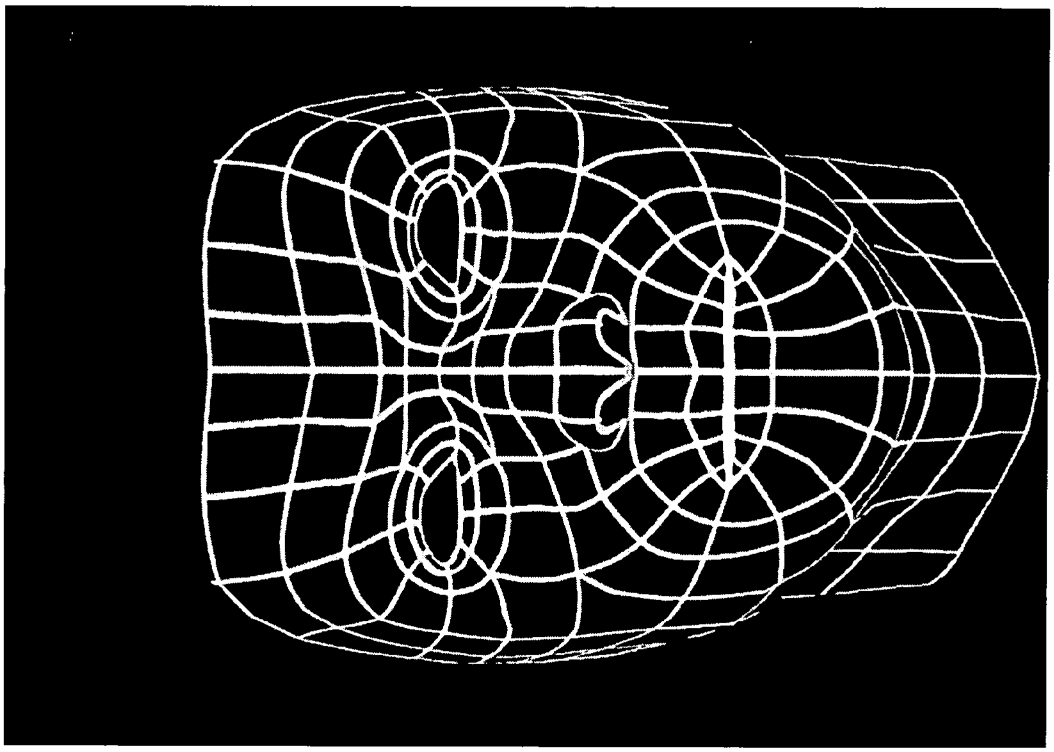


Fig. 6b

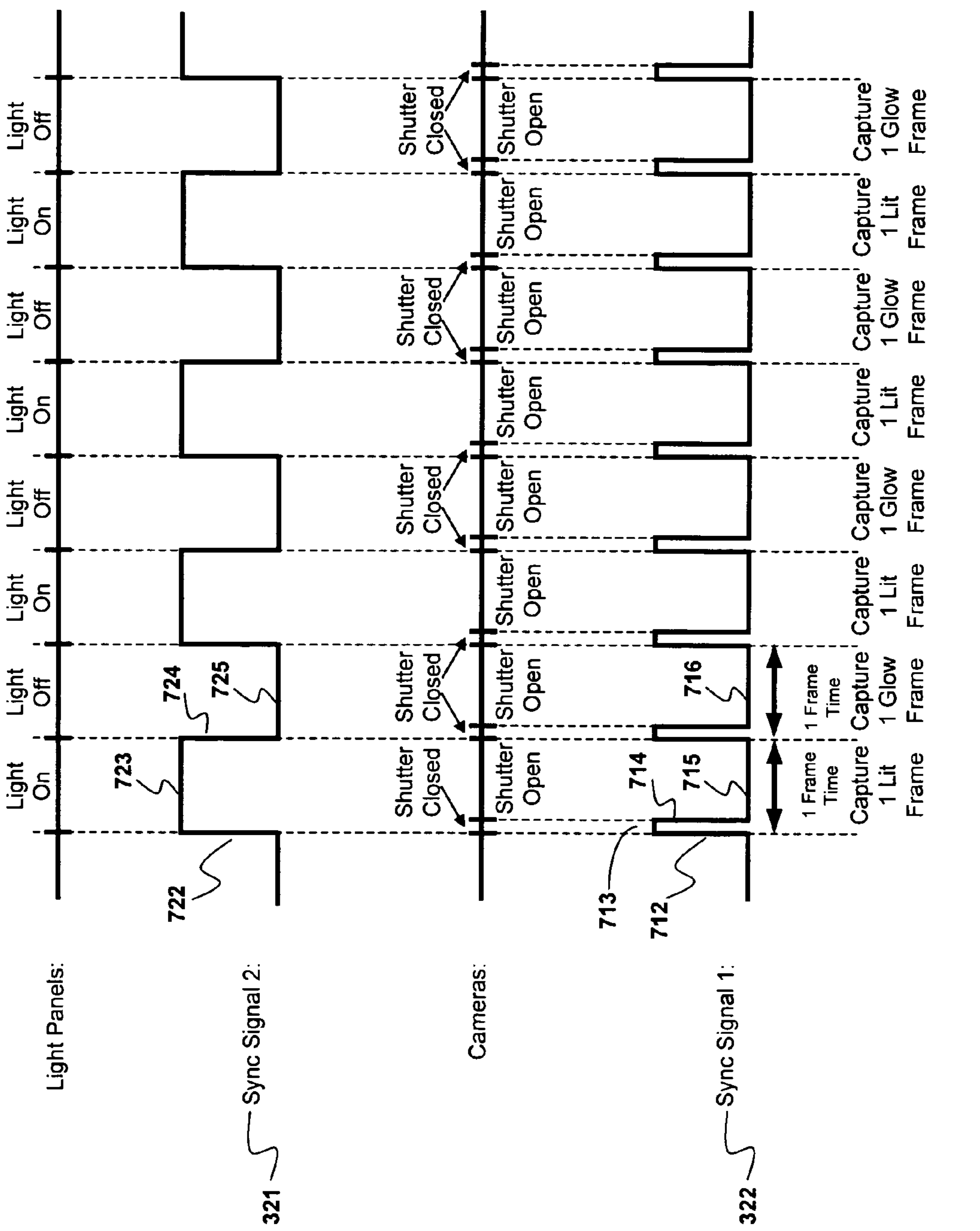

Light Panels:
Sync Signal 2:
Cameras:
Sync Signal 1:
321
322
Light On
Light Off
Shutter Closed
Shutter Open
Capture 1 Lit Frame
Capture 1 Glow Frame
1 Frame Time
722
723
724
725
712
713
714
715
716

Fig. 7

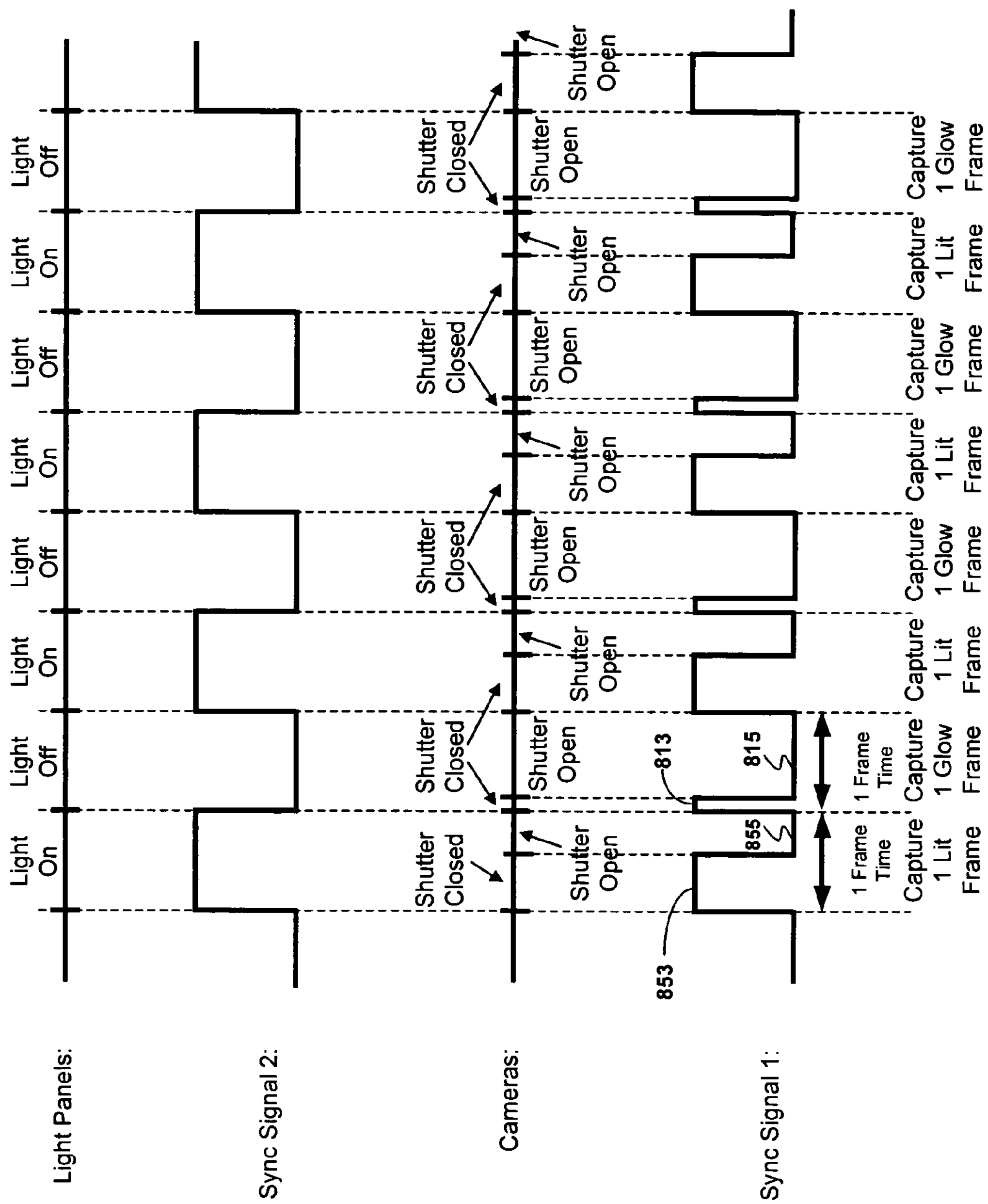

Light Panels:
Sync Signal 2:
Cameras:
Sync Signal 1:
Light On
Light Off
Light On
Light Off
Light On
Light Off
Light On
Light Off
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
853
855
813
815
1 Frame Time
1 Frame Time
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame

Fig. 8

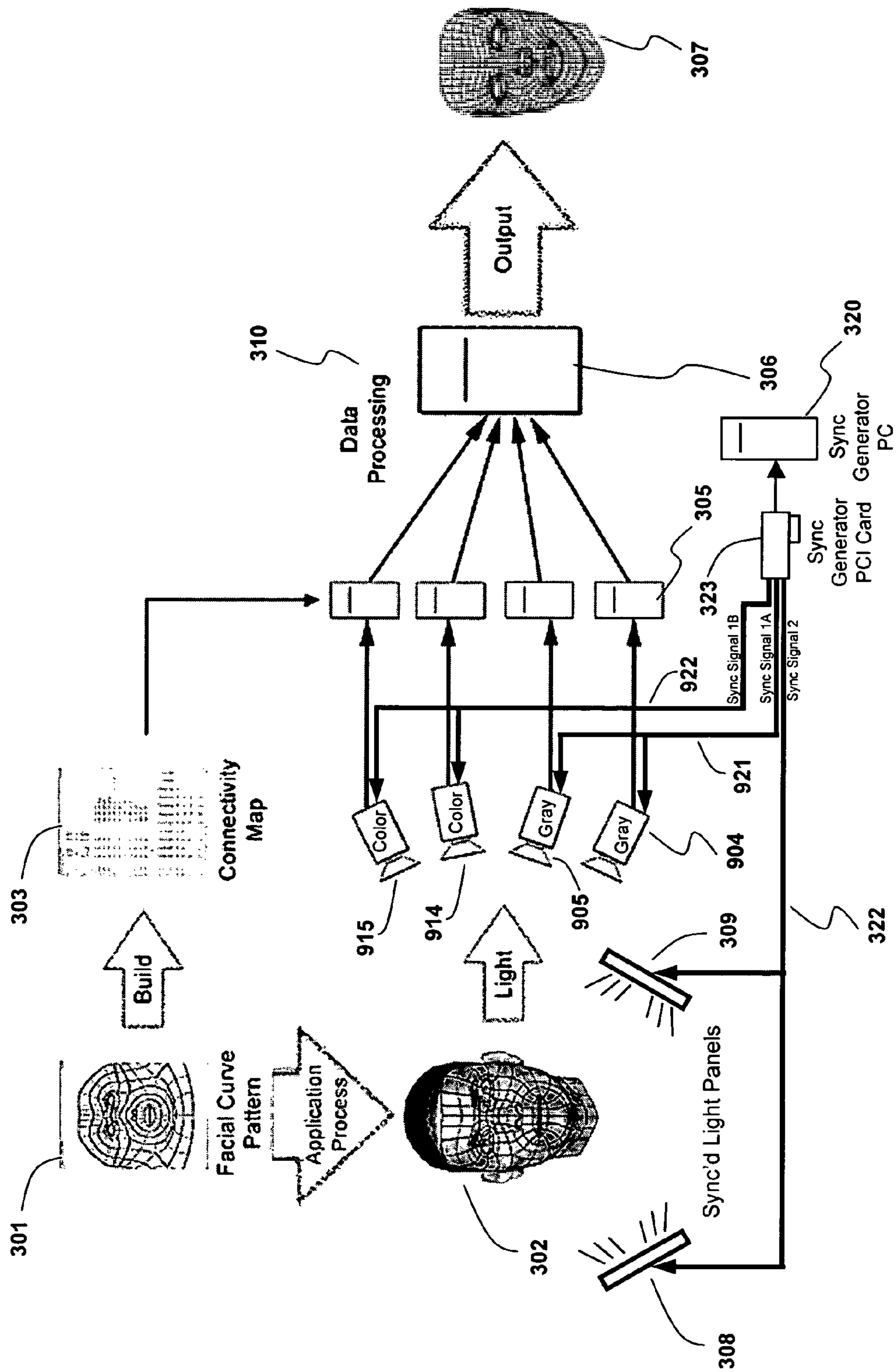
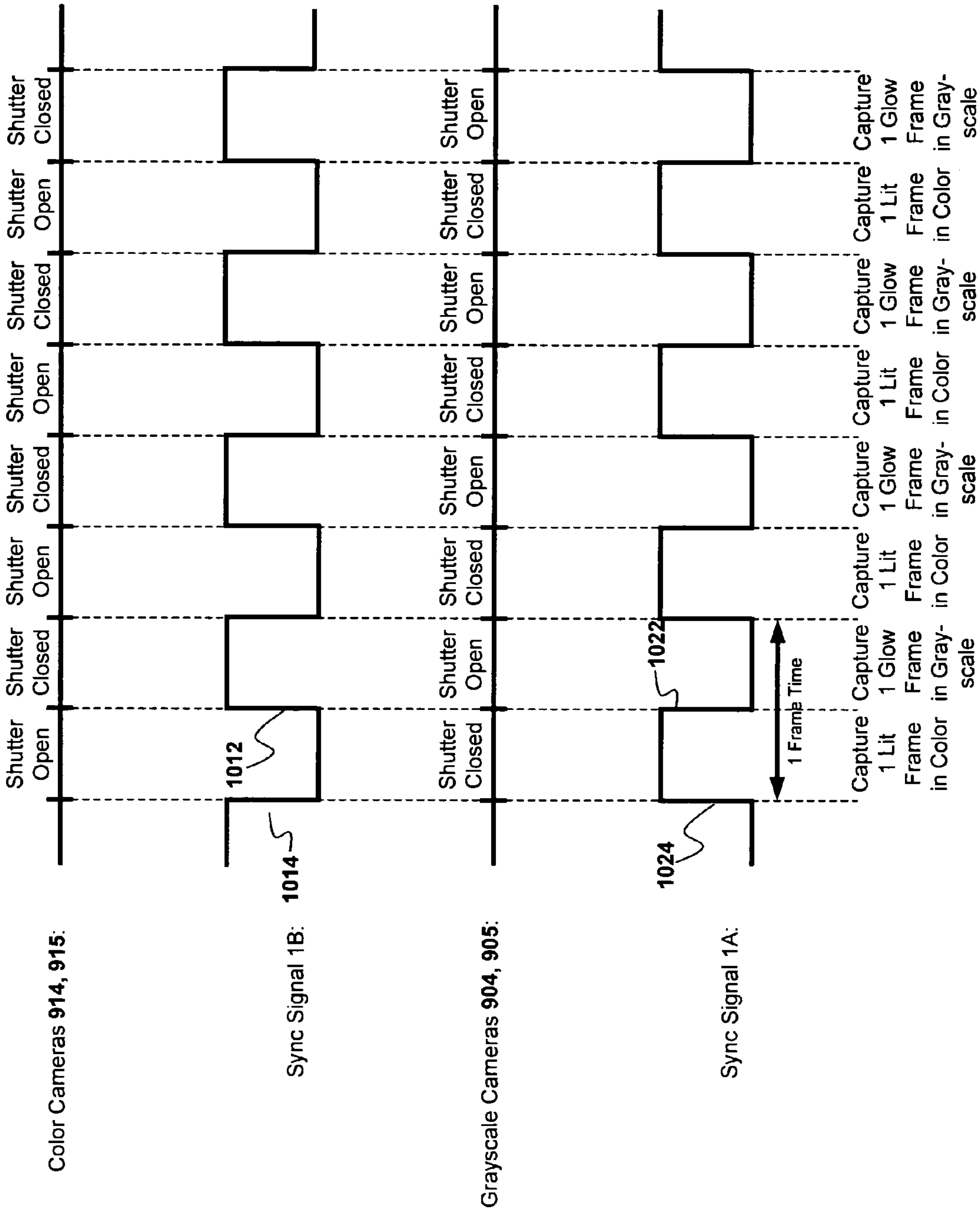

307
Output
310
Data Processing
306
320
Sync Generator PC
305
Sync Generator PCI Card
323
Sync Signal 1B
Sync Signal 1A
Sync Signal 2
922
921
303
Connectivity Map
Color
Color
Gray
Gray
904
915
914
905
Build
Light
309
322
301
Facial Curve Pattern
Application Process
302
Sync'd Light Panels
308

Fig. 9



Color Cameras **914**, **915**:
Sync Signal 1B:
Grayscale Cameras **904**, **905**:
Sync Signal 1A:
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
1012
1014
1022
1024
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Glow Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Glow Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Glow Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Glow Frame in Gray-scale

Fig. 10

APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING SHUTTER SYNCHRONIZATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of motion capture. More particularly, the invention relates to an improved apparatus and method for performing motion capture using shutter synchronization and/or using phosphorescent paint.

2. Description of the Related Art

"Motion capture" refers generally to the tracking and recording of human and animal motion. Motion capture systems are used for a variety of applications including, for example, video games and computer-generated movies. In a typical motion capture session, the motion of a "performer" is captured and translated to a computer-generated character.

As illustrated in FIG. **1** in a motion capture system, a plurality of motion tracking "markers" (e.g., markers **101**, **102**) are attached at various points on a performer's **100**'s body. The points are selected based on the known limitations of the human skeleton. Different types of motion capture markers are used for different motion capture systems. For example, in a "magnetic" motion capture system, the motion markers attached to the performer are active coils which generate measurable disruptions x, y, z and yaw, pitch, roll in a magnetic field.

By contrast, in an optical motion capture system, such as that illustrated in FIG. **1**, the markers **101**, **102** are passive spheres comprised of retro-reflective material, i.e., a material which reflects light back in the direction from which it came, ideally over a wide range of angles of incidence. A plurality of cameras **120**, **121**, **122**, each with a ring of LEDs **130**, **131**, **132** around its lens, are positioned to capture the LED light reflected back from the retro-reflective markers **101**, **102** and other markers on the performer. Ideally, the retro-reflected LED light is much brighter than any other light source in the room. Typically, a thresholding function is applied by the cameras **120**, **121**, **122** to reject all light below a specified level of brightness which, ideally, isolates the light reflected off of the reflective markers from any other light in the room and the cameras **120**, **121**, **122** only capture the light from the markers **101**, **102** and other markers on the performer.

A motion tracking unit **150** coupled to the cameras is programmed with the relative position of each of the markers **101**, **102** and/or the known limitations of the performer's body. Using this information and the visual data provided from the cameras **120-122**, the motion tracking unit **150** generates artificial motion data representing the movement of the performer during the motion capture session.

A graphics processing unit **152** renders an animated representation of the performer on a computer display **160** (or similar display device) using the motion data. For example, the graphics processing unit **152** may apply the captured motion of the performer to different animated characters and/or to include the animated characters in different computer-generated scenes. In one implementation, the motion tracking unit **150** and the graphics processing unit **152** are programmable cards coupled to the bus of a computer (e.g., such as the PCI and AGP buses found in many personal computers). One well known company which produces motion capture systems is Motion Analysis Corporation (see, e.g., www.motionanalysis.com).

SUMMARY

A method is described comprising: applying phosphorescent paint to specified regions of a performer's face and/or body; strobing a light source on and off, the light source charging the phosphorescent paint when on; and strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture images of the phosphorescent paint, wherein the shutters are open when the light source is off and the shutters are closed when the light source is open.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention can be obtained from the following detailed description in conjunction with the drawings, in which:

FIG. **1** illustrates a prior art motion tracking system for tracking the motion of a performer using retro-reflective markers and cameras.

FIG. **2** illustrates one embodiment of the invention which employs a curve pattern to track facial expression.

FIG. **3** illustrates one embodiment of the invention which synchronizes light panels and camera shutters.

FIG. **4** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **5** is a schematic representation of an exemplary LED array and the connectors for the synchronization signals.

FIG. **6***a* illustrates a set of exemplary illuminated curves painted on a performer's face during a lit frame.

FIG. **6***b* illustrates a set of exemplary illuminated curves painted on a performer's face during a "glow" frame.

FIG. **7** is a timing diagram illustrating the synchronization between the light panels and the camera shutters in an embodiment for capturing both lit frames and glow frames.

FIG. **8** is a timing diagram illustrating the synchronization between the light panels and the camera shutters in another embodiment for capturing both lit frames and glow frames.

FIG. **9** illustrates one embodiment of a system for capturing both lit frames and glow frames.

FIG. **10** illustrates a timing diagram associated with the system shown in FIG. **9**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Described below is an improved apparatus and method for performing motion capture using shutter synchronization and/or phosphorescent paint. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form to avoid obscuring the underlying principles of the invention.

The assignee of the present application previously developed a system for performing color-coded motion capture and a system for performing motion capture using a series of reflective curves painted on a performer's face. These systems are described in the co-pending applications entitled "APPARATUS AND METHOD FOR CAPTURING THE MOTION AND/OR

Expression of a Performer," Ser. No. 10/942,609, and Ser. No. 10/942,413, Filed Sep. 15, 2004. These applications are assigned to the assignee of the present application and are incorporated herein by reference.

As described in these co-pending applications, by analyzing curves rather than discrete data points on a performer's face, the motion capture system is able to generate significantly more surface data than traditional marker-based tracking systems. FIG. **2** illustrates an exemplary motion capture system described in the co-pending applications in which a predefined facial curve pattern **201** is adjusted to fit the topology of each performer's face **202**. In one embodiment, the three-dimensional (3-D) curve pattern is adjusted based on a 3-D map of the topology of the performer's face captured using a 3-D scanning system.

The curves defined by the curve pattern **201** are painted on the face of the performer using retro-reflective, non-toxic paint or theatrical makeup. As described in detail below, in one embodiment of the invention, non-toxic phosphorescent paint is used to create the curves.

As described in the co-pending applications, each curve painted on the performer's face has a unique identifying name and/or number (to support systematic data processing) and potentially a color that can be easily identified by the optical capture system. Once the curve pattern is applied, in one embodiment, the curve pattern is tracked by a motion capture processing system **210** comprised of one or more camera controllers **205** and a central motion capture controller **206** during the course of a performance. In one embodiment, each of the camera controllers **205** and central motion capture controller **206** is implemented using a separate computer system. Alternatively, the cameral controllers and motion capture controller may be implemented as software executed on a single computer system or as any combination of hardware and software.

In one embodiment, each of the camera controllers **205** and/or the motion capture controller **206** is programmed with data **203** representing the curve pattern **201**. The motion capture system **210** uses this information to trace the movement of each curve within the curve pattern during a performance. For example, the performer's facial expressions provided by each of the cameras **204** (e.g., as bitmap images) are analyzed and the curves identified using the defined curve pattern.

In one embodiment, the curve data **203** is provided to the motion capture system in the form of a "connectivity map," which is a text file representation of the curve pattern **201** which includes a list of all curves in the pattern and a list of all surface patches in the pattern, with each patch defined by its bounding curves. It is used by the camera controllers **205** and/or the central motion capture controller **206** to identify curves and intersections in the optically captured data. This, in turn, allows point data from the curves to be organized into surface patches and ultimately the triangulated mesh of a final 3-D geometry **207**.

In one embodiment of the invention, the efficiency of the motion capture system is improved by using phosphorescent paint and/or by precisely controlling synchronization between the cameras' shutters and the illumination of the painted curves. More specifically, referring to FIG. **3**, in one embodiment of the invention, the predefined facial curve pattern **301** is painted on the performer's face **202** using phosphorescent paint. In addition, light panels **308-309** (e.g., LED arrays) are precisely synchronized with the opening and closing of the shutters of the motion capture cameras **304**. In one embodiment, the synchronization between the light panels **308-309** and cameras **304** is controlled via synchronization signals **322** and **321**, respectively. As indicated in FIG. **3**, in one embodiment, the synchronization signals are provided from a peripheral component interface ("PCI") card **323** coupled to the PCI bus of a personal computer **320**. An exemplary PCI card is a PCI-6601 manufactured by National Instruments of Austin, Tex. However, the underlying principles of the invention are not limited to any particular mechanism for generating the synchronization signals.

The synchronization between the light sources and the cameras employed in one embodiment of the invention is illustrated in FIG. **4**. In this embodiment, the two synchronization signals **321**, **322** are the same. In one embodiment, the synchronization signals cycle between 0 to 5 Volts. In response to the synchronization signals **321**, **322**, the shutters of the cameras are periodically opened and closed and the light panels are periodically turned off and on, respectively. For example, on the rising edge **412** of the synchronization signals, the camera shutters are closed and the light panels are illuminated. The shutters remain closed and the light panels remain illuminated for a period of time **413**. Then, on the falling edge of the synchronization signals **414**, the shutters are opened and the light panels are turned off. The shutters and light panels are left in this state for another period of time **415**. The process then repeats on the rising edge **417** of the synchronization signals.

As a result, during the first period of time **413**, no image is captured by the cameras, and the phosphorescent paint is illuminated with light from the light panels **308-309**. During the second period of time **415**, the light is turned off and the cameras capture an image of the glowing phosphorescent paint on the performer. Because the light panels are off during the second period of time **415**, the contrast between the phosphorescent paint and the rest of the room is extremely high (i.e., the rest of the room is pitch black), thereby improving the ability of the system to differentiate the various curves painted on the performer's face. In addition, because the light panels are on half of the time, the performer will be able to see around the room during the performance. The frequency **416** of the synchronization signals may be set at such a high rate that the performer will not even notice that the light panels are being turned on and off. For example, at a flashing rate of 75 Hz or above, most humans are unable to perceive that a light is flashing and the light appears to be continuously illuminate. In psychophysical parlance, when a high frequency flashing light is perceived by humans to be continuously illuminated, it is said that "fusion" has been achieved. In one embodiment, the light panels are cycled at 120 Hz; in another embodiment, the light panels are cycled at 140 Hz, both frequencies far above the fusion threshold of any human. However, the underlying principles of the invention are not limited to any particular frequency.

FIG. **6*a*** is an exemplary picture of the performer during the first time period **413** (i.e., when the light panels are illuminated) and FIG. **6*b*** shows the illuminated reflective curves captured by the cameras **304** during the second time period **415** (i.e., when the light panels are turned off). During the first time period, the phosphorescent paint is charged by the light from the light panels and, as illustrated in FIG. **6*b***, when the light panels are turned off, the only light captured by the cameras is the light emanating from the charged phosphorescent paint. Thus, the phosphorescent paint is constantly recharged by the strobing of the light panels, and therefore retains its glow throughout the motion capture session. In addition, because it retains its glow for a period of time, if a performer happens to move so that for a few frames some of the phosphorescent lines are in shadow and not illuminated by the light panels, even though the phosphorescent paint is not getting fully charged for those frames, the paint will still retain its glow from previous frame times (i.e., when the paint was not in shadow).

As mentioned above, in one embodiment, the light panels **308**, **309** are LED arrays. A schematic of an exemplary LED array **501** and associated connection circuitry is illustrated in FIG. **5**. The synchronization signals are applied to the LED array **501** via connector J**2-1** illustrated to the left in FIG. **5**. In one embodiment, the connectors are RJ-45 connectors. The synchronization signal is initially inverted by inverter IC**2**B and the inverted signal is applied to the base of transistor Q**2**, causing transistor Q**2** to turn on and off in response to the inverted signal. This causes current to flow through resistor R**3**, thereby causing transistor Q**1** to turn on and off. This, in turn, causes the LEDs within the LED array **501** to turn on and off. In one embodiment, the inverted signal from IC**2**B is applied to three additional LED arrays as indicated in FIG. **5**. A plurality of additional connectors J**1-1**, J**1-2**, J**1-3**, and J**1-4** are provided for additional light panels (i.e., the light panels may be daisy-chained together via these connectors) using inverters IC**2**C, IC**2**D, IC**2**E and IC**2**F for buffering. If daisy-chaining without buffering is desired (e.g. due to critical timing requirements that would be hampered by the IC**2** propagation delays), then connector **J2-2** can be used. The voltage regulaor IC**1** used for the LED array (shown at the top of FIG. **5**) takes a 12V input and produces a 5V regulated output used by IC**2**. In one embodiment, transistors Q**1** is a MOSFET transistor. However, the underlying principles are not limited to any particular type of circuitry.

In one embodiment of the invention, the cameras are configured to capture pictures of the performer's face (e.g., FIG. **6***a*) in addition to capturing the phosphorescent curves (e.g., FIG. **6***b*). The pictures of the performer's face may then be used, for example, by animators as a texture map to interpolate between the curves and render and more accurate representation of the performer.

The signal timing illustrated in FIG. **7** represents one such embodiment in which an asymmetric duty cycle is used for the synchronization signal for the cameras (in contrast to the 50% duty cycle shown in FIG. **4**). In this embodiment, synchronization signal **2** remains the same as in FIG. **4**. The rising edge **722** of synchronization signal **2** illuminates the light panels; the panels remain on for a first time period **723**, turn off in response to the falling edge **724** of synchronization signal **2**, and remain off for a second time period **725**.

By contrast, synchronization signal **1**, which is used to control the shutters, has an asymmetric duty cycle. In response to the rising edge **712** of synchronization signal **1**, the shutters are closed. The shutters remain closed for a first period of time **713** and are then opened in response to the falling edge **714** of synchronization signal **1**. The shutters remain open for a second period of time **715** and are again closed in response to the rising edge of synchronization signal **1**. The signals are synchronized so that the rising edge of synchronization signal **1** always coincides with both the rising and the falling edges of synchronization signal **2**. As a result, the cameras capture one lit frame during time period **715** (i.e., when the shutters are open the light panels are illuminated) and capture one "glow frame" during time period **716** (i.e., when the shutters are open and the light panels are off).

In one embodiment, the data processing system **310** shown in FIG. **3** separates the lit frames from the glow frames to generate two separate streams of image data, one containing the images of the performer's face and the other containing phosphorescent curve data. The glow frames may then be used to generate the mesh **307** of the performer's face and the

lit frames may be used, for example, as a reference for animators (e.g., to interpolate between the curves) and/or as a texture map of the performer's face. The two separate video sequences may be synchronized and viewed next to one another on a computer or other type of image editing device.

Given the significant difference in overall illumination between the lit frames and the glow frames, some cameras may become overdriven during the lit frames if their light sensitivity is turned up very high to accommodate glow frames. Accordingly, in one embodiment of the invention, the sensitivity of the cameras is cycled between lit frames and glow frames. That is, the sensitivity is set to a relatively high level for the glow frames and is then changed to a relatively low level for the lit frames.

Alternatively, if the sensitivity of the cameras **304** cannot be changed on a frame-by-frame basis, one embodiment of the invention changes the amount of time that the shutters are open between the lit frames and the glow frames. FIG. **8** illustrates the timing of one such embodiment in which synchronization signal **1** is adjusted to ensure that the cameras will not be overdriven by the lit frames. Specifically, in this embodiment, during the period of time that synchronization signal **2** is causing the light panels to be illuminated, synchronization signal **1** causes the shutter to be closed for a relatively longer period of time than when synchronization signal **2** is not illuminating the light panels. In FIG. **8**, for example, synchronization signal **1** is high during time period **853**, thereby closing the shutter, and is low during period **855**, thereby opening the shutter. By contrast, during the glow frame, synchronization signal **1** is high for a relatively short period of time **813** and is low for a relatively longer period of time **815**.

In one embodiment, illustrated in FIG. **9**, both color and grayscale cameras are used and are synchronized using different synchronization signals. Specifically, in this embodiment, color cameras **914-915** are used to capture the lit frames and grayscale cameras **904-905** are used to capture the phosphorescent curves painted on the performer's face. One of the benefits of this configuration is that grayscale cameras typically have a relatively higher resolution and higher light sensitivity than comparable sensor resolution color cameras, and can therefore capture the phosphorescent curves more precisely. By contrast, color cameras are more well suited to capturing the color and texture of the performer's face. In addition, grayscale cameras may be adjusted to a relatively higher sensitivity than the color cameras.

As illustrated in FIG. **10**, in one embodiment, different synchronization signals, **1**A and **1**B are used to control the grayscale and color cameras, respectively. In FIG. **10**, synchronization signals **1**A and **1**B are **180** degrees out of phase. As a result, the falling edge **1014** of synchronization signal **1**B occurs at the same time as the rising edge **1024** of synchronization signal **1**A, thereby opening the shutters for the color cameras **914**, **915** and closing the shutters for the grayscale cameras **904**, **905**. Similarly, the falling edge **1012** of synchronization signal **1**B occurs at the same time as the falling edge **1022** of synchronization signal **1**A, thereby closing the shutters for the color cameras **914**, **915** and opening the shutters for the grayscale cameras **904**, **905**. The synchronization signal **2** for the light panels is not illustrated in FIG. **10** but, in one embodiment, is the same as it is in FIG. **4**, turning the light panels on when the color camera shutters are opened and turning the light panels off when the grayscale camera shutters are opened.

When the embodiments of the present invention described herein are implemented in the real world, the synchronization signals (e.g., **321** and **322** of FIG. **3**) may require slight delays between respective edges to accommodate delays in the cameras and LED arrays. For example, on some video cameras, there is a slight delay after rising edge **412** of FIG. **4** before the camera shutter closes. This can be easily accommodated by delaying signal **322** relative to signal **321**. Such delays are typically on the order of less than a millisecond. As such, when the system is started, the timing signals may initially need to be precisely calibrated by observing whether the video cameras **304** are capturing completely black frames and adjusting the timing signals **321** and **322** prior to the actual performance.

Although the embodiments described above describe the use of a series of curves painted on the face of a performer, the underlying principles of the invention are not limited to this implementation. For example, instead of curves, one embodiment of the invention uses markers dipped in phosphorescent paint to capture the skeletal motion of the performer using the shutter and light panel synchronization techniques described above (either in lieu of or in addition to the curves on the performer's face, and either in lieu of or in addition to retroreflective markers). Moreover, curves may also be painted on the body and/or clothing of the performer while still complying with the underlying principles of the invention.

In one embodiment, the phosphorescent paint applied to the performer's face is Fantasy F/XT Tube Makeup; Product #: FFX; Color Designation: GL; manufactured by Mehron Inc. of 100 Red Schoolhouse Rd. Chestnut Ridge, N.Y. 10977. In addition, in one embodiment, Basler A311f cameras **304** are used to capture the images of the performer. However, the underlying principles of the invention are not limited to any particular type of phosphorescent paint or camera.

Embodiments of the invention may include various steps as set forth above. The steps may be embodied in machine-executable instructions which cause a general-purpose or special-purpose processor to perform certain steps. Various elements which are not relevant to the underlying principles of the invention such as computer memory, hard drive, input devices, have been left out of the figures to avoid obscuring the pertinent aspects of the invention.

Alternatively, in one embodiment, the various functional modules illustrated herein and the associated steps may be performed by specific hardware components that contain hardwired logic for performing the steps, such as an application-specific integrated circuit ("ASIC") or by any combination of programmed computer components and custom hardware components.

Elements of the present invention may also be provided as a machine-readable medium for storing the machine-executable instructions. The machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of machine-readable media suitable for storing electronic instructions. For example, the present invention may be downloaded as a computer program which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Throughout the foregoing description, for the purposes of explanation, numerous specific details were set forth in order to provide a thorough understanding of the present system and method. It will be apparent, however, to one skilled in the art that the system and method may be practiced without some

of these specific details. Accordingly, the scope and spirit of the present invention should be judged in terms of the claims which follow.

What is claimed is:

1. A method comprising:

applying phosphorescent paint to regions of a performer's face and/or body;

strobing a light source on and off, the light source charging the phosphorescent paint when on; and

strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the phosphorescent paint ("glow frames") as the performer moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

2. The method as in claim **1** further comprising:

tracking the motion of the phosphorescent paint over time; and

generating motion data representing the movement of the performer's face and/or body using the tracked movement of the phosphorescent paint.

3. The method as in claim **1** wherein the phosphorescent paint is applied as a series of curves on the performer's face.

4. The method as in claim **1** wherein the phosphorescent paint is applied as a series of markers at specified areas of the performer's body.

5. The method as in claim **1** further comprising:

strobing the shutters of a second plurality of cameras synchronously with the strobing of the light source to capture images of the performer ("lit frames"), wherein the shutters of the second plurality of cameras are open when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

6. The method as in claim **5** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

7. The method as in claim **5** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

8. The method as in claim **5** wherein cameras capturing the lit frames have a sensitivity which is different from cameras capturing the glow frames.

9. The method as in claim **5** further comprising:

opening the shutters for a first period of time when the light source is on; and

opening the shutters for a second period of time when the light source is off;

wherein the first and second periods of time are unequal.

10. The method as in claim **5** wherein color cameras are used to capture the lit frames and grayscale cameras are used to capture the glow frames.

11. The method as in claim **10** wherein the grayscale cameras have a relatively higher sensitivity than the color cameras.

12. The method as in claim **10** wherein two different synchronization signals are used to control the shutters of the color and grayscale cameras.

13. The method as in claim **12** wherein the different synchronization signals are 180 degrees out of phase.

14. The method as in claim **1** wherein the light source comprises a light emitting diode (LED) array.

15. The method as in claim **1** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

16. The method as in claim **15** wherein the first period of time is longer than the second period of time.

17. The method as in claim **1** wherein the camera shutters are controlled by synchronization signals from a computer system.

18. The method as in claim **1** wherein strobing the shutters further comprises:

opening the shutters for a period of time when the light source is on to capture images of the performer's face and/or body.

19. The method as in claim **18** wherein after being opened to capture a lit frame, the shutters are closed and then opened again when the light source is off to capture the next glow frame, and then closed and then opened again when the light source is on to capture the next lit frame.

20. The method as in claim **18** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time wherein the first period of time is not equal to the second period of time.

21. The method as in claim **20** further comprising:

opening the shutters for a relatively shorter period of time when the light source is on; and

opening the shutters for a relatively longer period of time when the light source is off.

22. The method as in claim **18** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

23. The method as in claim **18** further comprising:

alternating sensitivity, of the cameras between capturing the lit frames and the glow frames.

24. A system comprising:

a synchronization signal generator to generate one or more synchronization signals;

a light source configured to strobe on and off responsive to a first one of the one or more synchronization signals, the light source charging phosphorescent paint applied to regions of a performer's face and/or body for a motion capture session; and

a plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture sequences of images of the phosphorescent paint ("glow frames") as the performer moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

25. The system as in claim **24** further comprising:

an image processing device generating motion data representing the movement of the performer's face and/or body using the tracked movement of the phosphorescent paint.

26. The system as in claim **24** wherein the phosphorescent paint is applied as a series of curves on the performer's face.

27. The system as in claim **24** wherein the phosphorescent paint is applied as a series of markers at specified areas of the performer's body.

28. The system as in claim **24** further comprising:

a second plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture images of the performer ("lit frames"), wherein the shutters of the second plurality of cameras are open when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

29. The system as in claim **28** further comprising an image processing device separating the lit frames from the glow frames to generate two separate sets of image data.

30. The system as in claim **28** wherein cameras capturing the lit frames have a sensitivity which is different from cameras capturing the glow frames.

31. The system as in claim **28** wherein at least some of the plurality of cameras are controlled to open the shutters for a relatively shorter period of time when the light source is on; and open the shutters for a relatively longer period of time when the light source is off.

32. The system as in claim **28** wherein color cameras are used to capture the lit frames and grayscale cameras are used to capture the glow frames.

33. The system as in claim **28** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

34. The system as in claim **33** wherein the grayscale cameras have a relatively higher sensitivity than the color cameras.

35. The system as in claim **33** wherein two different synchronization signals are used to control the shutters of the color and grayscale cameras.

36. The system as in claim **35** wherein the different synchronization signals are 180 degrees out of phase.

37. The system as in claim **24** wherein the light source comprises a light emitting diode (LED) array comprising at least one LED.

38. The system as in claim **24** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

39. The system as in claim **38** wherein the first period of time is longer than the second period of time.

40. The system as in claim **24** wherein the camera shutters are controlled by synchronization signals from a computer system.

41. The system as in claim **24** wherein strobing the shutters further comprises:

opening the shutters for a period of time when the light source is on to capture images of the performer's face and/or body.

42. The system as in claim **41** wherein after being opened to capture a lit frame, the shutters are closed and then opened again when the light source is off to capture the next glow frame, and then closed and then opened again when the light source is on to capture the next lit frame.

43. The system as in claim **42** wherein the image processing device separates the lit frames from the glow frames to generate two separate sets of image data.

44. The system as in claim **41** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, wherein the first period of time is not equal to the second period of time.

45. The system as in claim **44** wherein the shutters are opened for a relatively shorter period of time when the light source is on; and

wherein the shutters are opened for a relatively longer period of time when the light source is off.

46. The system as in claim **41** wherein sensitivity of the cameras is alternated between capturing the lit frames and the glow frames.

47. A method comprising:

applying phosphorescent paint to regions of a face and/or body or a performer;

strobing a light source on and off, the light source charging the phosphorescent paint when on; and

strobing the shutters of a plurality of cameras synchronously with the strobing of the light source to capture a sequence of images of the phosphorescent paint ("glow frames) and images of the object in motion ("lit frames"), wherein the shutters are closed and then opened when the light source is off to capture the glow frames and then closed and then opened when the light source is on to capture the lit frames.

48. The method as in claim **47** further comprising:

tracking the motion of the phosphorescent paint over time; and

generating motion data representing the movement of the object using the tracked movement of the phosphorescent paint.

49. The method as in claim **47** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time wherein the first period of time is not equal to the second period of time.

50. The method as in claim **49** further comprising:

opening the shutters for a relatively shorter period of time when the light source is on; and

opening the shutters for a relatively longer period of time when the light source is off.

51. The method as in claim **47** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

52. The method as in claim **47** further comprising:

alternating sensitivity of the cameras between capturing the lit frames and the glow frames.

* * * * *

Exhibit 3

US008659668B2

(12) **United States Patent**
Cotter et al.

(10) **Patent No.:** **US 8,659,668 B2**
(45) **Date of Patent:** ***Feb. 25, 2014**

(54) **APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING A RANDOM PATTERN ON CAPTURE SURFACES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 940 days.

This patent is subject to a terminal disclaimer.

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H04N 5/225	(2006.01)
H04N 5/335	(2011.01)
H04N 5/262	(2006.01)
G06K 9/00	(2006.01)

(52) **U.S. Cl.**
USPC **348/207.99**; 348/162; 348/239; 348/370; 348/371; 382/103; 382/108; 382/154

(58) **Field of Classification Search**
USPC 348/162, 207.99, 239, 370–371; 382/103, 108, 154
See application file for complete search history.

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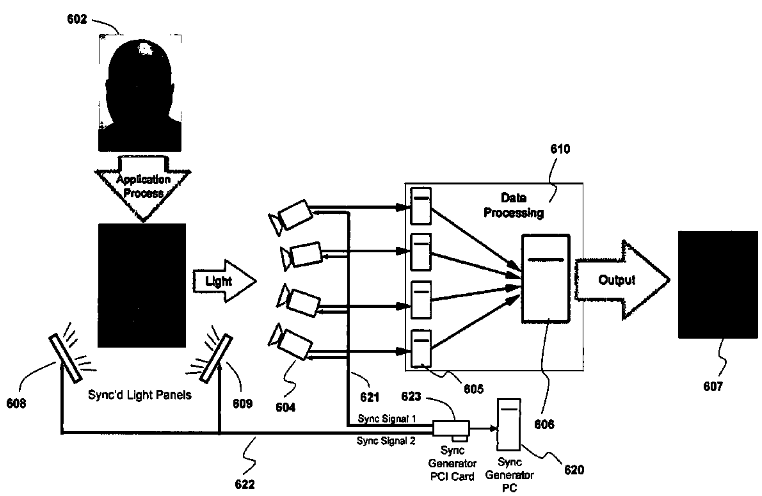
(57) **ABSTRACT**

A method is described comprising: applying a random pattern to specified regions of an object; tracking the movement of the random pattern during a motion capture session; and generating motion data representing the movement of the object using the tracked movement of the random pattern.

58 Claims, 30 Drawing Sheets



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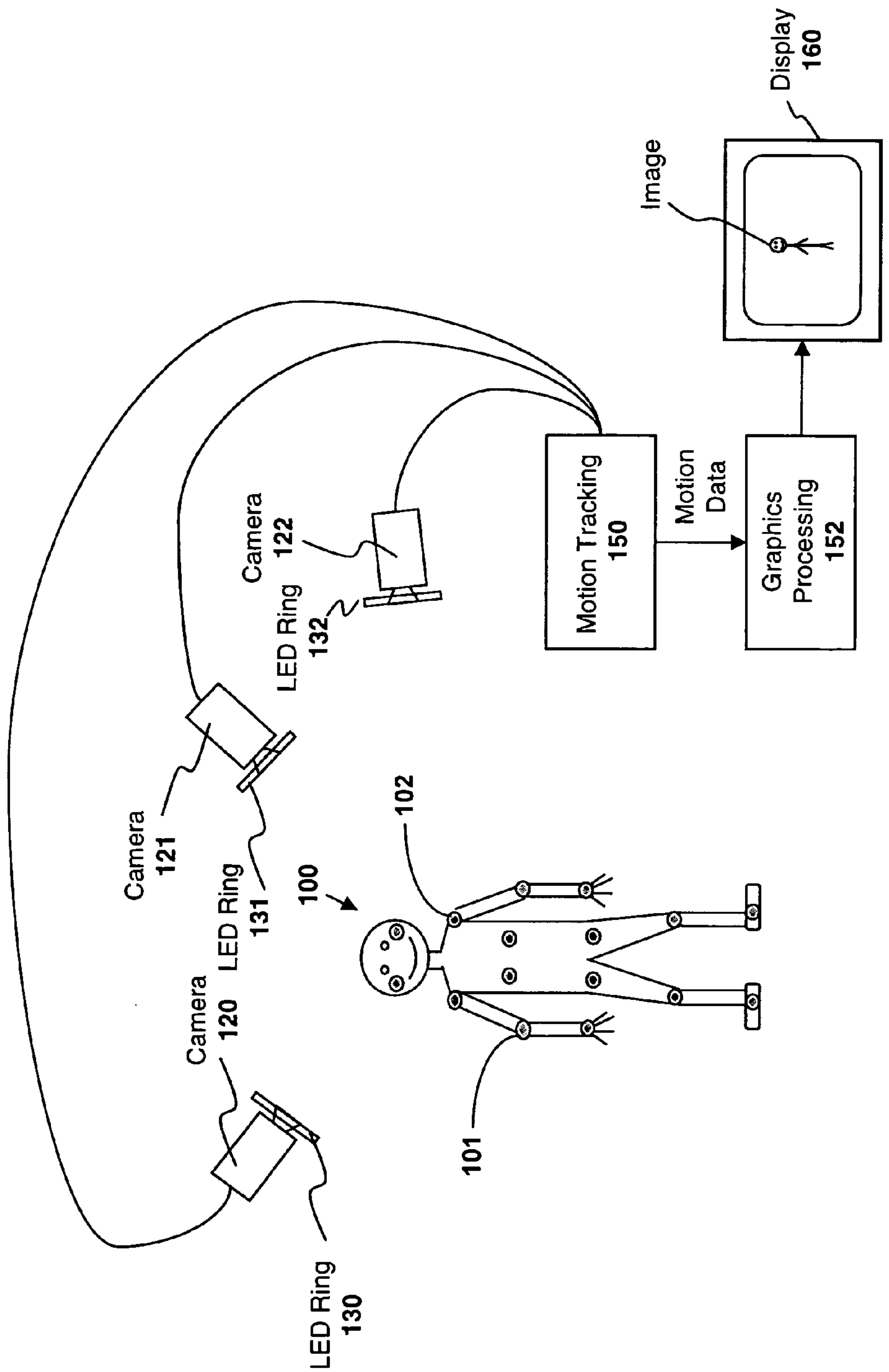

Fig. 1
(prior art)

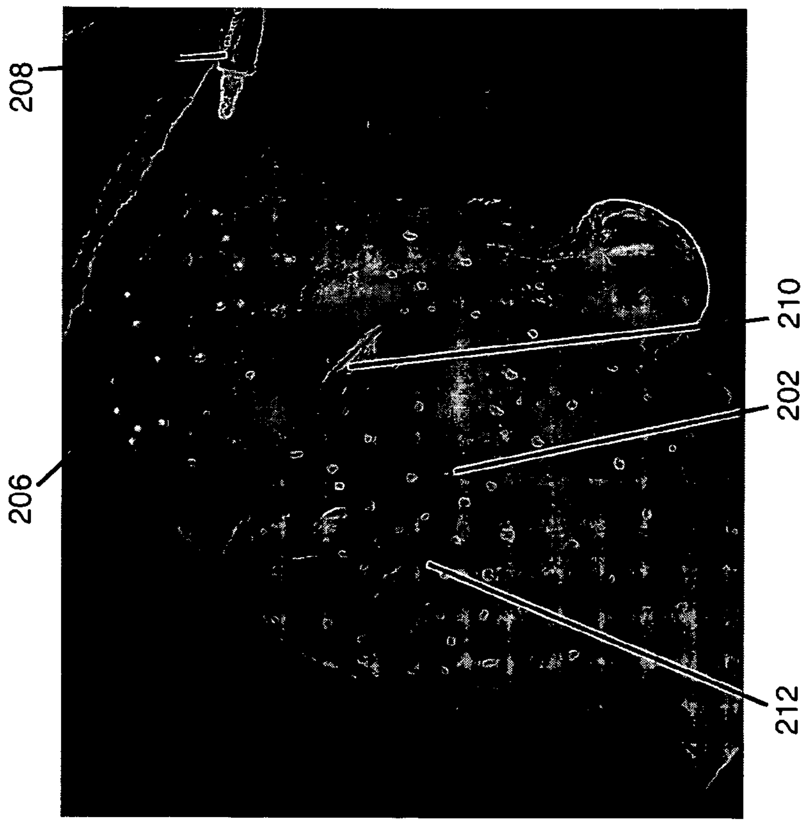

Fig. 2B
(prior art)

Fig. 2A
(prior art)

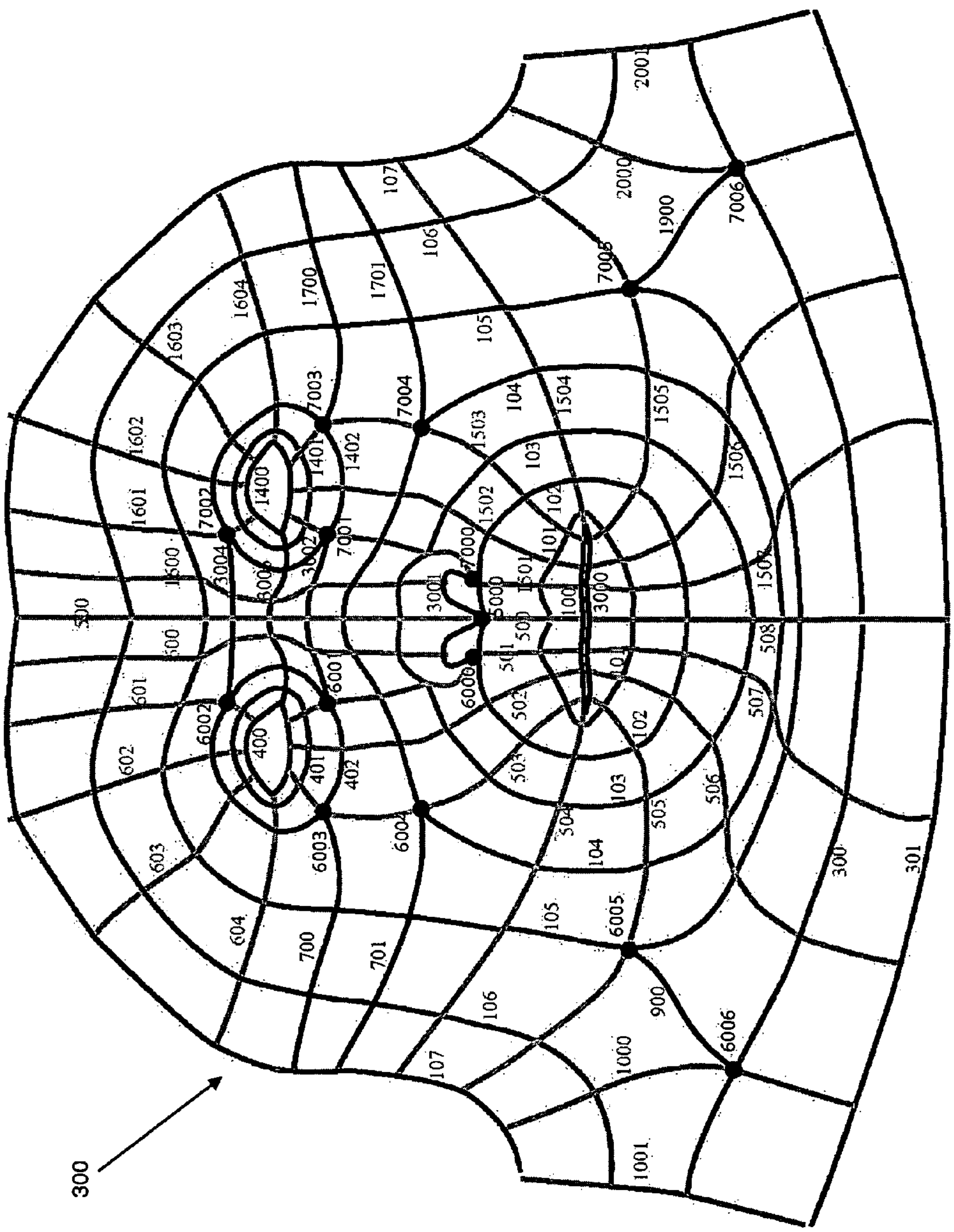

Fig. 3
(prior art)

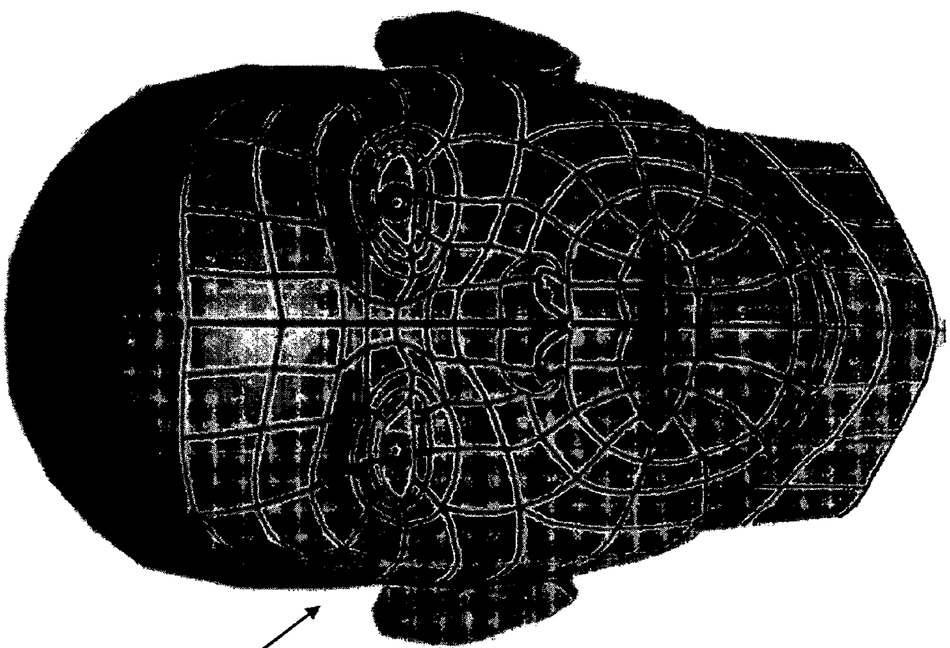

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Fig. 4
(prior art)

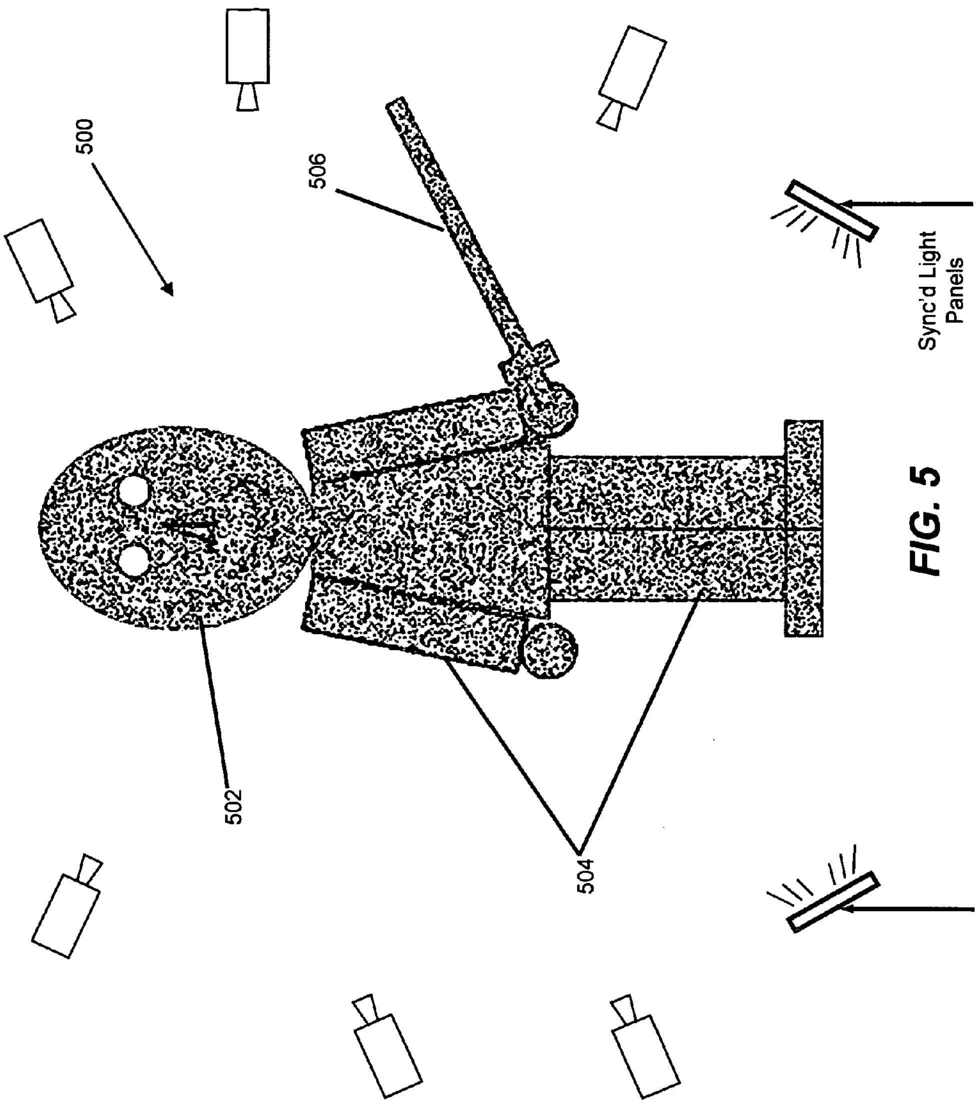


FIG. 5

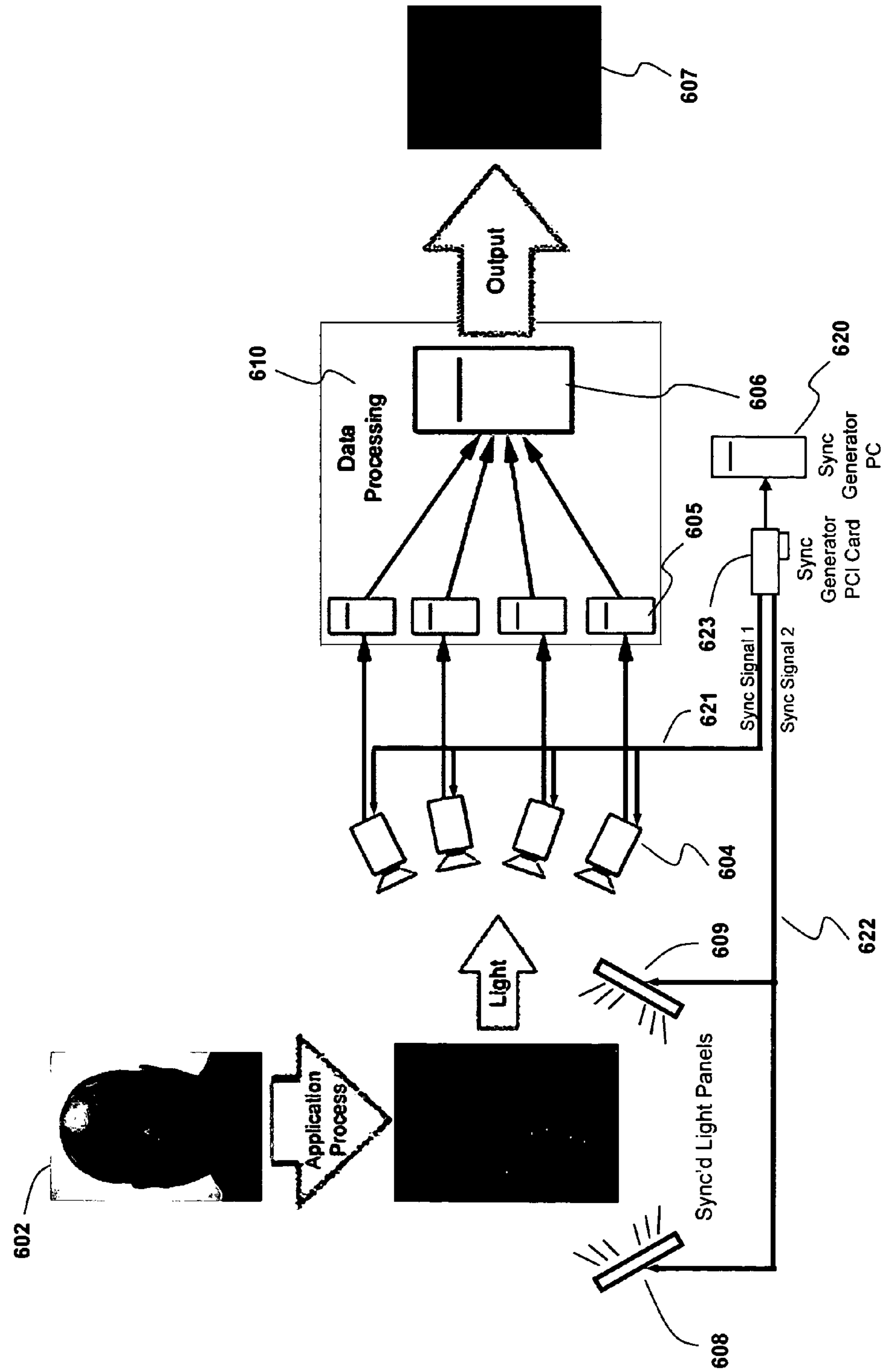
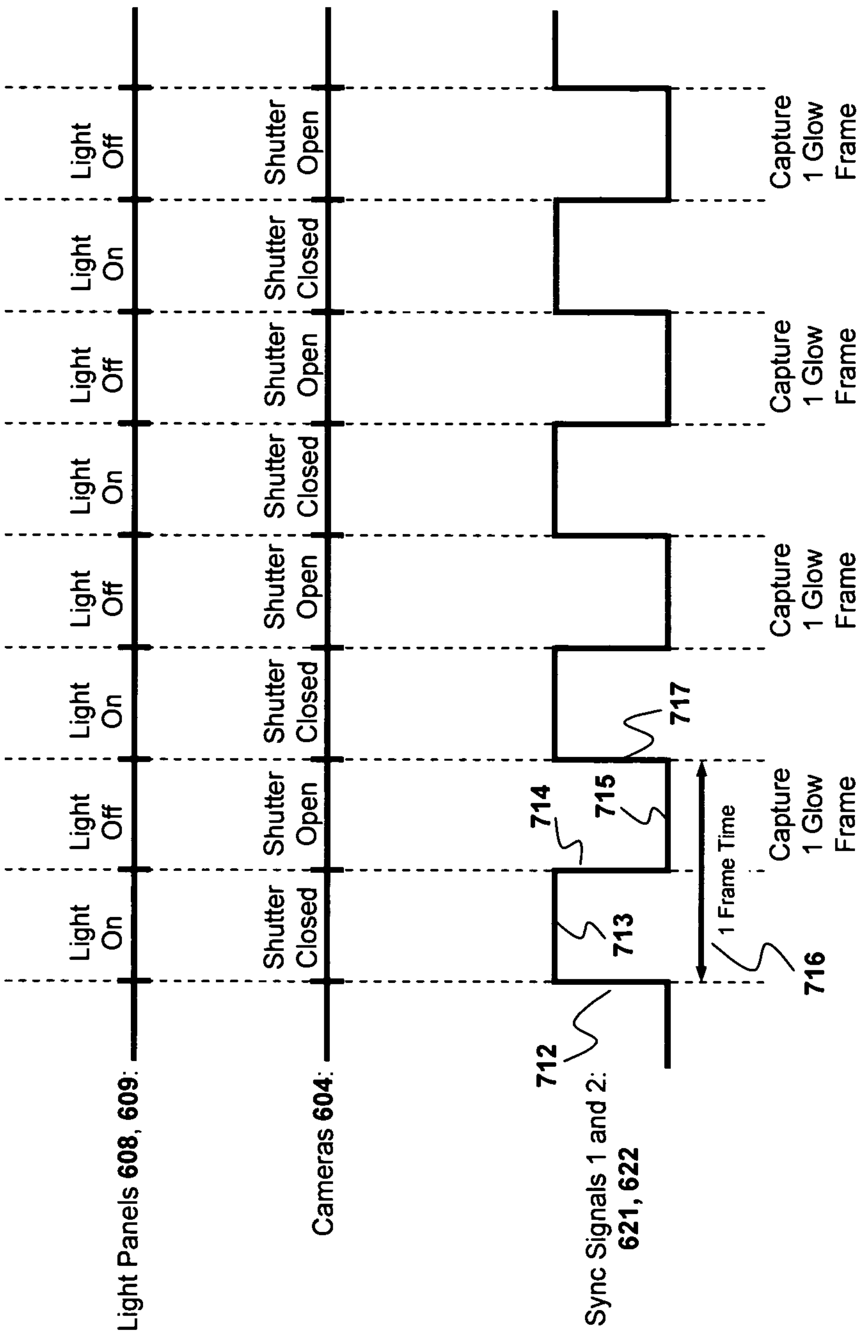

602
Application Process
Light
Sync'd Light Panels
608
609
604
622
621
Sync Signal 1
Sync Signal 2
623
Sync Generator PCI Card
Sync Generator PC
620
605
606
Data Processing
610
Output
607

Fig. 6



Light Panels 608, 609:
Light On
Light Off
Light On
Light Off
Light On
Light Off
Light On
Light Off
Cameras 604:
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Sync Signals 1 and 2: 621, 622
712
713
714
715
716
717
1 Frame Time
Capture 1 Glow Frame
Capture 1 Glow Frame
Capture 1 Glow Frame
Capture 1 Glow Frame

Fig. 7

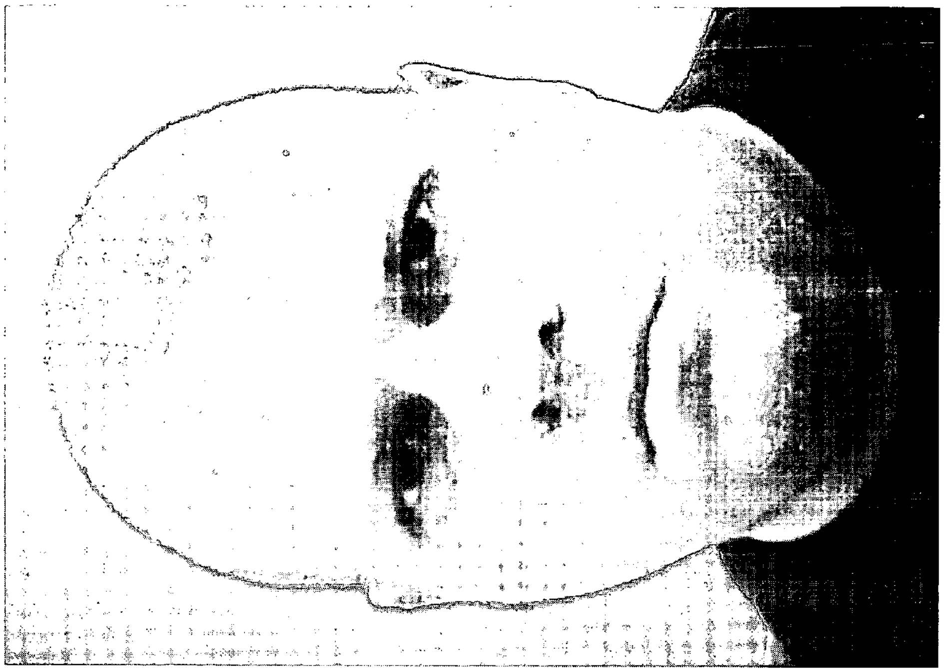


FIG. 8B

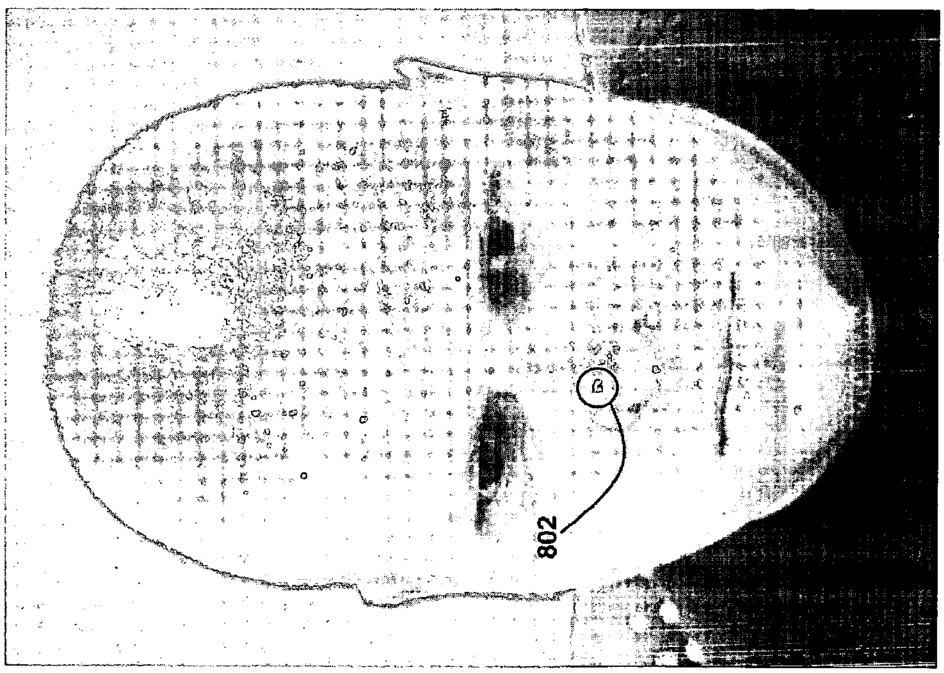


FIG. 8A

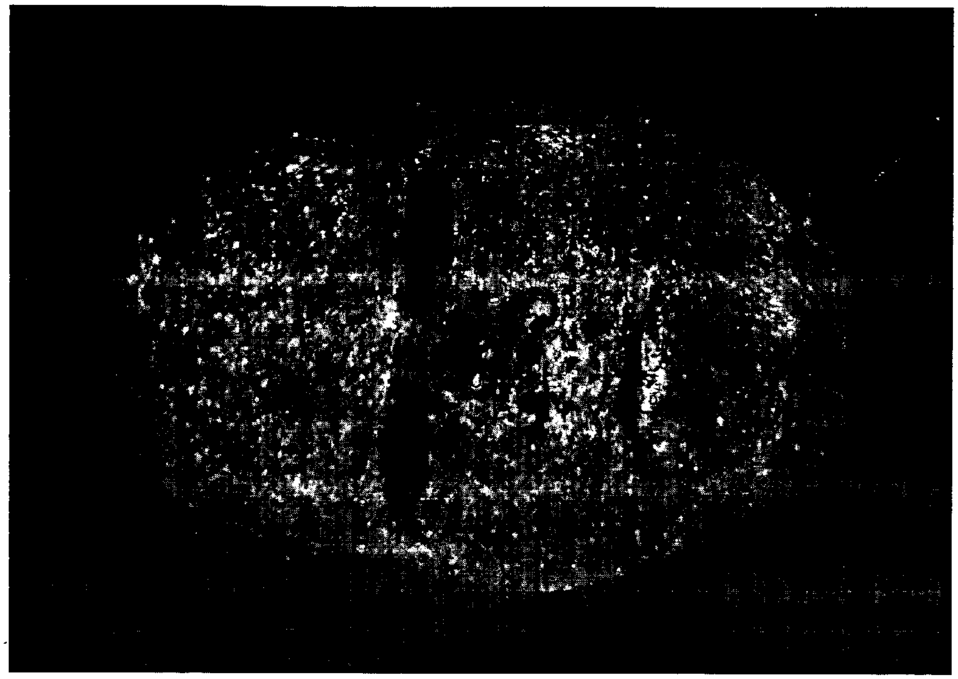
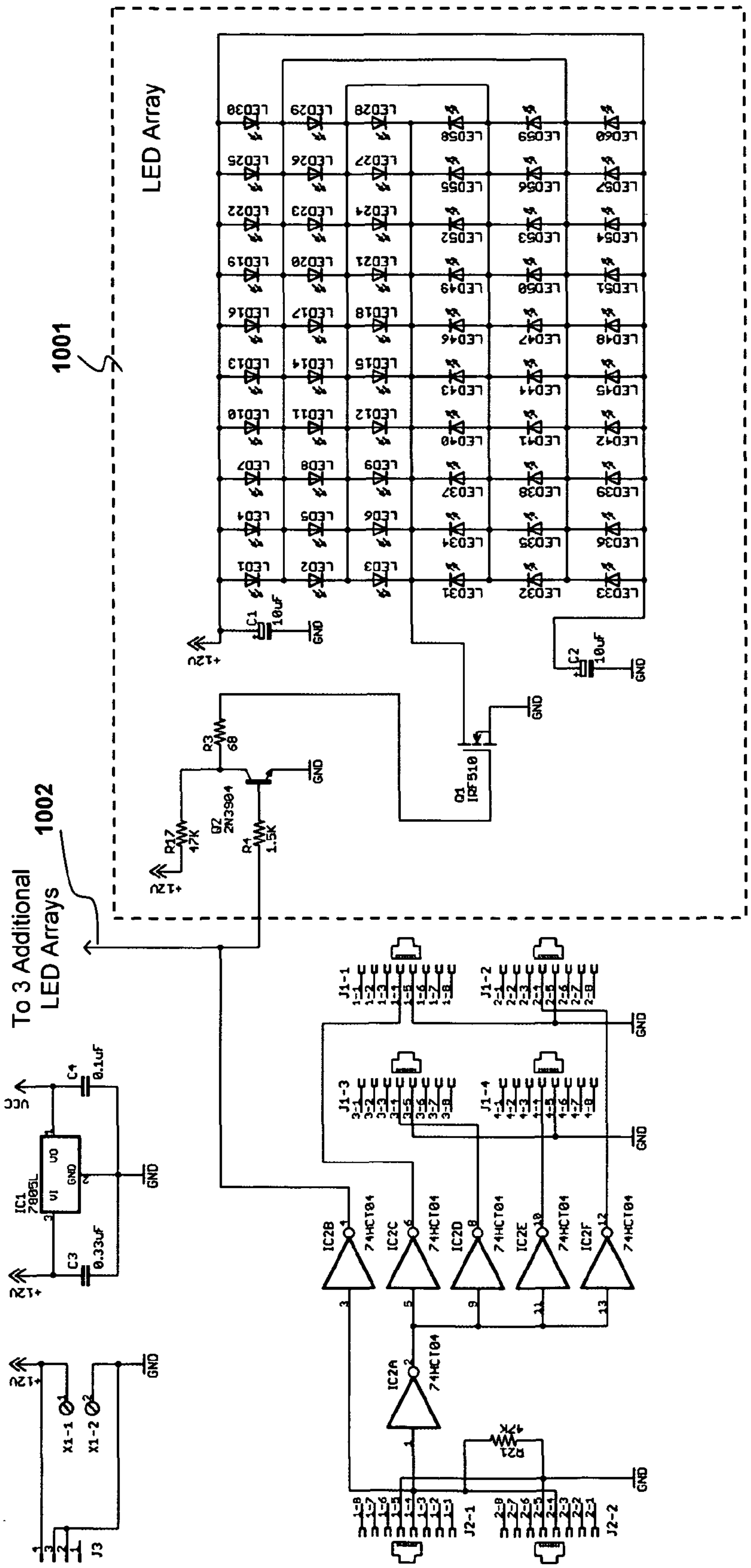


FIG. 9B

FIG. 9A



LED Array
1001
1002
To 3 Additional LED Arrays
IRF510
2N3904
74HCT04
7805L
GND
+12V
VCC

Fig. 10

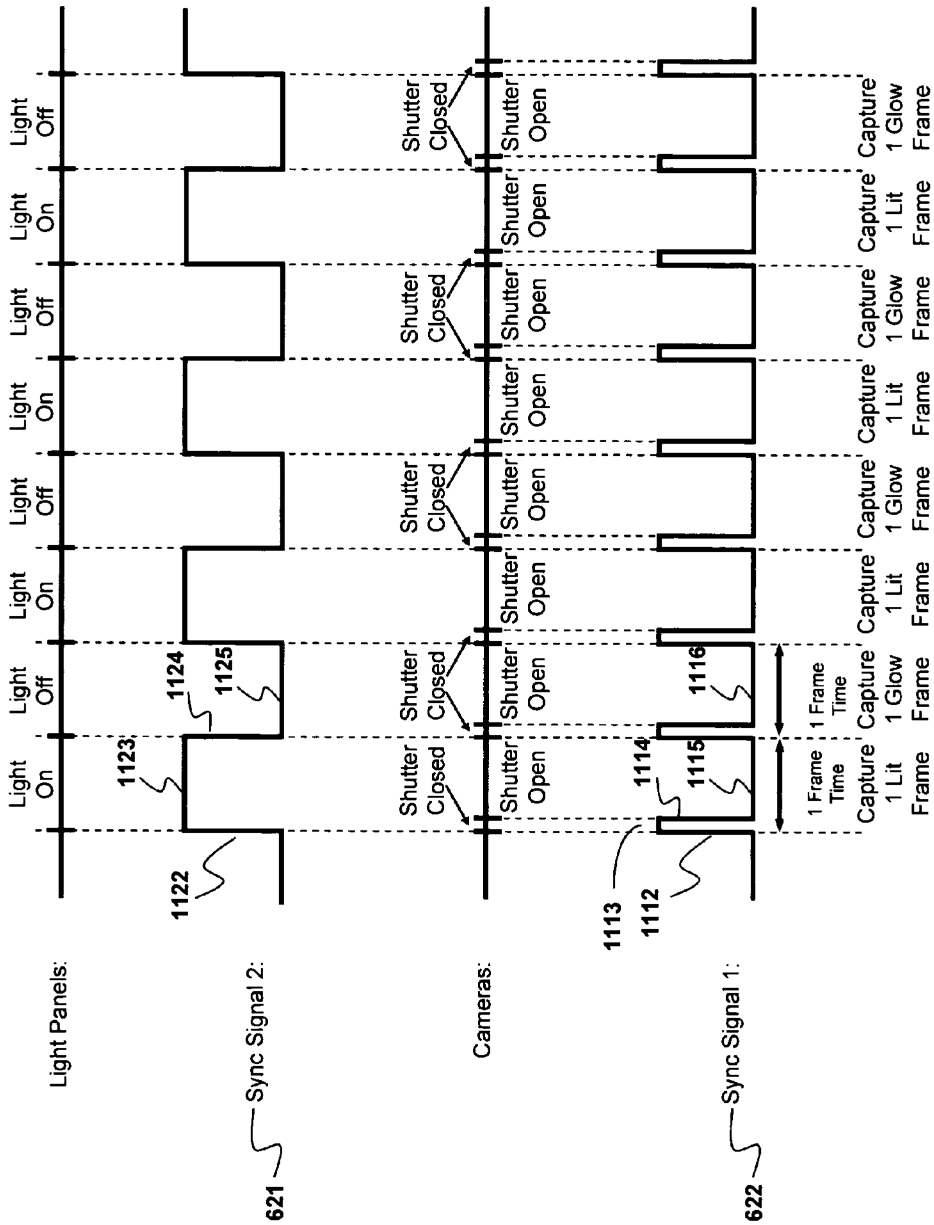

Light Panels:
Sync Signal 2:
Cameras:
Sync Signal 1:
621
622
1122
1123
1124
1125
1112
1113
1114
1115
1116
Light On
Light Off
Shutter Closed
Shutter Open
1 Frame Time
Capture 1 Lit Frame
Capture 1 Glow Frame

Fig. 11

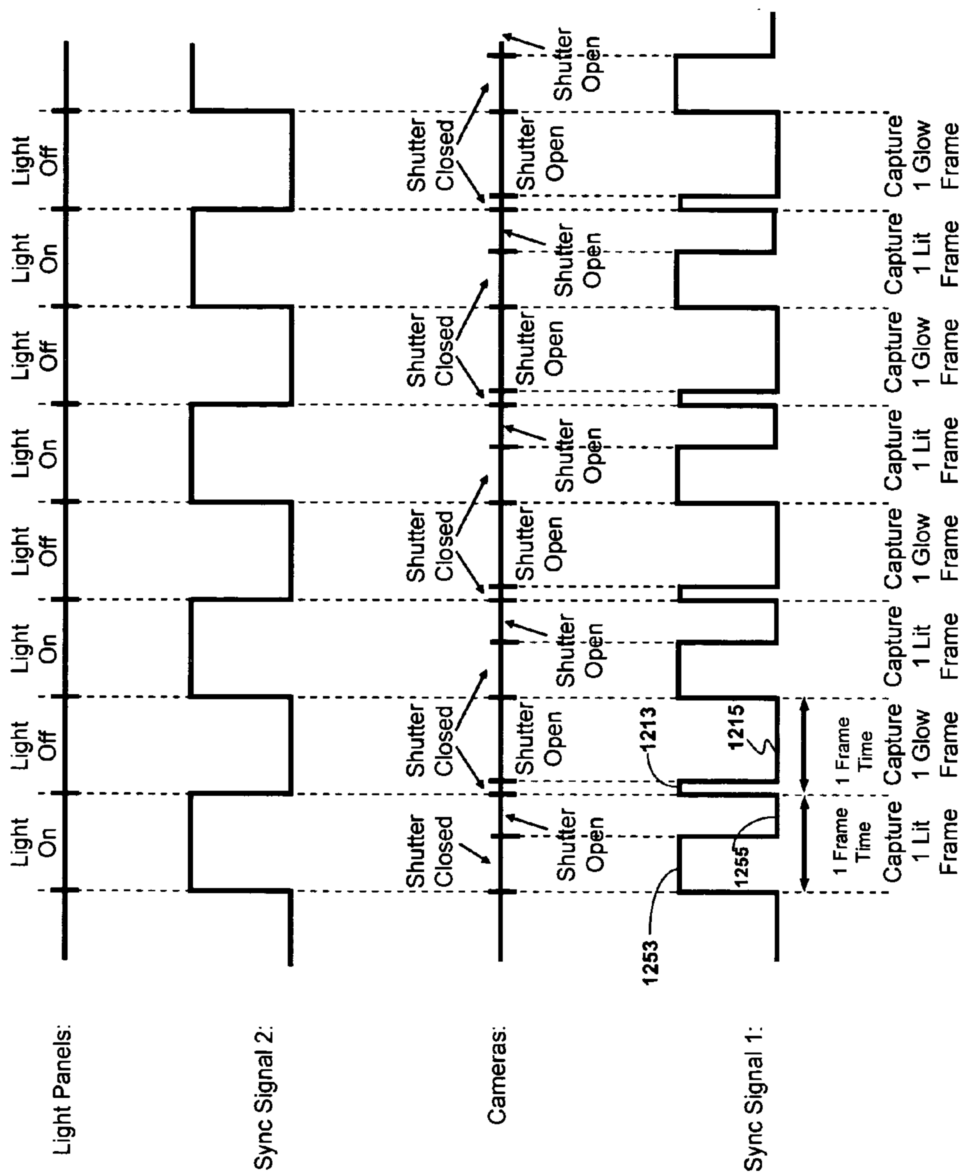

Light Panels:
Sync Signal 2:
Cameras:
Sync Signal 1:
Light On
Light Off
Light On
Light Off
Light On
Light Off
Light On
Light Off
Shutter Closed
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
Shutter Closed
Shutter Open
Shutter Open
1253
1255
1213
1215
1 Frame Time
1 Frame Time
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame
Capture 1 Lit Frame
Capture 1 Glow Frame

Fig. 12

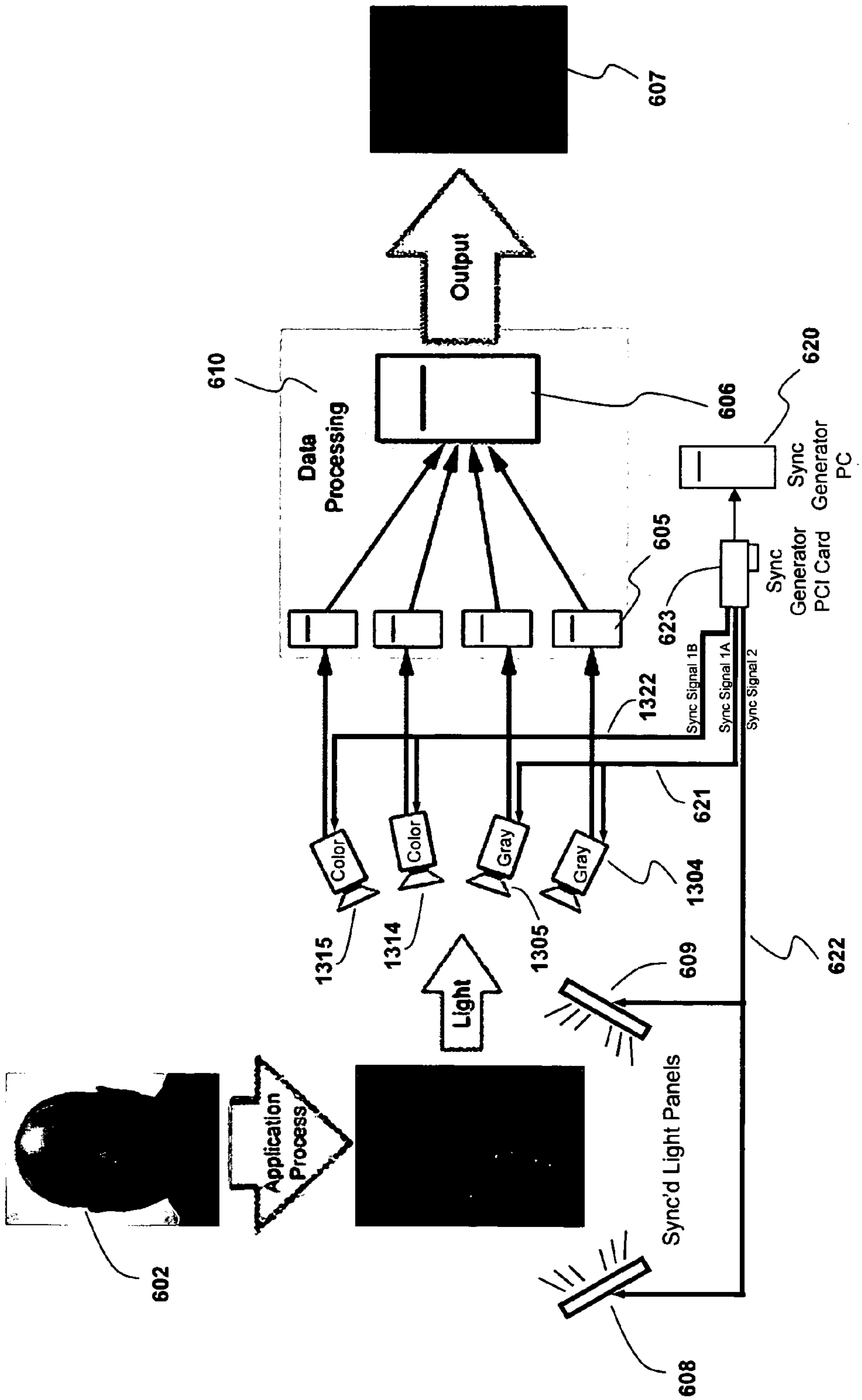

607
Output
610
Data Processing
606
620
Sync Generator PC
605
Sync Generator PCI Card
623
Sync Signal 1B
Sync Signal 1A
Sync Signal 2
1322
621
Color
Color
Gray
Gray
1304
1305
1314
1315
622
609
Light
Application Process
602
Sync'd Light Panels
608

Fig. 13

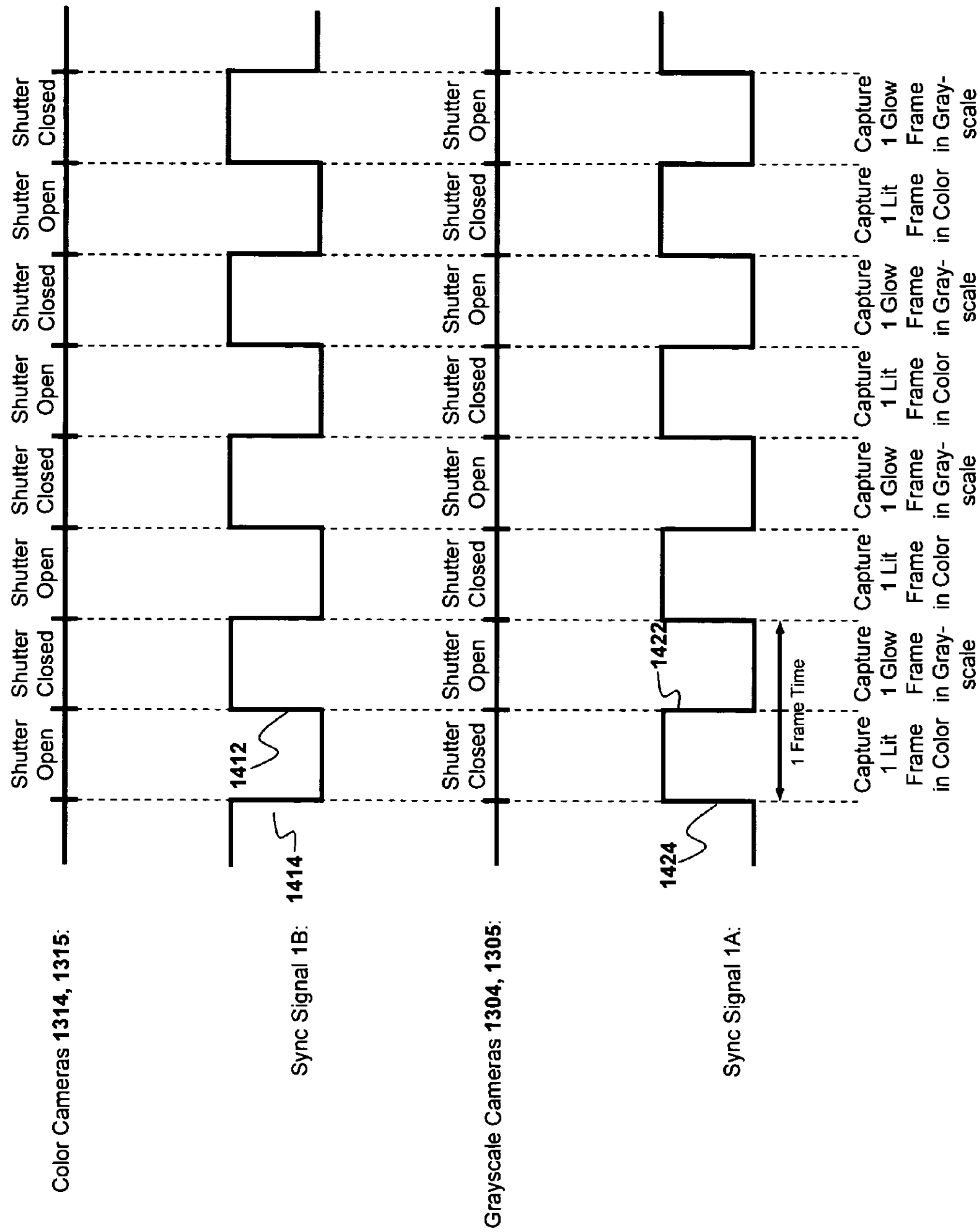
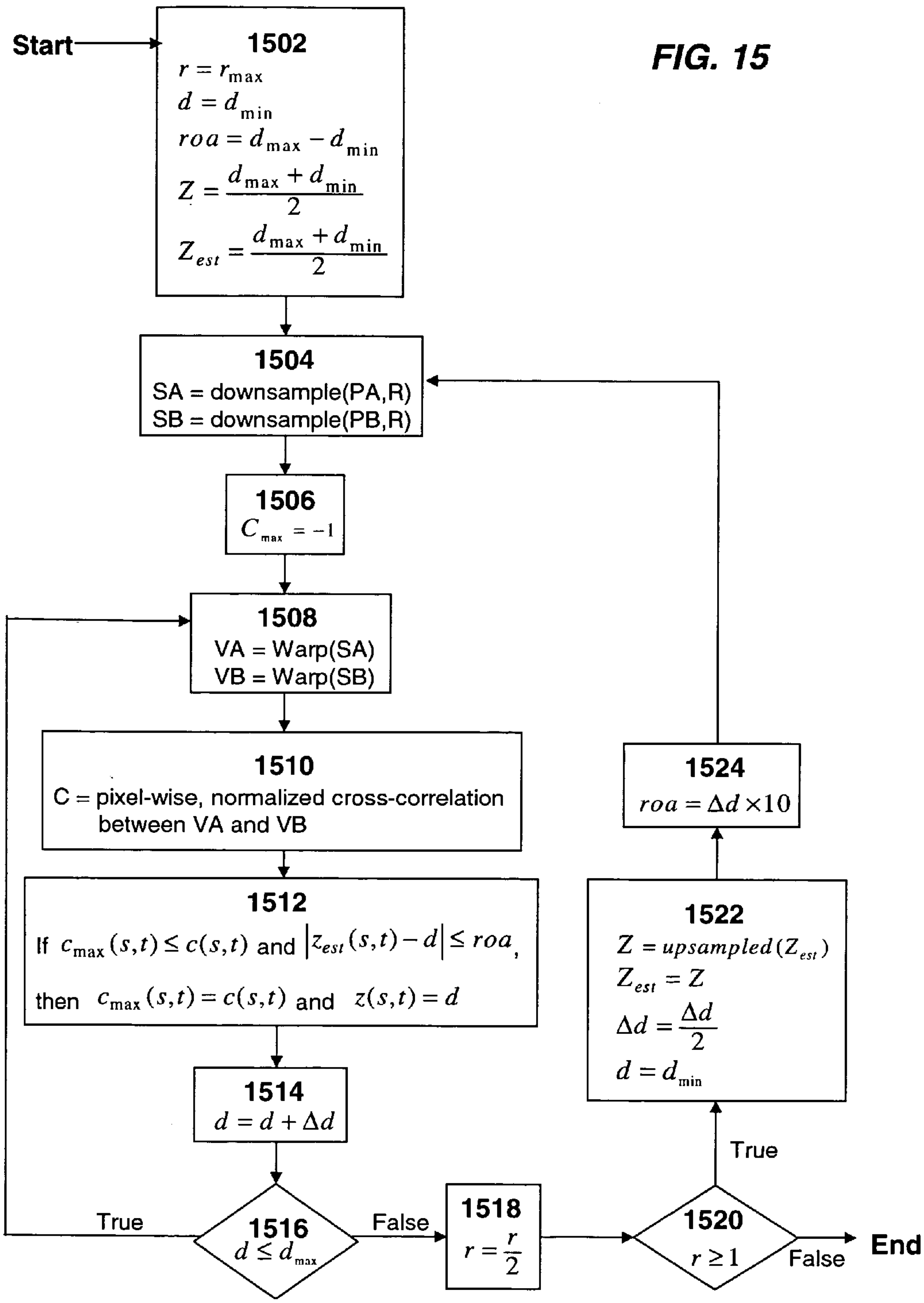

Color Cameras 1314, 1315:
Shutter Open
Shutter Closed
Sync Signal 1B:
1412
1414
Grayscale Cameras 1304, 1305:
Shutter Closed
Shutter Open
Sync Signal 1A:
1422
1424
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Glow Frame in Gray-scale

Fig. 14

FIG. 15


Start
1502
r = r_max
d = d_min
roa = d_max − d_min
Z = (d_max + d_min)/2
Z_est = (d_max + d_min)/2
1504
SA = downsample(PA,R)
SB = downsample(PB,R)
1506
C_max = −1
1508
VA = Warp(SA)
VB = Warp(SB)
1510
C = pixel-wise, normalized cross-correlation between VA and VB
1512
If c_max(s,t) ≤ c(s,t) and |z_est(s,t) − d| ≤ roa,
then c_max(s,t) = c(s,t) and z(s,t) = d
1514
d = d + Δd
1516
d ≤ d_max
True
False
1518
r = r/2
1520
r ≥ 1
True
False
End
1522
Z = upsampled(Z_est)
Z_est = Z
Δd = Δd/2
d = d_min
1524
roa = Δd × 10

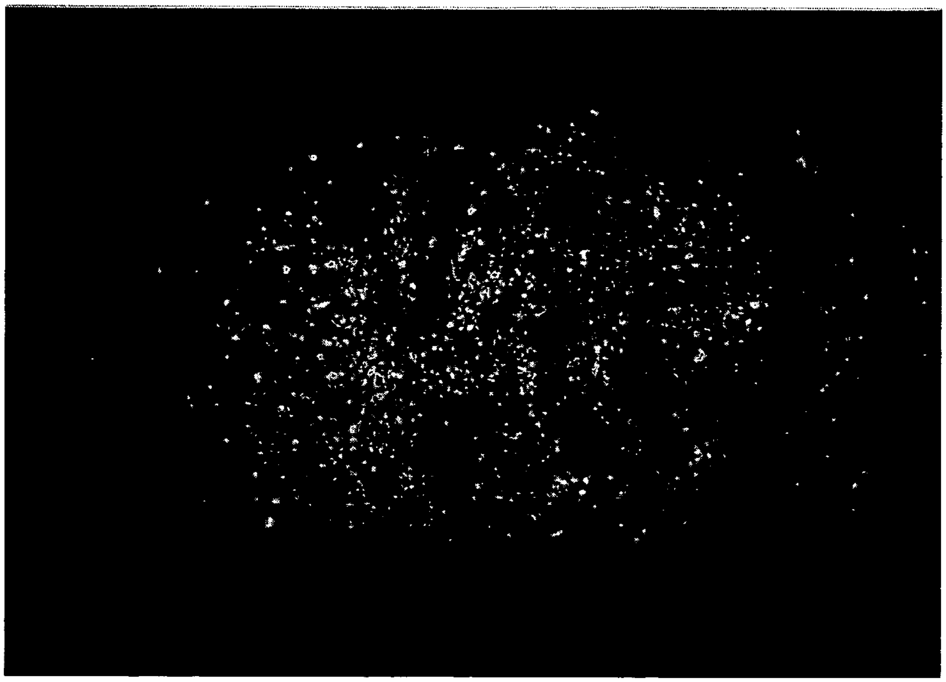


FIG. 16B

FIG. 16A

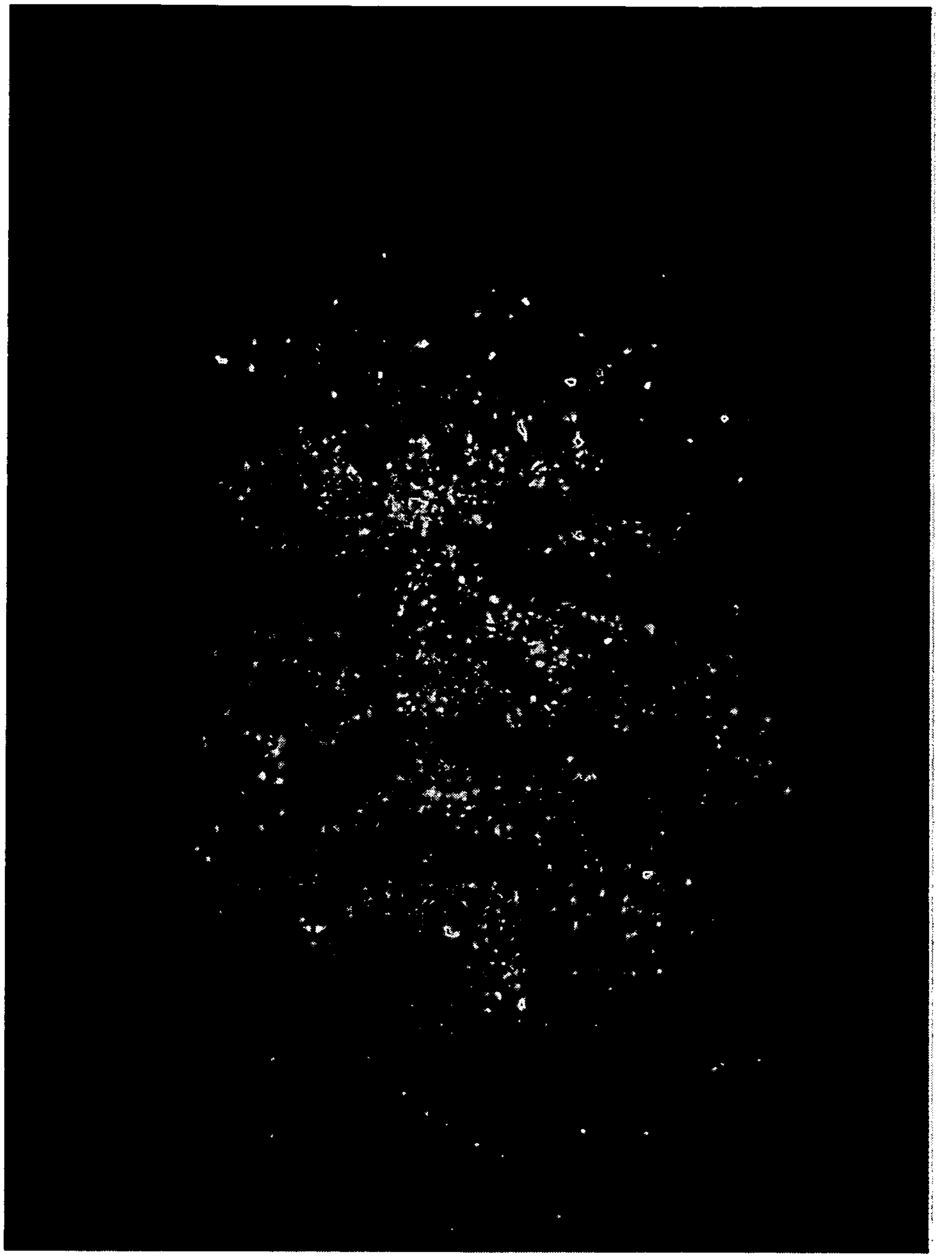


FIG. 17

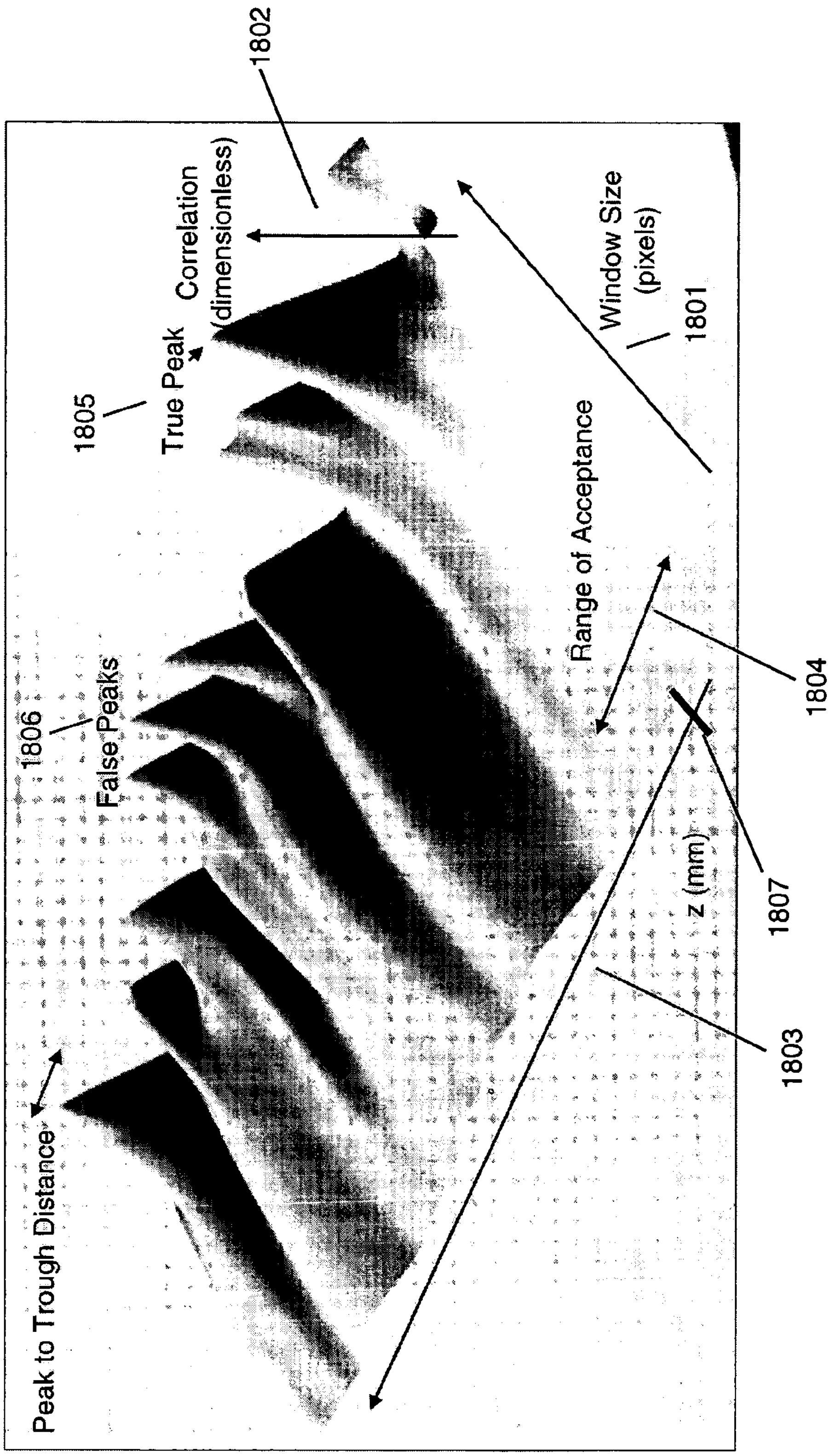

1802
Correlation (dimensionless)
True Peak
1805
Window Size (pixels)
1801
Range of Acceptance
1804
1806
False Peaks
z (mm)
1807
1803
Peak to Trough Distance

FIG. 18

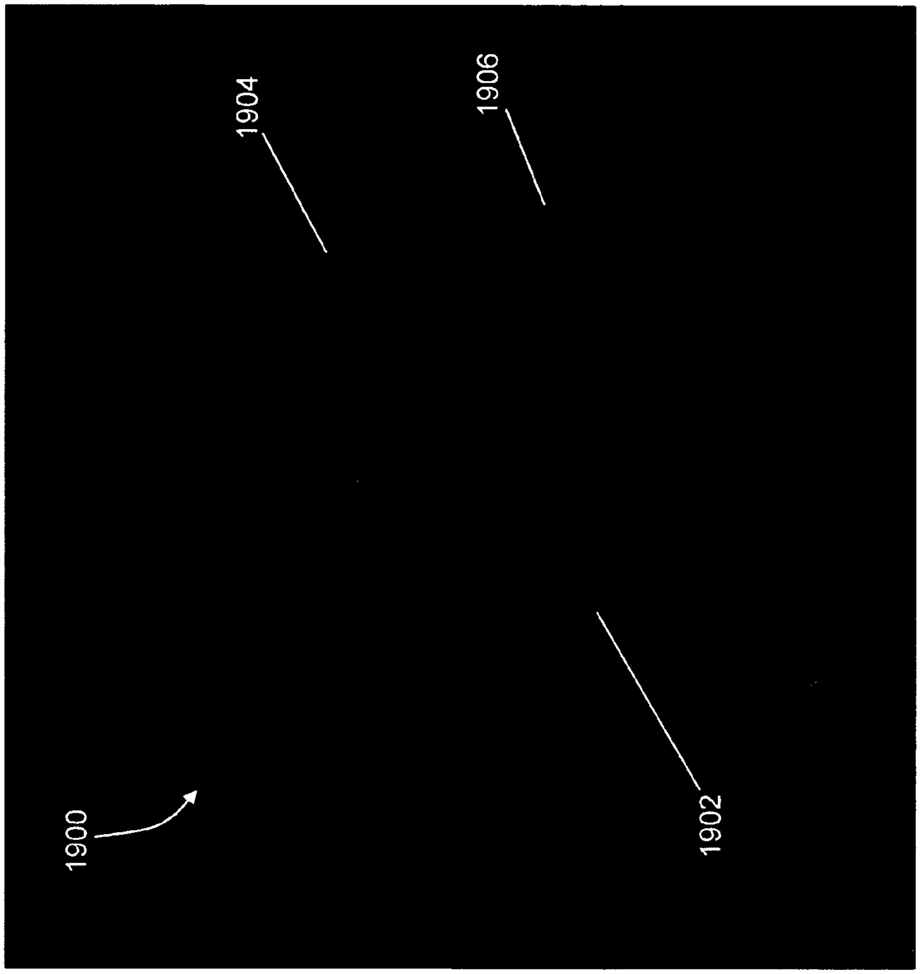


FIG. 19

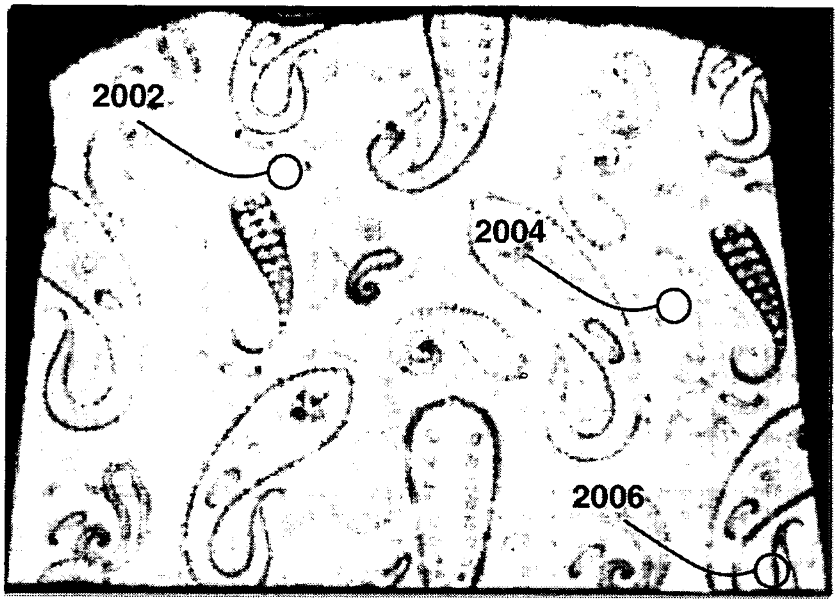


FIG. 20A

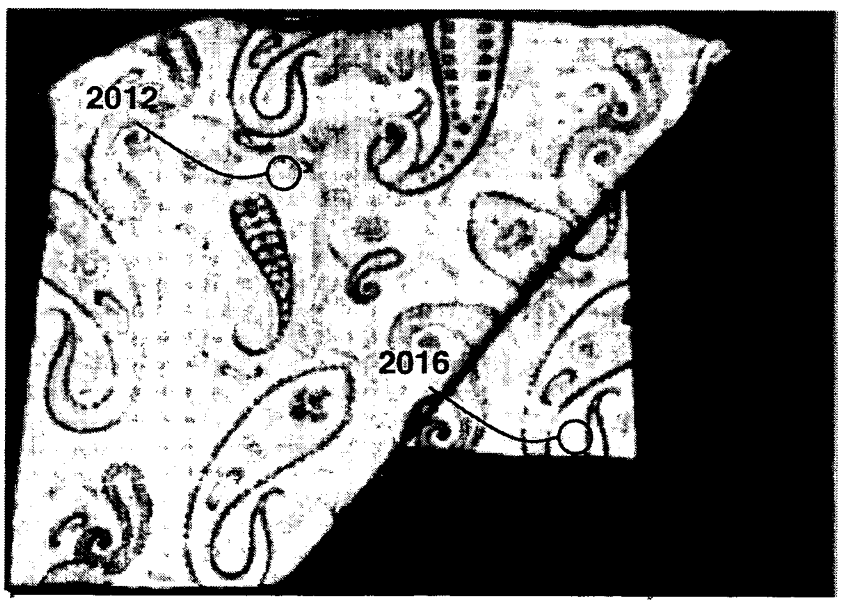


FIG. 20B

FIG. 21A

FIG. 21B

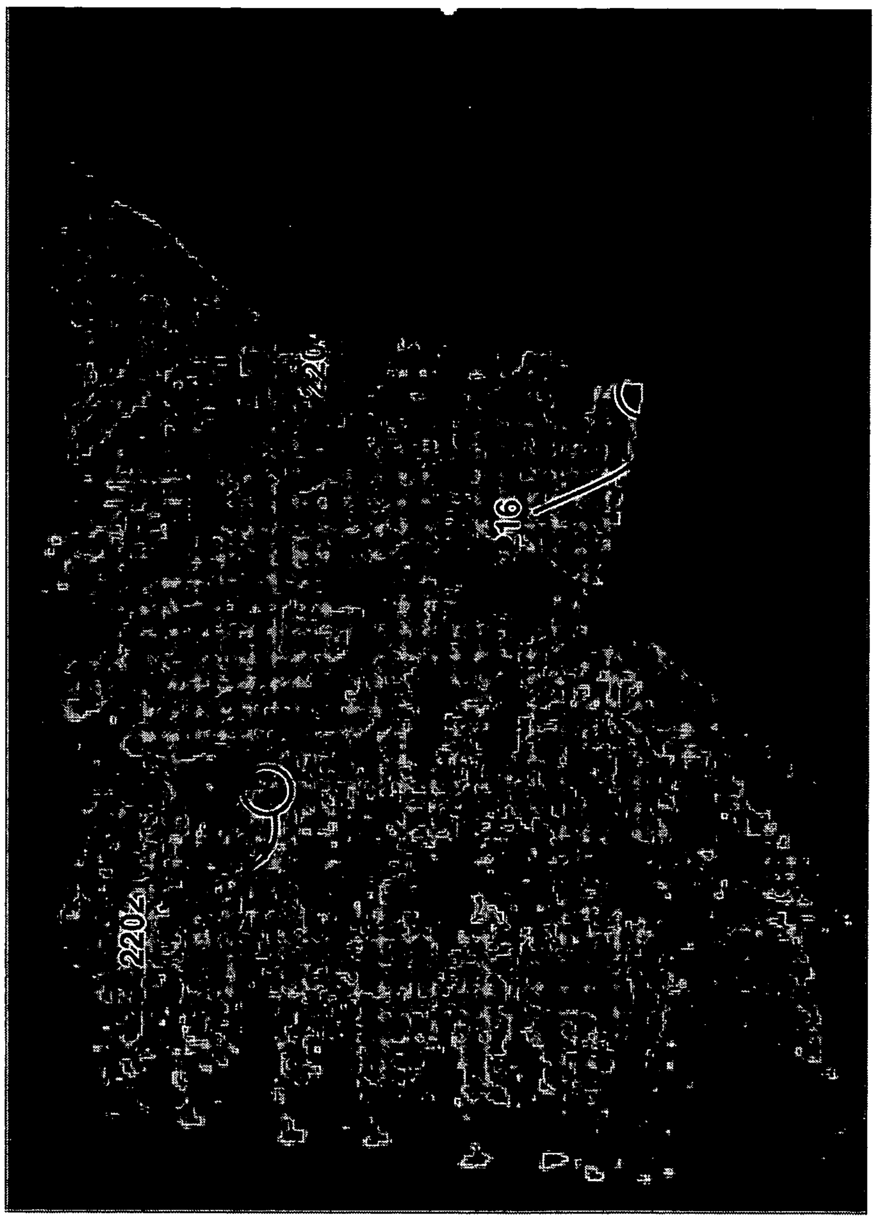


FIG. 22

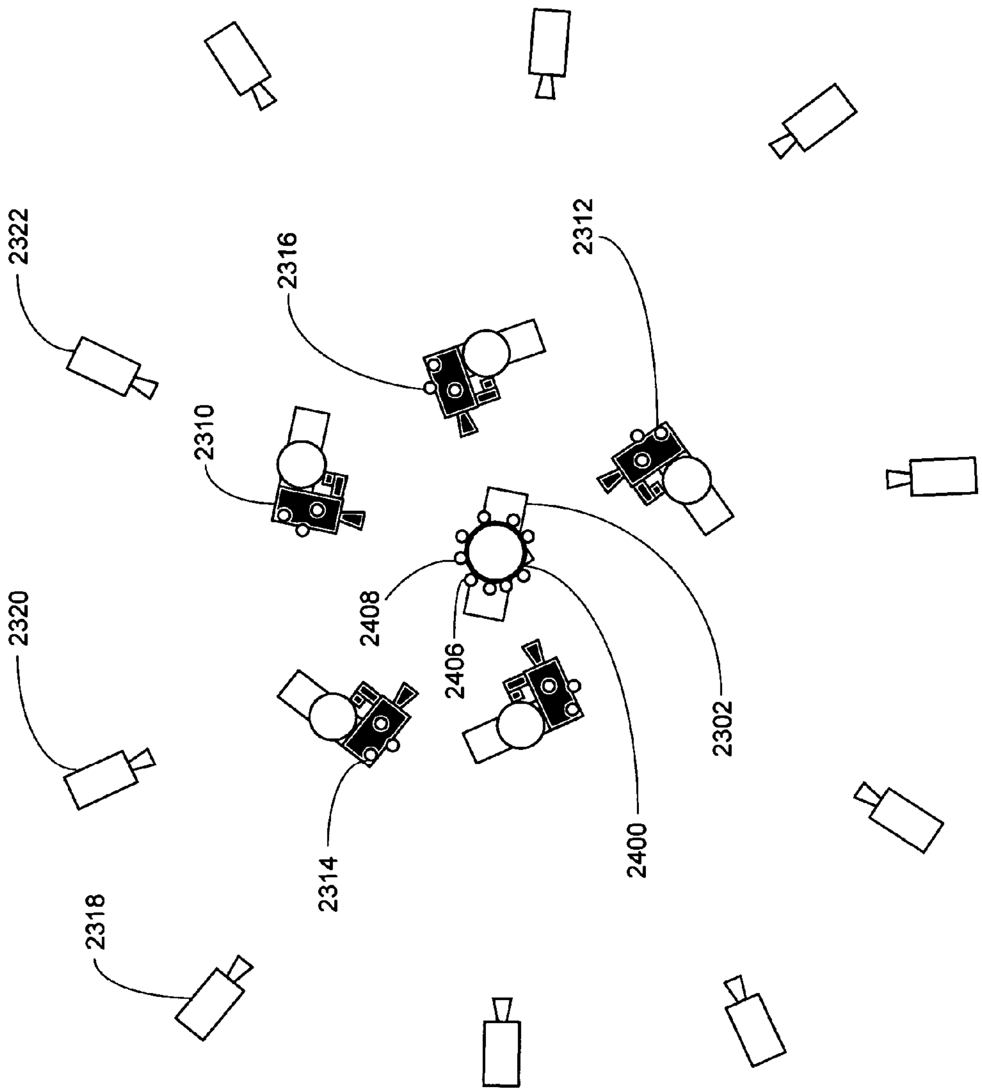


FIG. 23

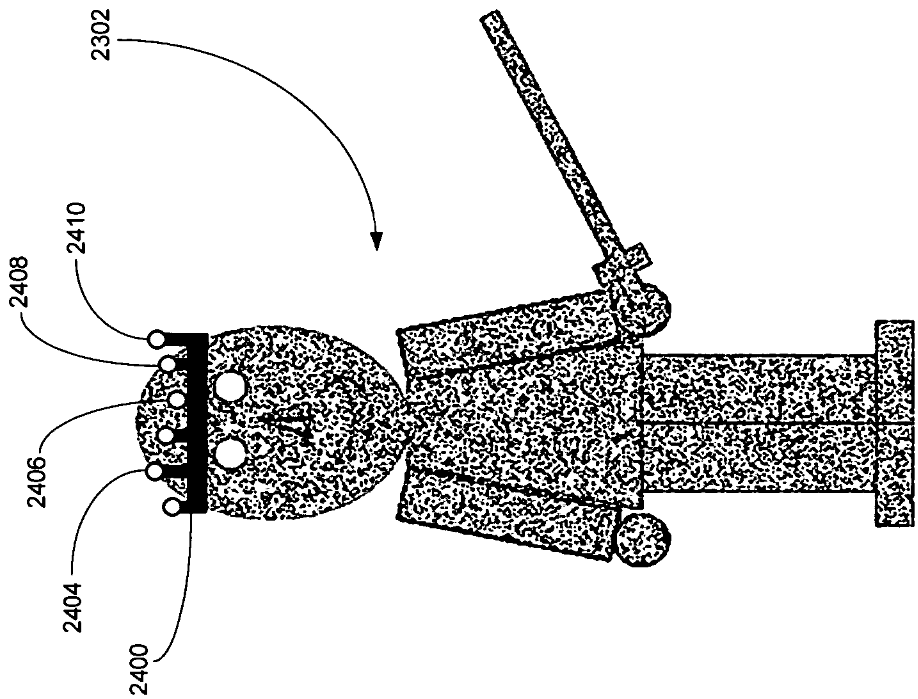


FIG. 24

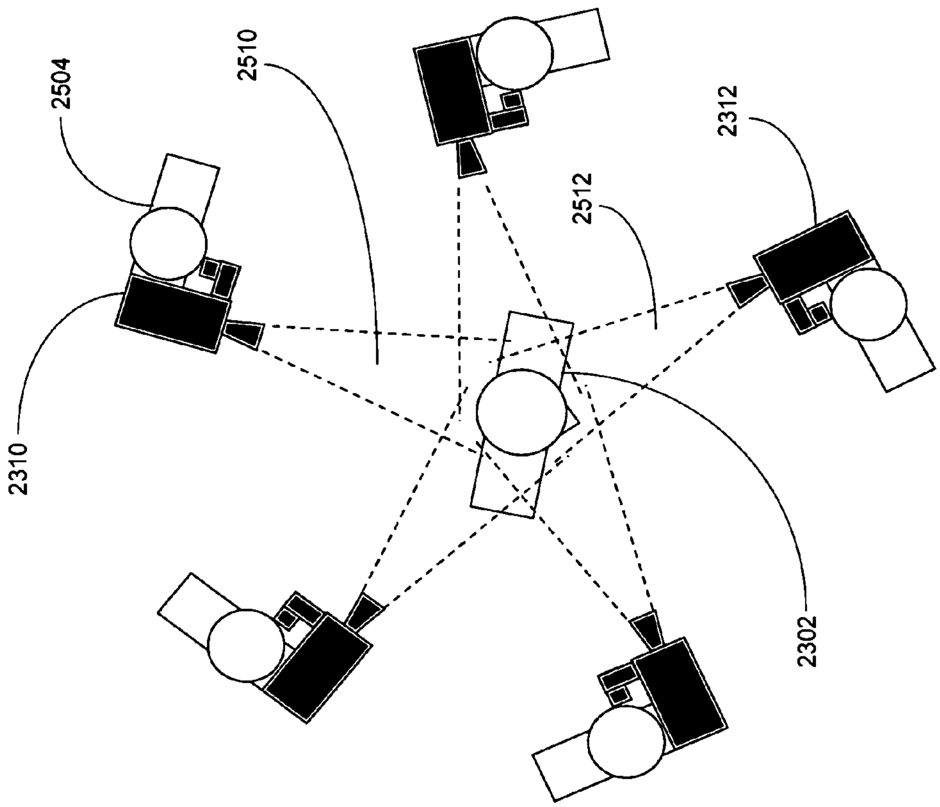


FIG. 25

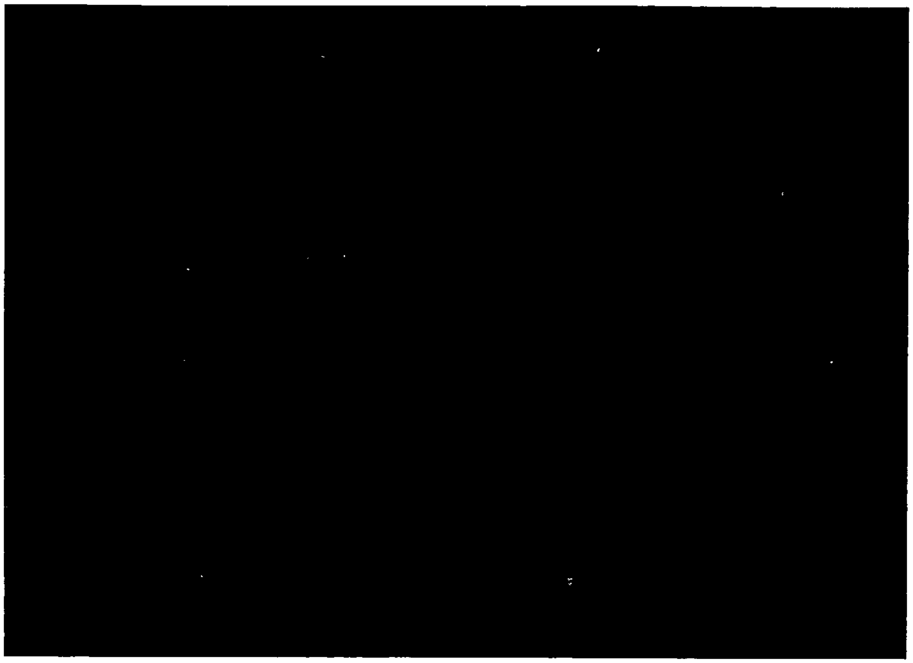


FIG. 26B

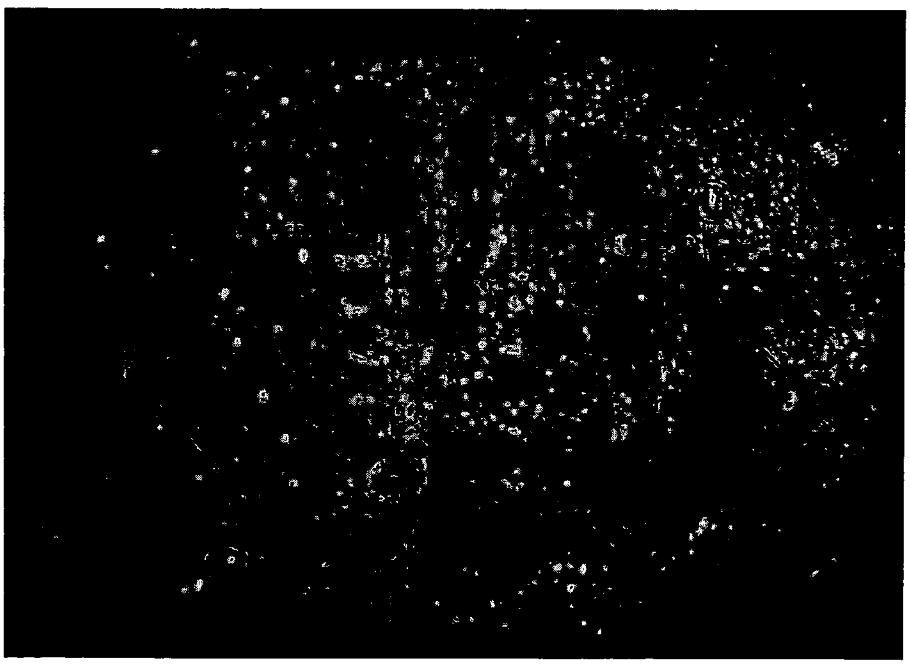


FIG. 26A

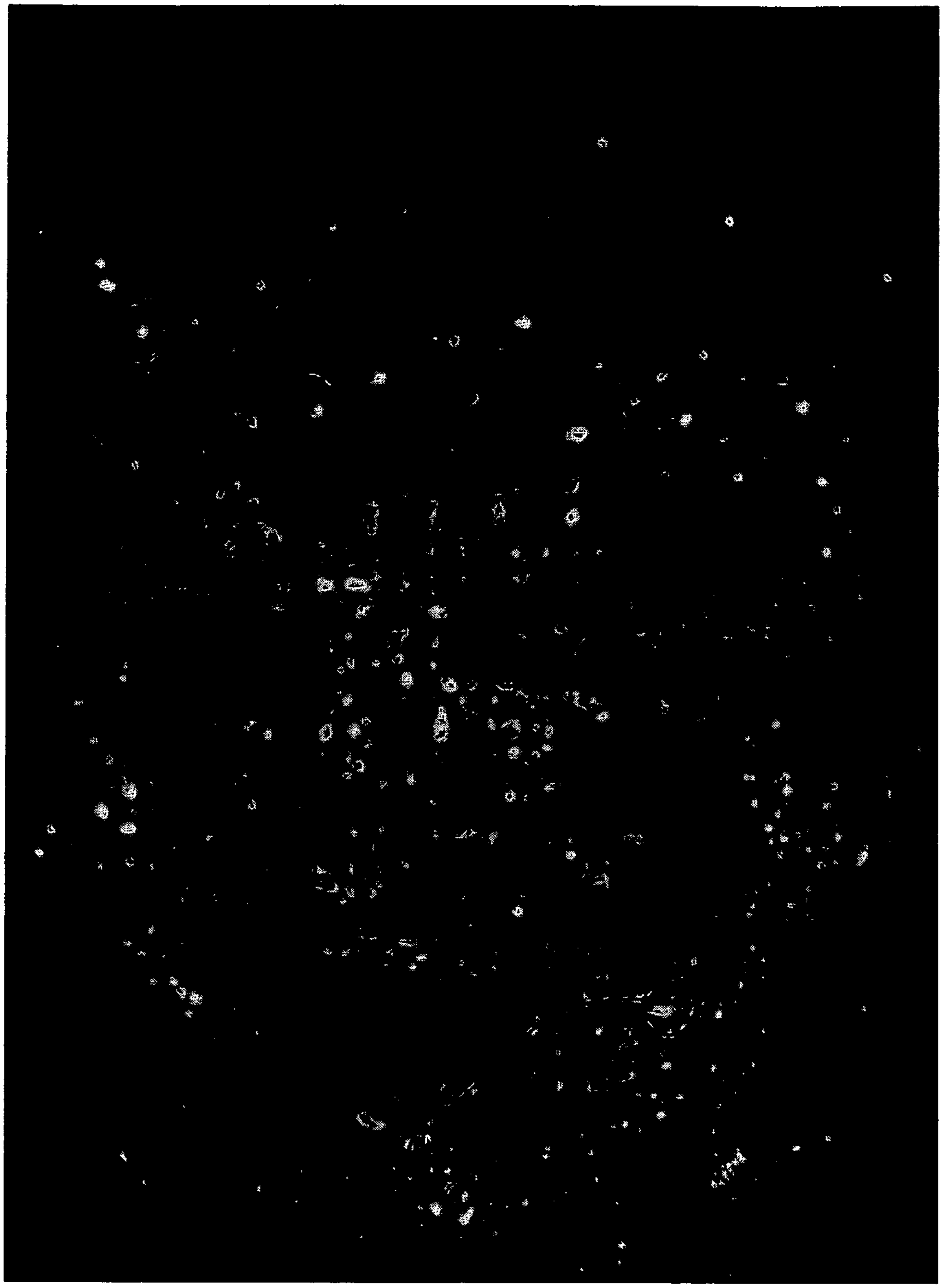


FIG. 27

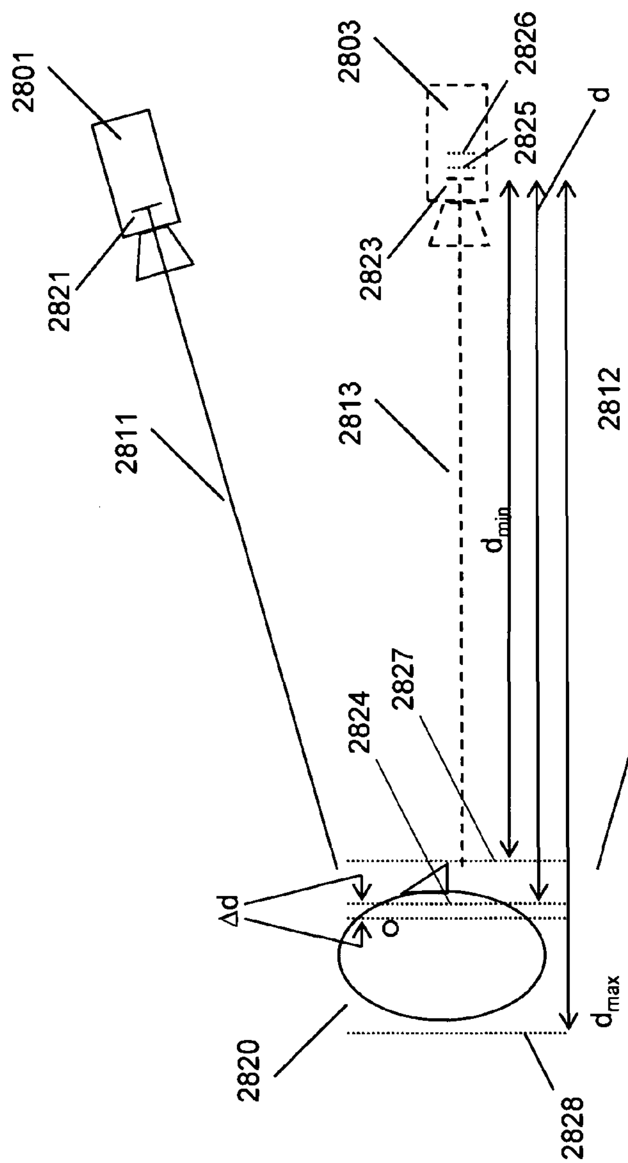
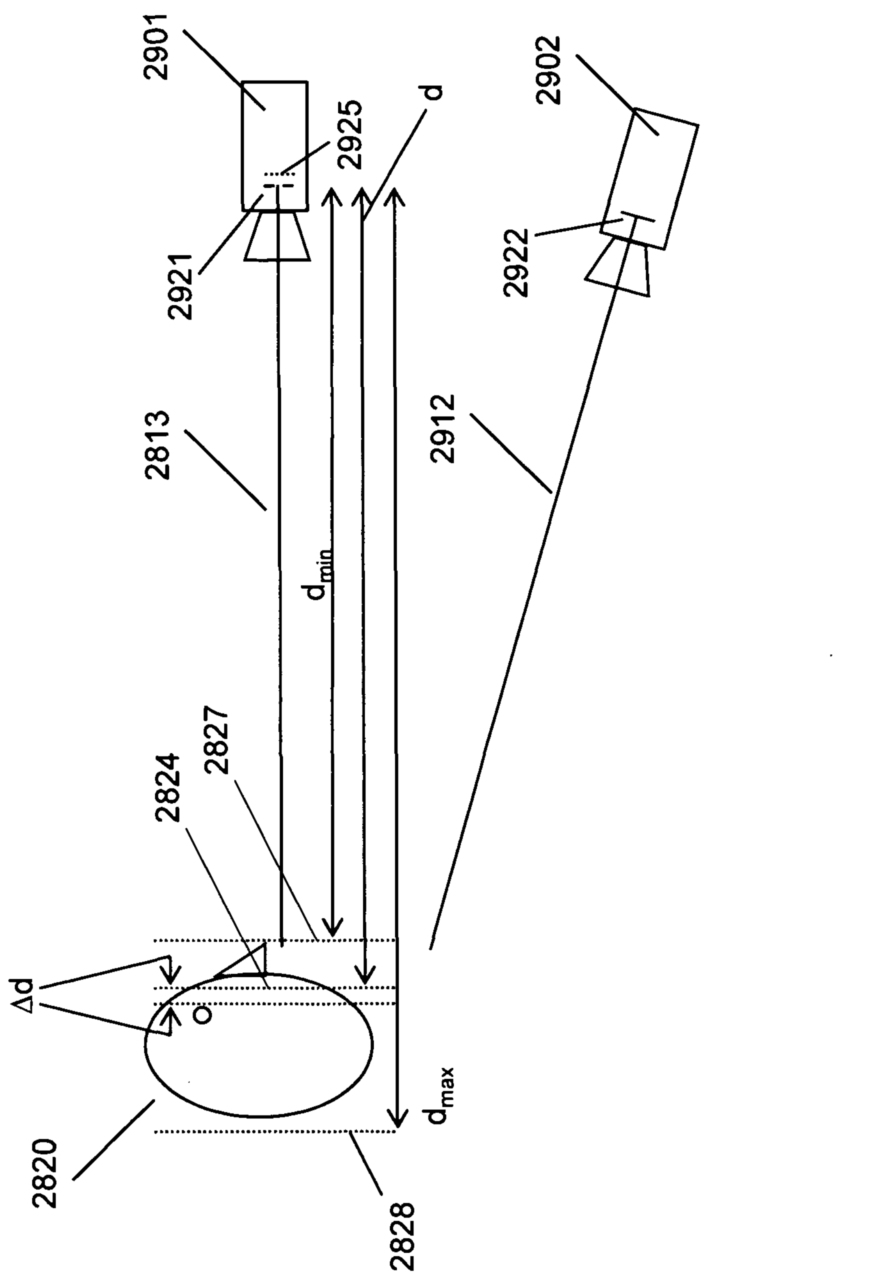
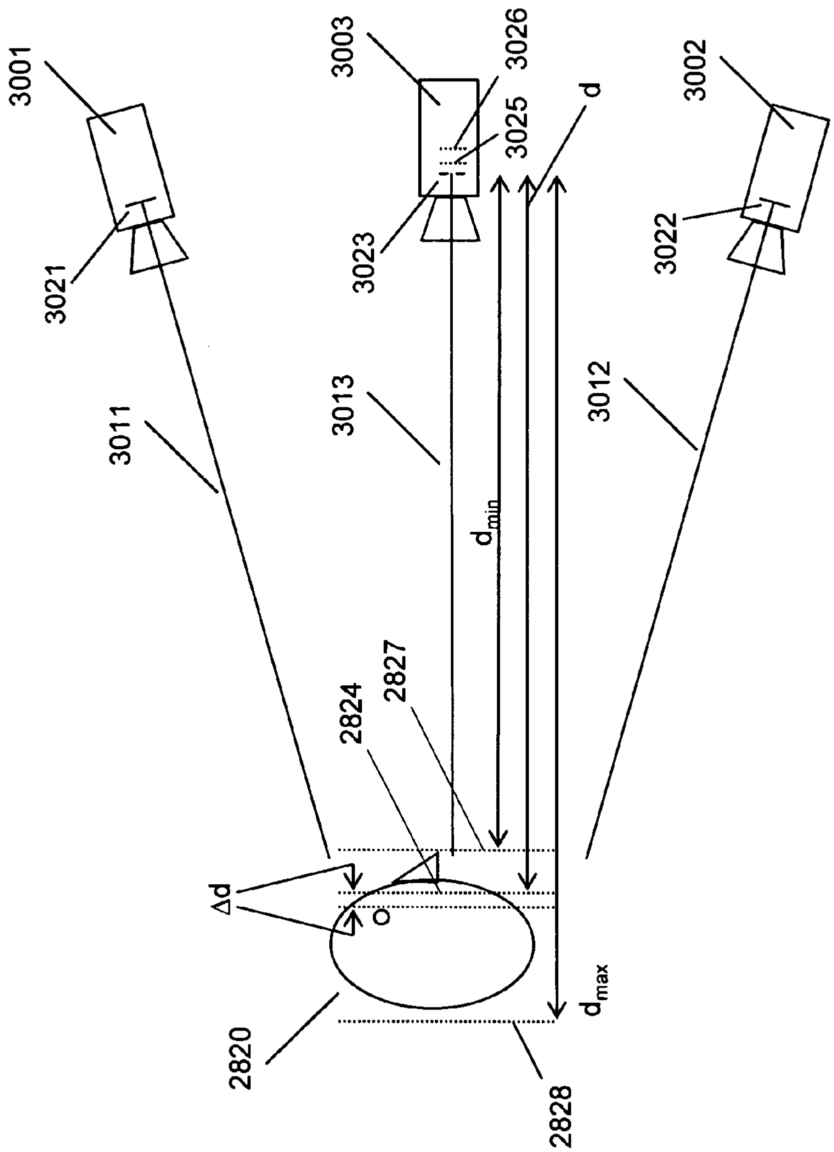

2801
2803
2826
2825
d
2802
2821
2823
2822
2811
2813
2812
d_{min}
2827
2824
Δd
O
d_{max}
2820
2828

FIG. 28



2901
2925
d
2902
2921
2922
2813
2912
d_{min}
2827
2824
Δd
2820
2828
d_{max}

FIG. 29



3001
3003
3026
3025
d
3002
3021
3023
3022
3011
3013
3012
d_{min}
2827
2824
Δd
2820
d_{max}
2828

FIG. 30

APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING A RANDOM PATTERN ON CAPTURE SURFACES

This application claims priority from Provisional Application Ser. No. 60/724,565, filed Oct. 7, 2005, entitled "Apparatus and Method for Performing Motion Capture Using a Random Pattern On Capture Surfaces."

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of motion capture. More particularly, the invention relates to an improved apparatus and method for performing motion capture using a random pattern of paint applied to a portion of a performer's face, body, clothing, and/or props.

2. Description of the Related Art

"Motion capture" refers generally to the tracking and recording of human and animal motion. Motion capture systems are used for a variety of applications including, for example, video games and computer-generated movies. In a typical motion capture session, the motion of a "performer" is captured and translated to a computer-generated character.

As illustrated in FIG. **1** in a traditional motion capture system, a plurality of motion tracking "markers" (e.g., markers **101**, **102**) are attached at various points on a performer's **100**'s body. The points are typically selected based on the known limitations of human anatomy. Different types of motion capture markers are used for different motion capture systems. For example, in a "magnetic" motion capture system, the motion markers attached to the performer are active coils which generate measurable disruptions x, y, z and yaw, pitch, roll in a magnetic field.

By contrast, in an optical motion capture system, such as that illustrated in FIG. **1**, the markers **101**, **102** are passive spheres comprised of retroreflective material, i.e., a material which reflects light back in the direction from which it came, ideally over a wide range of angles of incidence. A plurality of cameras **120**, **121**, **122**, each with a ring of LEDs **130**, **131**, **132** around its lens, are positioned to capture the LED light reflected back from the retroreflective markers **101**, **102** and other markers on the performer. Ideally, the retroreflected LED light is much brighter than any other light source in the room. Typically, a thresholding function is applied by the cameras **120**, **121**, **122** to reject all light below a specified level of brightness which, ideally, isolates the light reflected off of the reflective markers from any other light in the room and the cameras **120**, **121**, **122** only capture the light from the markers **101**, **102** and other markers on the performer.

A motion tracking unit **150** coupled to the cameras is programmed with the relative position of each of the markers **101**, **102** and/or the known limitations of the performer's body. Using this information and the visual data provided from the cameras **120-122**, the motion tracking unit **150** generates artificial motion data representing the movement of the performer during the motion capture session.

A graphics processing unit **152** renders an animated representation of the performer on a computer display **160** (or similar display device) using the motion data. For example, the graphics processing unit **152** may apply the captured motion of the performer to different animated characters and/or to include the animated characters in different computer-generated scenes. In one implementation, the motion tracking unit **150** and the graphics processing unit **152** are programmable cards coupled to the bus of a computer (e.g., such as the PCI and AGP buses found in many personal computers). One well known company which produces motion capture systems is Motion Analysis Corporation (see, e.g., www.motionanalysis.com).

One problem which exists with current marker-based motion capture systems is that when the markers move out of range of the cameras, the motion tracking unit **150** may lose track of the markers. For example, if a performer lays down on the floor on his/her stomach (thereby covering a number of markers), moves around on the floor and then stands back up, the motion tracking unit **150** may not be capable of re-identifying all of the markers.

Another problem which exists with current marker-based motion capture systems is that resolution of the image capture is limited to the precision of the pattern of markers. In addition, the time required to apply the markers on to a performer is long and tedious, as the application of the markers must be precise and when a large number of markers are used, for example on a face, in practice, the markers are very small (e.g. on the order of 1-2 mm in diameter). FIGS. **2***a* and **2***b* illustrate the tediousness of the process of applying markers to a performer. The positions **202** for the application of the markers **206** must first be created with a makeup pencil **204** or other fine tip marker. Once the pattern has been created, the markers **206** are applied. Because the markers **206** are only 1-2 mm in diameter, the markers **206** must be applied to the positions **202** using tweezers (not shown) and an adhesive **208**.

Another problem with current marker-based motion systems is that application of the markers must be kept away from certain areas of the performer, such as the eyes **210** and the lips **212** of a performer, because the markers may impede the free motion of these areas. In addition, secretions (e.g., tears, saliva) and extreme deformations of the skin (e.g., pursing the lips **212**) may cause the adhesive **208** to be ineffective in bonding the markers **206** on certain places of the skin. Additionally, during performances with current motion capture systems, markers may fall off or be smudged such that they change position on the performer, thus requiring a halt in the performance capture session (and a waste of crew and equipment resources) to tediously reapply the markers and often recalibrate the system.

Another current approach to accomplishing motion capture is to optically project a pattern or sequence of patterns (typically a grid of lines or other patterns) onto the performer. One or more cameras is then used to capture the resulting deformation of the patterns due to the contours of the performer, and then through subsequent processing a point cloud representative of the surface of the performer is calculated. Eyetronics-3d of Redondo Beach, Calif. is one company that utilizes such an approach for motion capture.

Although projected-pattern motion capture is quite useful for high-resolution surface capture, it suffers from a number of significant limitations in a motion capture production environment. For one, the projected pattern typically is limited to a fairly small area. If the performer moves out of the area of the projection, no capture is possible. Also, the projection is only in focus within a given depth of field, so if the performer moves too close or too far from the projected pattern, the pattern will be blurry and resolution will be lost. Further, if an object obstructs the projection (e.g. if the performer raises an arm and obstructs the projection from reaching the performer's face), then the obstruction region cannot be captured. And finally, as the captured surface deforms through successive frames (e.g. if the performer smiles and the cheek compresses), the motion capture system is not able to track points on the captured surface to see where they moved from frame to frame. It is only able to capture what the new geometry of the surface is after the deformation. Markers can be placed on the surface and can be tracked as the surface deforms, but the tracking will be of no higher resolution than that of the markers. For example, such a system is described in the paper "Spacetime Faces: High Resolution Capture for Modeling and Animation", by Li Zhang, et. al., of University of Washington.

As computer-generated animations becomes more realistic, cloth animation is used increasingly. Cloth simulation is quite complex because so many physical factors impact the simulation. This results in typically very long computation time for cloth simulation and many successive iterations of the simulation until the cloth achieves the look desired for the animation.

There have been a number of prior art efforts to capture cloth (and similar deformable and foldable surfaces) using motion capture techniques. For example, in the paper "Direct Pattern Tracking On Flexible Geometry" by Igor Guskow of University of Michigan, Ann Arbor. et. al, an approach is proposed where a regular grid is drawn on cloth and captured. More sophisticated approaches are described in other papers by Igor Guskow, et. al., such as "Multi-scale Features for Approximate Alignment of Point-based Surfaces", "Extracting Animated Meshes with Adaptive Motion Estimation", and "Non-Replicating Indexing for Out-of-Core Processing of Semi-Regular Triangular Surface Meshes". But none of these approaches are suitable for a motion capture production environment. Issues include production inefficiencies such as complex preparation of a specific geometric pattern on the cloth and capture quality limitations depending on lighting or other environmental issues.

Accordingly, what is needed is an improved apparatus and method for tracking and capturing deformable and foldable surfaces in an efficient production environment.

SUMMARY

A method according to one embodiment of the invention is described comprising: applying a random pattern to specified regions of a performer's face and/or body and/or other deformable surface; tracking the movement of the random pattern during a motion capture session; and generating motion data representing the movement of the performer's face using the tracked movement of the random pattern.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention can be obtained from the following detailed description in conjunction with the drawings, in which:

FIG. **1** illustrates a prior art motion tracking system for tracking the motion of a performer using retroreflective markers and cameras.

FIG. **2***a* illustrates a prior art method of drawing a pattern with a makeup pencil for positioning the reflective markers for motion capture.

FIG. **2***b* illustrates a prior art method of applying the markers after drawing the pattern as in FIG. **2***a*.

FIG. **3** illustrates a prior art curve pattern, flattened into a 2D image, that replaces the markers of FIG. **1** for use with another motion tracking system.

FIG. **4** illustrates a face with the prior art curve pattern of FIG. **3** applied.

FIG. **5** illustrates a random pattern applied to all parts of a performer's face, body, and props.

FIG. **6** illustrates one embodiment of the invention which employs the performer with the random pattern in FIG. **5** to track movement and/or facial expression with synchronized light panels and camera shutters.

FIG. **7** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIGS. **8***a* and **8***b* are frames captured at the same time, with external visible light present, of an elevated view and a frontal view, respectively, of a performer with a random pattern of phosphorescent paint applied to the face.

FIGS. **9***a* and **9***b* are frames captured at the same time, without external visible light present, from the same perspectives as FIGS. **8***a* and **8***b*, respectively, of the performer with the random pattern of paint applied to the face.

FIG. **10** is a schematic representation of an exemplary LED array and the connectors for the synchronization signals.

FIG. **11** is a timing diagram illustrating the synchronization between the light panels and the camera shutters in an embodiment for capturing both lit frames and glow frames.

FIG. **12** is a timing diagram illustrating the synchronization between the light panels and the camera shutters in another embodiment for capturing both lit frames and glow frames.

FIG. **13** illustrates one embodiment of a system for capturing both lit frames and glow frames.

FIG. **14** illustrates a timing diagram associated with the system shown in FIG. **13**.

FIG. **15** illustrates the method of correlating captured frames from two cameras of the motion capture system to create a 3D surface.

FIGS. **16***a* and **16***b* are the frame captures of FIGS. **9***a* and **9***b* mapped to a common coordinate system.

FIG. **17** is a frame with the frame captures of FIGS. **16***a* and **16***b* overlapping each other.

FIG. **18** illustrates an example of the correlation graph in order to determine the depth of a point in FIG. **17**.

FIG. **19** is an example of a resulting 3D texture map from the correlation method of FIG. **15** and rendering.

FIGS. **20***a* and **20***b* are frames captured; at two separate points in time, from the same camera position, and with external visible light present; of a cloth with a random pattern of phosphorescent paint applied to both sides.

FIGS. **21***a* and **21***b* are frame captures, without external visible light present, corresponding to FIGS. **20***a* and **20***b*, respectively, of the cloth with the random pattern of paint applied to both sides.

FIG. **22** is a frame with the frame captures of FIGS. **21***a* and **21***b* overlapping each other.

FIG. **23** illustrates one embodiment of the camera positioning for the motion capture system of FIG. **6** or **13**.

FIG. **24** illustrates the performer in FIG. **23** wearing a crown of markers.

FIG. **25** illustrates, from FIG. **23**, the inner ring of cameras' fields of view of the performer.

FIGS. **26***a* and **26***b* are frames captured at successive moments in time, without external visible light present and each from the same perspective of a performer with the random pattern of paint applied to the face.

FIG. **27** is a frame with the frame captures of FIGS. **26***a* and **26***b* overlapping each other.

FIG. **28** illustrates the imaginary camera positioning described in FIG. **15**.

FIG. **29** illustrates the imaginary camera at the same perspective as an existing camera.

FIG. **30** illustrates correlation between frames captured by three cameras

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Described below is an improved apparatus and method for performing motion capture using a random pattern of paint applied to portions of a performer's face and/or body. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form to avoid obscuring the underlying principles of the invention.

The assignee of the present application previously developed a system for performing color-coded motion capture and a system for performing motion capture using a series of reflective curves **300**, illustrated generally in FIG. **3** and shown painted on the face of a performer **400** in FIG. **4**. These systems are described in the co-pending applications entitled "Apparatus and Method for Capturing the Motion and/or Expression of a Performer," Ser. No. 10/942,609, and Ser. No. 10/942,413, Filed Sep. 15, 2004. These applications are assigned to the assignee of the present application and are incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture using shutter synchronization and phosphorescent paint. This system is described in the co-pending application entitled "Apparatus and Method for Performing Motion Capture Using Shutter Synchronization," Ser. No. 11/077,628, Filed Mar. 10, 2005 (hereinafter "Shutter Synchronization" application). Briefly, in the Shutter Synchronization application, the efficiency of the motion capture system is improved by using phosphorescent paint and by precisely controlling synchronization between the motion capture cameras' shutters and the illumination of the painted curves. This application is assigned to the assignee of the present application and is incorporated herein by reference.

Unlike any prior motion capture systems, in one embodiment of the present invention, illustrated generally in FIG. **5**, a random pattern of phosphorescent paint is applied to the performer's face **502**, body or clothing **504** and/or props **506** (e.g., a sword). The amount of paint applied to the performer may vary, i.e., with certain areas having relatively more or less paint in relation to other areas. No paint may be used on some areas whereas other areas may be saturated with paint. In another embodiment, multiple colors of phosphorescent paint may be applied to create the random pattern on the performer. In addition, in one embodiment, the random pattern may be used concurrently with different structured patterns, such as the curve pattern described in co-pending application Ser. Nos. 10/942,609 and 10/942,413 or the marker system of FIG. **1**.

In one embodiment, the phosphorescent paint applied to the performer's face is Fantasy F/XT Tube Makeup; Product #: FFX; Color Designation: GL; manufactured by Mehron Inc. of 100 Red Schoolhouse Rd. Chestnut Ridge, N.Y. 10977. In another embodiment, paint viewable in visible light is used to apply the random pattern and visible light is used when capturing images. However, the underlying principles of the invention are not limited to any particular type of paint. In another embodiment, if a liquid surface is to be captured, particles that float in the liquid can be distributed across the surface of the liquid. Such particles could be phosphorescent particles, retroreflective spheres, or other materials which are visible with high contrast compared to the light emission of the liquid when it is captured.

As mentioned briefly above, in one embodiment, the efficiency of the motion capture system is improved by using phosphorescent paint and/or by precisely controlling synchronization between the cameras' shutters and the illumination of the random pattern. Specifically, FIG. **6** illustrates one embodiment in which the random pattern is painted on the performer's face **602** using phosphorescent paint and light panels **608-609** (e.g., LED arrays) are precisely synchronized with the opening and closing of the shutters of the motion capture cameras **604**. The room in which the capture is performed is sealed from light so that it is completely, or nearly completely dark, when the light panels **608-609** are off. The synchronization between the light panels **608-609** and cameras **604** is controlled via synchronization signals **622** and **621**, respectively. As indicated in FIG. **6**, in one embodiment, the synchronization signals are provided from a peripheral component interface ("PCI") card **623** coupled to the PCI bus of a personal computer **620**. An exemplary PCI card is a PCI-6601 manufactured by National Instruments of Austin, Tex. However, the underlying principles of the invention are not limited to any particular mechanism for generating the synchronization signals.

The synchronization between the light sources and the cameras employed in one embodiment of the invention is illustrated graphically in FIG. **7**. In this embodiment, the two synchronization signals **621**, **622** are the same. In one embodiment, the synchronization signals cycle between 0 to 5 Volts. In response to the synchronization signals **621**, **622**, the shutters of the cameras are periodically opened and closed and the light panels are periodically turned off and on, respectively. For example, on the rising edge **712** of the synchronization signals, the camera shutters are closed and the light panels are illuminated. The shutters remain closed and the light panels remain illuminated for a period of time **713**. Then, on the falling edge of the synchronization signals **714**, the shutters are opened and the light panels are turned off. The shutters and light panels are left in this state for another period of time **715**. The process then repeats on the rising edge **717** of the synchronization signals.

As a result, during the first period of time **713**, no image is captured by the cameras, and the random pattern of phosphorescent paint is illuminated with light from the light panels **608-609**. During the second period of time **715**, the light is turned off and the cameras capture an image of the glowing phosphorescent paint on the performer. Because the light panels are off during the second period of time **715**, the contrast between the phosphorescent paint and the rest of the room (including the unpainted regions of the performer's body) is extremely high (i.e., the rest of the room is pitch black), thereby improving the ability of the system to differentiate the various patterns painted on the performer's face from anything else in the cameras' **604** fields of view. In addition, because the light panels are on half of the time, the performer will be able to see around the room during the performance. The frequency **716** of the synchronization signals may be set at such a high rate that the performer will not even notice that the light panels are being turned on and off. For example, at a flashing rate of 75 Hz or above, most humans are unable to perceive that a light is flashing and the light appears to be continuously illuminated. In psychophysical parlance, when a high frequency flashing light is perceived by humans to be continuously illuminated, it is said that "fusion" has been achieved. In one embodiment, the light panels are cycled at 120 Hz; in another embodiment, the light panels are cycled at 240 Hz, both frequencies far above the fusion threshold of any human. However, the underlying principles of the invention are not limited to any particular frequency.

FIGS. **8***a* and **8***b* are exemplary pictures of the performer **602** during the first time period **713** (i.e., when the light panels are illuminated) from different reference angles and FIGS. **9***a* and **9***b* show the illuminated random pattern captured by the cameras **604** during the second time period **715** (i.e., when the light panels are turned off). During the first time period, the random pattern of phosphorescent paint (the paint as applied in FIGS. **8***a* and **8***b* is mostly transparent in visible light, but where the random pattern is particularly dense, it can be seen in visible light as small spots of white such as **802** in FIG. **8***a*) is charged by the light from the light panels and, as illustrated in FIGS. **9***a* and **9***b*, when the light panels are turned off, the only light captured by the cameras is the light emanating from the charged phosphorescent paint (and the particularly dense spot **802** can be seen in FIG. **9***a* as spot **902**). Thus, the phosphorescent paint is constantly recharged by the strobing of the light panels, and therefore retains its glow throughout the motion capture session. In addition, because it retains its glow for a period of time, if a performer happens to move so that for a few frames some of the random pattern of phosphorescent paint is in shadow and not illuminated by the light panels, even though the phosphorescent paint is not getting fully charged for those frames, the paint will still retain its glow from previous frame times (i.e., when the paint was not in shadow).

Note also that the random paint pattern varies both spatially (i.e. paint dot placements) and in amplitude (i.e., paint dot density, since denser (thicker) dots generally phosphoresce more light) resulting in a frame capture by cameras **604** during the glow interval **715** that is modulated randomly in horizontal and vertical spatial dimensions as well as in brightness.

As mentioned above, in one embodiment, the light panels **608**, **609** are LED arrays. A schematic of an exemplary LED array **1001** and associated connection circuitry is illustrated in FIG. **10**. The synchronization signals are applied to the LED array **1001** via connector J**2**-**1** illustrated to the left in FIG. **10**. In one embodiment, the connectors are RJ-45 connectors. The synchronization signal is initially inverted by inverter IC**2**B and the inverted signal is applied to the base of transistor Q**2**, causing transistor Q**2** to turn on and off in response to the inverted signal. This causes current to flow through resistor R**3**, thereby causing transistor Q**1** to turn on and off. This, in turn, causes the LEDs within the LED array **501** to turn on and off. In one embodiment, the inverted signal from IC**2**B is applied to three additional LED arrays as indicated in FIG. **10**. A plurality of additional connectors J**1**-**1**, J**1**-**2**, J**1**-**3**, and J**1**-**4** are provided for additional light panels (i.e., the light panels may be daisy-chained together via these connectors) using inverters IC**2**C, IC**2**D, IC**2**E and IC**2**F for buffering. If daisy-chaining without buffering is desired (e.g. due to critical timing requirements that would be hampered by the IC**2** propagation delays), then connector J**2**-**2** can be used. The voltage regulator IC**1** used for the LED array (shown at the top of FIG. **10**) takes a 12V input and produces a 5V regulated output used by IC**2**. In one embodiment, transistors Q**1** is a MOSFET transistor. However, the underlying principles are not limited to any particular type of circuitry.

In one embodiment of the invention, the cameras are configured to capture pictures of the performer's face (e.g., FIGS. **8***a* and **8***b*) in addition to capturing the random pattern (e.g., FIGS. **9***a* and **9***b*). The pictures of the performer's face may then be used, for example, by animators as a texture map for correlating regions of the random pattern and rendering a more accurate representation of the performer. The phosphorescent paint as applied in FIGS. **8***a* and **8***b* is largely transparent in visible light, allowing for an almost unaltered capture of the underlying image of the performer's face. Prior art motion capture systems have obscured much of the object to be captured by utilizing opaque marking materials such as retroreflective markers or high-contrast paint, or by utilizing patterns projected onto the face. All of these prior art techniques have made it difficult to capture a largely unaltered visible light image of the object being captured. Further, prior art optical motion capture techniques have relied upon specific visible light lighting conditions. For example, retroreflective markers rely upon a light source around the camera lens, paint pattern capture techniques rely upon reasonably uniform lighting of the face (e.g. shadows and highlights are avoided) and projected pattern techniques rely upon projected light. In one embodiment of the invention, the motion is only captured during the glow interval **715**.

During the visible light interval **713**, virtually any lighting arrangement is possible so long as the phosphorescent paint is adequately charged (i.e., such that the pattern is within the light sensitivity capability of cameras **604**) before it dims. This gives enormous creative control to a director who wishes to achieve dramatic effects with the lighting of the performers when their visible light images are captured. Such creative control of lighting is an integral part of the art of film making. Thus, not only does the present invention allow for largely unobstructed visible light capture of the performers, but it allows for creative control of the lighting during such visible light image capture.

The signal timing illustrated in FIG. **11** represents an embodiment in which an asymmetric duty cycle is used for the synchronization signal for the cameras (in contrast to the 50% duty cycle shown in FIG. **7**). In this embodiment, synchronization signal **2** remains the same as in FIG. **7**. The rising edge **1122** of synchronization signal **2** illuminates the light panels; the panels remain on for a first time period **1123**, turn off in response to the falling edge **1124** of synchronization signal **2**, and remain off for a second time period **1125**.

By contrast, synchronization signal **1**, which is used to control the shutters, has an asymmetric duty cycle. In response to the rising edge **1112** of synchronization signal **1**, the shutters are closed. The shutters remain closed for a first period of time **1113** and are then opened in response to the falling edge **1114** of synchronization signal **1**. The shutters remain open for a second period of time **1115** and are again closed in response to the rising edge of synchronization signal **1**. The signals are synchronized so that the rising edge of synchronization signal **1** always coincides with both the rising and the falling edges of synchronization signal **2**. As a result, the cameras capture one lit frame during time period **1115** (i.e., when the shutters are open the light panels are illuminated) and capture one "glow frame" during time period **1116** (i.e., when the shutters are open and the light panels are off).

In one embodiment, the data processing system **610** shown in FIG. **6** separates the lit frames from the glow frames to generate two separate streams of image data, one containing the images of the performer's face and the other containing phosphorescent random pattern data. The glow frames may then be used to generate the 3D point cloud that specifies surface **607** (shown enlarged in FIG. **19**) of the performer's face and the lit frames may be used, for example, as a reference for animators. Such reference could be used, for example, to better synchronize a texture map of the face, or if the resulting animated face is different from the performer's face (e.g. if it is a caricature), such reference could be used to help the animator know what expression the performer is intending during that frame of the performance. and/or to assist in generating the texture map derived from visible light capture **602** (shown enlarged in FIGS. **8**a and **8**b) of the performer's face. The two separate video sequences may be synchronized and viewed next to one another on a computer or other type of image editing device.

Given the significant difference in overall illumination between the lit frames and the glow frames, some cameras may become overdriven during the lit frames if their light sensitivity is turned up very high to accommodate glow frames. Accordingly, in one embodiment of the invention, the sensitivity of the cameras is cycled between lit frames and glow frames. That is, the sensitivity is set to a relatively high level for the glow frames and is then changed to a relatively low level for the lit frames.

Alternatively, if the sensitivity of the cameras **604** cannot be changed on a frame-by-frame basis, one embodiment of the invention changes the amount of time that the shutters are open between the lit frames and the glow frames. FIG. **12** illustrates the timing of one such embodiment in which synchronization signal **1** is adjusted to ensure that the cameras will not be overdriven by the lit frames. Specifically, in this embodiment, during the period of time that synchronization signal **2** is causing the light panels to be illuminated, synchronization signal **1** causes the shutter to be closed for a relatively longer period of time than when synchronization signal **2** is not illuminating the light panels. In FIG. **12**, for example, synchronization signal **1** is high during time period **1253**, thereby closing the shutter, and is low during period **1255**, thereby opening the shutter. By contrast, during the glow frame, synchronization signal **1** is high for a relatively short period of time **1213** and is low for a relatively longer period of time **1215**.

In one embodiment, illustrated in FIG. **13**, both color and grayscale cameras are used and are synchronized using different synchronization signals. Specifically, in this embodiment, color cameras **1314-1315** are used to capture the lit frames and grayscale cameras **1304-1305** are used to capture the phosphorescent random pattern painted on the performer's face. One of the benefits of this configuration is that grayscale cameras typically have a relatively higher resolution and higher light sensitivity than comparable sensor resolution color cameras, and can therefore capture the phosphorescent pattern more precisely. By contrast, color cameras are better suited to capturing the color and texture of the performer's face.

As illustrated in FIG. **14**, in one embodiment, different synchronization signals, **1**A and **1**B are used to control the grayscale and color cameras, respectively. In FIG. **14**, synchronization signals **1**A and **1**B are 180 degrees out of phase. As a result, the falling edge **1414** of synchronization signal **1**B occurs at the same time as the rising edge **1424** of synchronization signal **1**A, thereby opening the shutters for the color cameras **1314**, **1315** and closing the shutters for the grayscale cameras **1304**, **1305**. Similarly, the rising edge **1412** of synchronization signal **1**B occurs at the same time as the falling edge **1422** of synchronization signal **1**A, thereby closing the shutters for the color cameras **1314**, **1315** and opening the shutters for the grayscale cameras **1304**, **1305**. The synchronization signal **2** for the light panels is not illustrated in FIG. **14** but, in one embodiment, is the same as it is in FIG. **7**, turning the light panels on when the color camera shutters are opened and turning the light panels off when the grayscale camera shutters are opened.

When the embodiments of the present invention described herein are implemented in the real world, the synchronization signals (e.g., **621** and **622** of FIG. **6**) may require slight delays between respective edges to accommodate delays in the cameras and LED arrays. For example, on some video cameras, there is a slight delay after rising edge **712** of FIG. **7** before the camera shutter closes. This can be easily accommodated by delaying signal **622** relative to signal **621**. Such delays are typically on the order of less than a millisecond. As such, when the system is started, the timing signals may initially need to be precisely calibrated by observing whether the video cameras **604** are capturing completely black frames and adjusting the timing signals **621** and **622** prior to the actual performance.

The random pattern of phosphorescent paint may be applied to the performer through a variety of techniques. In one embodiment, paint is applied to a sponge roller and the sponge roller is rolled across the specified portion of the performer. FIGS. **8**a-**9**b illustrate a pattern applied by this technique. Other exemplary techniques comprise (i) spraying the paint with an airbrush, (ii) applying paint through a stencil, or (iii) flicking a wire brush containing paint such that the droplets of paint are splattered onto the surface to be captured. The desired result is any random pattern, ideally with a 1/n random distribution, but high-quality can be achieved with patterns which are far less than ideal. It should be noted that the above paint application techniques are not exhaustive but are merely several embodiments of the present invention.

During the application of paint, parts of the performer that are not intended to be touched by the paint may be covered. Parts of the performer that are typically screened from the paint application are the inside of the mouth and the eyeballs. These parts of the performer may have a random pattern applied to them through alternate techniques. In one exemplary technique, a random pattern of phosphorescent paint is applied to a contact lens, which is then placed over the performer's eyeball. In another exemplary technique, tooth caps embedded with a random pattern of phosphorescent pigments are placed over the teeth of the performer. In one embodiment, frames are captured during lit intervals **1115** and glow intervals **1116**, and the performer's irises and/or pupils (which are smooth and geometric) are tracked during lit interval **1115** using visible light, while other parts of the performer's body are captured from phosphorescent paint patterns during glow intervals **1116**,

In one embodiment of the present invention, live performers and/or sets are captured at the same time as motion capture performers, who are to be generated and rendered in the future, by the motion capture system illustrated in FIG. **13**. The set is in a room illuminated by the synchronized LED lights **606**, **609** of the motion capture system. The live-action performers and sets are captured by color cameras **1314-1315** during the frame intervals when the lights are on, and the motion-captured performers are captured by the grayscale cameras **1304-1305** during the frame intervals when the lights are off.

To compute the 3D surface **607** of FIGS. **6** and **13**, images of the performer/paint are captured within the field of view of at least two cameras. Correlation of the motion capture data from the at least two cameras is performed in order to create a 3D surface of regions of the performer. The correlated regions of the captured data from all of the cameras are then correlated to create a final 3D surface **607**.

In one embodiment of the present invention, a correlation may be performed by Data Processing system **610** (which may incorporate one or more computing systems **605** per camera **604** and/or may incorporate one or more computing systems **606** to process the aggregated camera capture data) at a low resolution for each pair of frames from two cameras with overlapping fields of view to determine regions of the pair of frames that highly correlate to each other. Then, another correlation of the regions determined to have high correlation at low resolution is performed at a higher resolution in order to construct a 3D surface for the two frames. Correlation may also be performed on at least two successive time frame captures from the same view of reference in order to determine and track movement and/or expressions of the performer.

FIG. **15** is a flowchart illustrating one specific embodiment of a method for correlating two frame captures from two different perspectives (e.g., the captures of FIGS. **9**A and **9**B). Before discussing the flowchart of FIG. **15**, certain concepts must be introduced. Referring to FIG. **28**, Camera **2801** captures frame PA in a stream of frames via sensor **2821**. Camera **2802** captures frame PB via sensor **2822** at the same time frame PA is captured. Through the correlation technique described in FIG. **15**, the resulting correlated frame from frame PA and frame PB will be from the perspective of an imaginary or "virtual" camera, visualized as imaginary camera **2803** in FIG. **28**.

The following variables will be used in discussing FIG. **15**.

r: Variable r is the sensor resolution divisor for downsampling. For example, if a 640×480 pixel resolution frame is downsampled to 160×120 pixels, then r equals 4 (640/160 and 480/120 equal 4).

r_{max}: Variable r_{max} is the maximum sensor resolution divisor r can equal. Thus, the largest downsampling that can occur will use rmax.

SA: SA is the downsample of frame PA of factor of r. Downsampling can be performed using various filters such as a bilinear filter, a bicubic filter, or other filters and/or techniques known in the art. Thus, in the example in the definition of r, SA is 160×120 pixels in size, where PA was downsampled from 640×480 with a value of r equals 4 to a size of (640/4)×(480/4).

SB: SB is the downsample of PB as through the same process described in the definition of SA. As will be seen in FIG. **15**, correlations of frames PA and PB are first performed at lower resolutions (e.g., SA and SB) and then performed at gradually higher resolutions in order to prevent regions of frames PA and PB from falsely having high correlations with one another. For example, in a particular frame, a spot on a performer's chin may be falsely be identified as having a high correlation with a spot on the ear.

d_{min}: The distance d_{min}, illustrated in FIG. **28**, is the distance between the imaginary camera's sensor **2823** (the visualization of the frame buffer) and the plane perpendicular to line **2813** of a capture point of the object **2820** closest to the imaginary sensor **2823**. Thus, in the example of FIG. **28**, the closest point is the tip of the nose of performer **2820**. The plane of the point is visualized as plane **2827**. It will be understood by one in the art through discussion of FIG. **15** that d_{min} can be set to a value less than the value described above. In other exemplary embodiments, d_{min} can be user defined or set to the beginning of the field of focal depth for camera **2801** and/or **2802**.

d_{max}: The distance d_{max} is the distance between the imaginary camera's sensor **2823** (the visualization of the frame buffer) and the plane perpendicular to line **2813** of a capture point of the object **2820** farthest away from the imaginary sensor **2823**. Thus, in the example of FIG. **28**, the farthest point is the back of the head of performer **2820**. The plane of the point is defined in the same way as for dmin. It will be understood by one in the art through discussion of FIG. **15** that d_{max} can be set to a value greater than the value described above, as shown plane **2828** in FIG. **28**. In other exemplary embodiments, d_{max} can be user defined or set to the end of the field of focal depth for camera **2801** and/or **2802**. In yet other exemplary embodiments d_{max} can be user defined or set to further depth of the captured object in the fields of view of cameras **2801** and **2802**.

d: The distance d is the distance between the imaginary camera's sensor **2823** and the imaginary plane of capture **2824**. During the process of FIG. **15**, frames PA and PB are correlated as if captured from the same point of reference. Hence, the frame stored in the frame buffer in correlating PA and PB is like a frame being captured via the imaginary sensor **2823** from the imaginary capture plane **2824**. Thus, during discussion of FIG. **15**, frames SA and SB will be reference converted using a perspective transform, or "warped", as if they were projected on imaginary plane **2824**. Distance d will change between d_{min} and d_{max}. Therefore, frames SA and SB will be warped multiple times as if projected on the moving imaginary plane **2824**.

Δd: Δd is the increment that distance d changes between frames. Thus, it can be visualized that the imaginary plane **2824** moves Δd distance from d_{min} to d_{max} where at each increment, the correlation of PA and PB is performed (as described in greater detail below). The user can choose a larger or smaller Δd, depending on the precision of reconstruction resolution in the z dimension that is desired.

VA: VA is the reference conversion of SA ("Virtual A"). In other words, VA is the resulting matrix (i.e., 2 dimensional frame buffer) of warping SA to the reference of the imaginary plane **2824**. Matrix VA can be visualized as the frame SA (**2825**) captured via imaginary sensor **2823**, but of course limited to what is in view of camera **2801**. For example, if the underside of the nose of head **2820** is obstructed from camera **2801**'s view then VA will not contain image information from the underside of the nose.

VB: VB is the reference conversion of SB ("Virtual B"). In other words, VB is the resulting matrix (i.e., 2 dimensional frame buffer) of warping SB to the reference of the imaginary plane **2824**. Matrix VB can be visualized as the frame SB (**2826**) captured via imaginary sensor **2823**. VA and VB are two matrices of perspective converted matrices SA and SB that will be correlated against each other in the process illustrated in FIG. **15**.

Z[m,n]: Matrix Z is originally of size m×n. The size of Z is originally equal to the size of capture frames PA and PB. Because of correlation at different resolutions, though, Z will be downsampled and upsampled. Thus, each element of Z is notated as z(j,k), where j is between 1 and m/r and k is between 1 and n/r. After the process illustrated in FIG. **15**, when correlation is finished performing at the highest resolution (when r=1), z(j,k)+d_{min} is the measure of depth of pixel j,k in the frame being correlated. Thus, pixel j,k of the resulting frame can be visualized as being z(j,k)+d_{min} distance away from the imaginary camera **2803**. Hence, once the correlation process of FIG. **15** is complete, the Z matrix can be used to render a 3D image of the object **2820**.

Z_{est}[m,n]: Matrix Z_{est} (an estimate of Z) is a matrix originally of size m×n. The existence and use of Z_{est} allows for the manipulation of z(j,k) values without changing the values stored in Z. Z_{est} will be the same size as Z through the downsampling and upsampling in the process described in FIG. **15**.

roa: roa stands for Range of Acceptance and is the range of distances z(j,k) is allowed to deviate at a given resolution stage of the process illustrated in FIG. **15**. For example, object

2820 is known to be within distance d_{min} and d_{max} of imaginary camera **2803**. Therefore, initial roa could be set to d_{max}-d_{min}, as in FIG. **15**, because no z(j,k) can be larger than this value. roa is refined each time a higher resolution pair of frames are beginning to be correlated, as will be seen in FIG. **15**.

C[(m/r),(n/r)]: Matrix C is a matrix of the correlation values for a pixel-wise, normalized cross-correlation between VA and VB at a specific d. The pixel-wise, normalized cross-correlation is well known in the art. An exemplary illustration and discussion of one pixel-wise, normalized cross-correlation is "Cross Correlation", written by Paul Bourke, copyright 1996 (http://astronomy.swin.edu.au/~pbourke/other/correlate/). In one embodiment of the present invention, the values are normalized to the range on −1 to 1. Since correlation will be performed at varying resolutions, the size of the matrix will depend on the amount of downsampling of the original frames (e.g., PA and PB). For example, if PA and PB are downsampled to 80×60, C will be of size 80×60. Each element of C is notated as c(s,t) where s is between 1 and m/r and t is between 1 and n/r.

C_{max}[(m/r),(n/r)]: Matrix C_{max} is a matrix wherein c_{max}(s,t) is the maximum value of c(s,t) when comparing all c(s,t) values for a specific s and t over all d's (e.g., d_{min}, $d_{min}+\Delta d$, $d_{min}+2\Delta d$, . . . , d_{max}). Hence, C_{max} contains the largest correlation value computed for each pair of pixels va(s,t) and vb(s,t) of matrices VA and VB. The d at which the largest correlation value is determined for pixel s,t will be stored in z(s,t) as the optimal d for the pair of pixels. When r is 1, the d's stored will create the wanted final Z matrix.

Beginning discussion of FIG. **15**, step **1502** is entered wherein d, r, ROA, Z, and Z_{est} are initialized. Their initial values are set to the following:

$$r = r_{max}$$

$$d = d_{min}$$

$$roa = d_{max} - d_{min}$$

$$Z = \frac{d_{max} + d_{min}}{2}$$

$$Z_{est} = \frac{d_{max} + d_{min}}{2}$$

In one embodiment, r_{max} is defined by the user, but it may be determined in a variety of ways including, but not limited to, setting a static variable for all correlations or depending the variable on d_{min} and/or d_{max}. It will be understood by one in the art through matrix algebra that Z=a means; for all j,k; z(j,k) equal a. Such notation will be used throughout the discussion of FIG. **15**.

Step **1504** is then entered, where the frames PA and PB are downsampled to the size m/r×n/r and stored as SA and SB, respectively. Thus, for the first pass through step **1504**, the size of SA and SB will be $m/r_{max} \times n/r_{max}$. As previously discussed, downsampling is well known in the art and may be performed by various filters and/or techniques including, but not limited to, bilinear filtering and bicubic filtering.

Proceeding to step **1506**, C_{max} is set to an initial value, where:

$$C_{max}=-1$$

All elements of matrix C_{max} may be set equal to any number or be user defined. The value of −1 is one value that ensures that for every c_{max}(s,t), at least one c(s,t) will be greater than c_{max}(s,t) because the minimum of a correlation value is typically 0. In the present embodiment illustrated in FIG. **15**, C_{max} will be of the same size as SA and SB for every resolution because, as previously stated, the size of C_{max} is m/r×n/r.

In step **1508**, SA and SB are perspective transformed (warped) to the plane **2824** in FIG. **28** and stored in VA and VB, respectively, which can be visualized as frame captures **2825** and **2826** of the imaginary camera **2803** in FIG. **28** (**2825** and **2826** are shown as being located behind **2823** for the sake of illustration, but spatially, they are coincident with **2823**). It is understood and well known in the art that the two matrices VA and VB can be stored as one matrix utilizing a 3rd dimension of length 2 to store both frame buffers or stored in a variety of other ways.

Proceeding to step **1510**, a pixel-wise, normalized cross-correlation between VA and VB is performed and stored in C. It is understood in the art that substitutable functions may be performed, such as not normalizing the data before cross-correlation or correlating regions other than pixels.

In step **1512**, every element in C_{max} is compared to its respective element in C, and the corresponding element of Z is compared to determine if it lies within the range of acceptance. Hence, for every (s,t) in C, C_{max}, and Z:

$$\text{If } c_{max}(s,t) \le c(s,t) \text{ and } |z_{est}(s,t)-d| \le roa,$$

$$\text{then } c_{max}(s,t)=c(s,t) \text{ and } z(s,t)=d$$

In one embodiment of the invention, the above conditional statement can be implemented in software through the use of multiple "for" loops for variables s and t. It will be appreciated by one in the art that the above conditional statement can be implemented in a variety of other ways. Once the final iteration of step **1512** has been performed for a specific resolution, matrix Z will be the best estimate of d values for each pixel corresponding to the depth of each pixel of the object captured away from d_{min}.

Once all conditional statements are performed in step **1512**, d is incremented in step **1514**. Thus,

$$d=d+\Delta d$$

As previously discussed, Δd is a user defined value to increment d. Δd can be visualized as the distance for moving imaginary plane **2824** a Δd distance past the imaginary plane's **2824** previous position.

Proceeding to decision block **1516**, the procedure determines if the final cross-correlation **1510** of VA and VB and comparison step **1512** at a specific distance d has been performed. The process can be visually perceived in FIG. **28** as determining whether the imaginary plane **2824** has been moved far enough to be positioned behind imaginary plane **2828**. Mathematically, the process block determines if:

$$d \le d_{max}$$

If true, then the procedure has not finished all iterations of cross-correlating VA and VB at a specific resolution. Hence, the procedure loops back to step **1508**. If the above statement is false, then the procedure has finished cross-correlating VA and VB at a specific resolution. Therefore, the procedure flows to step **1518**.

In step **1518**, the sensor resolution divisor r is decreased. In the illustrated embodiment, r is decreased by:

$$r = \frac{r}{2}$$

Decreasing r leads to cross-correlation being performed at a higher resolution because SA and SB are the downsampling of PA and PB, respectively, by the magnitude of r. Thus, for example, if r is 8, then r/2 is 4. Hence, the size of SA and SB increases from, for example, 80×60 to 160×120 where PA and PB are of size 480×360. Other exemplary embodiments of decreasing r exist such as, but not limited to, a user defined array of specific r values or dividing by a different value other than 2. Dividing by 2 means that the frame captures PA and PB will be downsampled at a magnitude of factors of two (e.g., 2×, 4×, 8×, . . .).

Once r has been decreased, decision block **1520** is reached. Decision block **1520** determines whether r has been decreased to less than 1. As previously discussed, when r equals 1, no downsampling of PA and PB occurs. Therefore, in the current embodiment, when r is less than 1 (e.g., r=0.5), the previous cross-correlations were performed at the highest resolution (e.g., 640×480 if PA and PB are of size 640×480) and the attained Z matrix is the desired matrix to help render a 3D surface of the object. If r is greater than or equal to 1, then cross-correlation has not yet been performed at the highest resolution. Thus, the decision block determines if:

$$r \geq 1$$

If false, the procedure illustrated in FIG. **15** has completed and the flowchart is exited. If the above statement is true, then the procedure flows to step **1522**. If, as in one previously discussed embodiment r is decreased by an array of specific values in step **1518**, then one skilled in the art will notice that the logic of decision block **1518** will change to logic needed to determine if the last value in the array of specific values iterated through in block **1518** has been reached during the flow of the flowchart a number of times equal to the number of elements in the array. One skilled in the art will know how to change the logic of decision block **1520** depending on the logic of step **1518**.

In step **1522**, some of the variables are adjusted before cross-correlating at a higher resolution. The following variables are set as:

$$Z = \text{upsampled}(Z_{est})$$

$$Z_{est} = Z$$

$$\Delta d = \frac{\Delta d}{2}$$

$$d = d_{\min}$$

Z_{est} is upsampled and stored in Z. In order to determine the magnitude of upsampling, one skilled in the art will notice that the value of dividing r in step **1518** is the magnitude of upsampling. In the present embodiment, the magnitude of upsampling is 2. For example, Z_{est} (if currently of size 160×120) is upsampled to size 320×240 and stored in Z. The magnitude of upsampling can be determined by dividing the original value of r in step **1518** by the decreased value of r in step **1518**. If an array of defined r values is used for step **1518**, then the magnitude of upsampling can be determined from the array. As previously stated, upsampling is well known in the art and can be performed with a variety of filters and/or techniques including, but not limited to, bilinear filtering and bicubic filtering. Once Z has been stored, Z_{est} is set equal to Z (the result of upsampling Z_{est} for determining Z).

In addition to setting the values of Z and Z_{est}, Δd is decreased. In the current embodiment, Δd is divided by 2. Δd is decreased because when cross-correlating at higher resolutions, the increment of increasing d should be smaller in order to determine better z values for each pixel s,t. Visually, at higher resolution, the user will want the imaginary screen **2824** in FIG. **28** to move at smaller intervals between d_{min} and d_{max}. Δd may be decreased in any manner known in the art, such as, but not limited to, dividing by a different value or using Δd values defined by a user in an array the size of 1 greater than the number of iterations of step **1522** during flow of the flowchart.

Furthermore, d is reset to equal d_{min}. Visually, this can be illustrated, in FIG. **28**, as resetting the imaginary plane **2824** to the position of imaginary plane **2827**, which is a d_{min} distance from the imaginary camera **2803** along path **2813**.

Proceeding to step **1524**, roa is decreased. roa is decreased because prior cross-correlation at a lower resolution helps to determine a smaller range of acceptance for z values after cross-correlating at a higher resolution. In the current embodiment, roa is decreased by the following equation.

$$roa = \Delta d \times 10$$

For the first time performing step **1524**, Δd×10 should be less than the difference between d_{max} and d_{min}, which is the value roa was originally set to equal. 10 was found to be a good multiple of Δd for the current embodiment, but roa can be decreased in a variety of ways including, but not limited to, multiplying Δd by a different value than 10 and dividing roa by a value.

After decreasing roa, the procedure loops back to step **1504** to perform cross-correlation at a higher resolution, wherein the flowchart is followed until exiting the procedure at decision block **1520**.

FIG. **15** illustrates only one embodiment of the present invention. It will be known to someone skilled in the art that not all of the steps and processes illustrated in FIG. **15** must be followed. Instead, FIG. **15** should only be used as a guideline for implementing one embodiment of the present invention. Alternate embodiments may comprise, but are not limited to, using a larger Δd value for incrementing d and then performing a curve regression on the correlation values for each pixel s,t in order to determine a maxima of the curve and thus extrapolate a z value corresponding to the maxima. The above alternate embodiment may allow for faster processing as less pixel-wise, normalized cross-correlations need to be performed at each resolution.

Another embodiment of the present invention is illustrated in FIG. **29**. FIG. **29** illustrates the imaginary camera as envisioned in FIG. **28** as being at the position of one of the cameras **2901** or **2902**. In FIG. **29**, the imaginary camera can be envisioned as camera **2901**. Thus, the frame buffer **2823** visualized in FIG. **28** can be visualized as the sensor **2921** of the camera **2901**. Hence, in this alternate embodiment, the flowchart of FIG. **15** is changed such that VA=SA in step **1508**. Since the frame buffer is from the perspective of camera **2901**, the frame capture of **2901** does not need to be perspective converted (warped). All other aspects of the previously discussed embodiment of the invention are included in this alternate embodiment.

In a further embodiment of the present invention, more than two cameras are used for cross-correlation. FIG. **30** illustrates frame captures from three cameras being cross-correlated. The imaginary camera **2803** as visualized in FIG. **28** is visualized as one of the cameras **3001**, **3002**, or **3003**. In the specific alternate embodiment, the imaginary camera is visualized as the camera **3003**, where frame buffers **3025** and **3026** correspond to the warped frame captures of cameras **3001** and **3002**, respectively (for the sake of illustration, frame buffers **3025** and **3026** are shown as being located behind sensor **3023**, but they will be warped to a position that coincides spatially with sensor **3023**). Since multiple pairs of frames are cross-correlated, the flowchart of FIG. **15** is amended for the alternate embodiment such that, in step **1510**, matrix C is the average of the two correlations performed between frame buffers **3023** and **3025**, and between **3023** and **3026**. Thus, matrix C can be mathematically annotated as:

$$C = \frac{C_B + C_C}{2}$$

where CB is the pixel-wise, normalized cross-correlation correlation between a warped frame **3025** of camera **3001** and a frame **3023** of camera **3003** and CC is the pixel-wise, normalized cross-correlation between a warped frame **3026** of camera **3002** and a frame **3023** of camera **3003**. The alternate embodiment may also be expanded to include any number of cameras over 3, each with their capture frame warped to the position of frame **3023** of camera **3002** and then pixel-wise, normalized cross-correlated with frame **3023**, with all of the correlated results averaged to produce a value of C per pixel. Furthermore, the cross-correlations may be combined by means other than a simple average. In addition, the alternate embodiment may set the frame buffer perspective, as visualized as sensor **2823** in imaginary camera **2803** of FIG. **28**, outside of any of the existing cameras **3001-3003**. For example, an imaginary camera could be visualized as existing between cameras **3001** and **3002** such that the frame captures of all cameras would need to be warped to the perspective of the imaginary camera before cross-correlation. Other embodiments exist of the present invention, and the scope of the present invention should not be limited to the above examples and illustrations.

FIGS. **16***a* and **16***b* and **17** help illustrated visually what the correlation algorithm is doing. FIGS. **16***a* and **16***b* illustrate frame captures **1600** and **1610**. The frame captures **1600** and **1610** are perspective converted (warped) as an example of step **1508** in FIG. **15** at full resolution (i.e. when r=1). A user would be able to see with the naked eye that regions **1602**, **1604**, and **1606** correspond to regions **1612**, **1614**, and **1616**, respectively. Colors red and green have been used for illustration purposes only, as the capture can be performed in any format such as, for example, grayscale.

FIG. **17** is an example of the frames **1600** and **1610** being overlapped as frame **1700**, as may be an example of storing VA and VB as one matrix of arrays in step **1508** of FIG. **15**. A user would be able to see with the naked eye that the depth d is currently set such that region **1704** has a higher correlation than regions **1702** and **1706** (region **1604** and **1614** are closer in to each other than are the other region pairs). The color yellow (red+green) illustrates high correlation between overlapping pixels at a depth d while high concentrations of red and/or green color illustrates lower correlation between overlapping pixels at a depth d. Color yellow has been used for illustration purposes only.

FIG. **18** is an example of the graph for determining z(s,t) (**1803**) for a specific pixel s,t at a specific resolution (identified by window size **1801**). The range of acceptance (roa) **1804** (which had been determined by prior correlations at lower resolution) limits the values that z can equal so as to remove false peaks **1806** of correlation values from consideration in order to determine the correct correlation value corresponding to a correct d value for pixel s,t. In the example, mark **1807** identifies the z **1803** that corresponds to the true

peak **1805**. False peaks can result from any number of reasons, including noise in the captured signal, random regions with similar patterns, or because the area being captured is quite oblique to the capturing camera and produces a distorted image. Thus, the successive reduction of resolution, illustrated by the process shown in FIG. **15** is very effective eliminating false peaks from consideration when determining the correct z value in the capture reconstruction. It will be recognized by those skilled in the art that FIG. **18** is only an illustration of the pixel-wise, normalized cross-correlation and comparison process of steps **1510** and **1512** of FIG. **15** and should not be considered as a limitation of the determination of values for matrix Z.

The Z matrix output from FIG. **15** can then be rendered into a 3D surface. FIG. **19** is a 2D representation of the 3D surface **1900** created by correlating the frames represented in FIGS. **9***a* and **9***b*. It should be noted that the "splotchy" or "leathery" appearance of the 3D surface **1900** is related to the low resolution of the cameras used to capture the frames of the performer (e.g., 0.3 Megapixels).

The processes just described for determining the surface of a captured object can be used for a single frame, or it can be re-applied successively for multiple frames of an object in motion. In this case, if the reconstructed images such as that of FIG. **19** are played back in succession, a 3D animation of the captured surface will be seen. In an alternative embodiment, the same process is reapplied to successive frames of an object that is not moving. In that case, the resulting reconstructed z values can be averaged among the frames so as to reduce noise. Alternatively, other weightings than an averaging can be used, including for example, using the z value at each pixel which was derived with the highest correlation value amongst all the reconstructed frames.

During motion capture, some regions of a performer may be captured by only one camera. When the system of one embodiment correlates the region with other regions from cameras with overlapping fields of view, the correlation determines that the region is distinct (i.e. it does not have a high correlation with any other captured region) and the system can then establish that the region is visible but its position can not be reconstructed into a 3D surface. FIG. **19** illustrates at **1902** an artifact created on the 3D surface **1900** by having only one camera capture a region (i.e. this object was captured by 2 cameras, one above the head and one below the head; the top of the nose obstructed the camera above the head from having visibility of the nostrils, so only the camera below the head had visibility of the nostrils). In addition, artifacts and errors may occur where the region is at an angle too oblique in relation to the cameras' optical axis (as shown by the artifact **1904**, a region oblique to both cameras) or where the pattern is out of view of all cameras in the motion capture system (as shown by the artifact **1906**).

For regions that may be out of view of any camera of the motion capture system, the random patterns on all surfaces desired to be captured may be captured and stored by the motion capture system before initiating a motion capture sequence. To capture and store the random pattern, the performer (with any other objects desired to be captured) stands in such a way that each region to be captured is visible to at least one camera. The captured patterns are stored in a database in memory (e.g., RAM or hard disk). If the region is only seen by one camera, then the pattern stored is the pattern captured by that one camera. If it is seen by multiple cameras, then the views of the region by each of the multiple cameras is stored as a vector of patterns for that region. In some cases, it is not possible to find one position where the random pattern areas on the performer and all other objects to be captured can be seen by at least one camera. In this case, the performer and/or objects are repositioned and captured through successive frames until all random pattern areas have been captured by at least one camera in at least one frame. Each individual frame has its captured patterns correlated and stored as described previously in this paragraph, and then correlations are performed among all of the stored patterns from the various frames. If a region of one frame is found to correlate with the region of another, then each frame's images of the region (or one or both frame's multiple images, if multiple cameras in one or both frames correlate to the region) is stored as a vector of patterns for that region. If yet additional frames capture regions which correlate to the said region, then yet more images of that region are added to the vector of images. In the end, what is stored in the database is a single vector for each random pattern area of every surface desired to be captured by the system.

Note that the size of the areas analyzed for correlation in the previous paragraph is dependent on the desired resolution of the capture and the achievable resolution of the cameras, given their distance from the objects to be captured. By moving the cameras closer to the objects to be captured and by using higher pixel resolution cameras, smaller areas can be captured and correlated. But, higher resolutions will result in higher computational overhead, so if an application does not require the full achievable resolution of the system, then lower resolution can be used by simply correlating the captured regions at a lower resolution. Or, to put it another way, random patterns can be correlated whether they are correlated at the full resolution of the cameras or at a lower resolution. In one embodiment of the invention, the desired capture resolution can be specified by the user.

Once the region database has been created as described previously, the motion capture session can begin and the motion of a performance can be captured. After a sequence of frames of the motion of a performance is captured, for each given frame, all of the regions stored in the region database are correlated against the captured regions. If a given stored region does not correlate with any of the captured regions (even regions captured by only a single camera), then the system will report that the given region is out of view of all cameras for that frame.

A 3D modeling/rendering and animation package (such as Maya from Alias Systems Corp. of Toronto, Ontario Canada) can link a texture map or other surface treatments to the output of the motion capture system for realistic animation. For example, if the character to be rendered from the motion capture data has a distinctive mole on her cheek, the texture map created for that character would have a mole at a particular position on the cheek. When the first frame is taken from the motion capture system, the texture map is then fitted to the surface captured. The mole would then end up at some position on the cheek for that frame captured from the performer, and the motion capture system would identify that position by its correlation to its region database.

The motion capture system of the present invention can correlate successive time interval frame captures to determine movement of the performer. In one embodiment of the present invention, the distance and orientation between correlated regions of the random pattern captured in successive time frames are measured to determine the amount and direction of movement. To illustrate, FIGS. **26***a* and **26***b* are frames **2600**, **2610** captured by a camera separated by ⅛th of a second in time. The data of the frames **2600**, **2610** are colored red and green, respectively, for illustrative purposes only. The frame captures can be performed in any color, grayscale or any capture technique known in the art.

In FIG. **27**, the frame **2700** is the overlapping of frames **2600** and **2610** from FIGS. **26***a* and **26***b*, respectively. Uniformly yellow areas of frame **2700** are regions of the random pattern that appear in the same position in both frames **2600** and **2610** (i.e. they do not move in the ⅛th-second time interval). Where areas of red and/or green in frame **2700** exist, the random pattern moved in the time interval between the capture of the frames **2600** and **2610**. For example, region **2702** is uniformly yellow and thus represents little or no movement between corresponding spots **2602** and **2612**. In contrast, region **2704** comprises a pair of red and green spots corresponding to a green spot **2604** and a red spot **2614**, thus representing more movement during the ⅛th-second time interval from frame **2600** to frame **2610** than that of region **2702**. The colors of red, green, and yellow for frame **2700** are for illustrative purposes only.

Thus utilizing the recognition of movement in successive frame captures, in one embodiment of the invention, the 3D modeling/rendering/and animation package can link the texture map or other surface treatments to the recognized directions and distances of movement for regions of the random pattern during successive frame captures of the motion capture system to achieve realistic animation.

Utilizing the previous example of the mole within the 3D texture rendered by the package, in a successive new frame where the area of the cheek with the mole would move, that region of the 3D texture with the mole would also move. For example, suppose the mole was located at spot **2604** during frame time **2600**. The motion capture system would correlate the region with the region database and would identify that the region is now at a new position **2614** on the new surface that it outputs for the new frame **2610**. This information would be used by the 3D modeling/rendering and animation package, and the package would move the mole on the texture map for the cheek to the new position **2614**. In this manner, the texture map would stay locked to the changing surface features during the performance.

The precise frame-to-frame surface region tracking described in the previous paragraph would be very difficult to achieve with an arbitrary position on the performer (e.g. the performer's face) using prior art motion capture systems. With a retroreflective marker-based system (such as that used on the face shown in FIGS. **2***a* and **2***b*), the only positions on the performers that can be tracked precisely are those which happen to be positions containing a marker. With a line-based system (such as that shown in FIG. **4**), the only positions that can be tracked precisely are those at the intersections of the lines, and only approximately at positions on the lines between the intersections. And with a system using patterns projected on the face, no positions can be tracked precisely, unless some markers are applied to the face, and then the tracking is no better than a marker- or line-based system. Thus, this invention is a dramatic improvement over prior-art systems in tracking positions on deformable surfaces (such as a face) while capturing the surfaces at high resolution.

Although the present invention may be utilized to capture any surface or object with an applied random pattern, one application for which the invention is particularly useful is capturing the motion of moving fabric. In one embodiment, a random pattern is applied to a side of the cloth or article of clothing. In another embodiment of the present invention, a random pattern is applied to both sides of a cloth or article of clothing. In yet another embodiment, each side of the cloth is coated with a random pattern of a different color paint (in the case of phosphorescent paint, a paint that phosphoresces in a different color) in relation to the paint applied to the other side in order to better differentiate the two sides.

FIGS. **20***a* and **20***b* illustrate captured frames with external visible light of a cloth with an applied random pattern of phosphorescent paint (the phosphorescent paint as applied is largely transparent in visible light, but where it is especially dense, it can be seen in as a smattering of yellow on the cloth's blue and lavender paisley print pattern). FIGS. **21***a* and **21***b* illustrate the captured frames, without external visible light, corresponding to the captured frames of FIGS. **20***a* and **20***b*, respectively. FIGS. **21***a* and **21***b* are colored red and green, respectively, for descriptive purposes only in the forthcoming description of FIG. **22**. For the present invention, the frames may be captured in any color or in grayscale.

The motion capture system of the present invention handles cloth in the same way it handles a performer. In one embodiment, prior to a motion capture session, the cloth with the random pattern applied is unfolded and held in such a way that each region on both sides of the cloth can be captured by at least one camera. A region database is then created for all regions on both sides of the cloth.

During the capture session, for each frame, the regions that are visible to at least 2 cameras are correlated and their surface positions are output from the motion capture system along with the regions in the region database that correlate to the regions on the surface, as illustrated in FIG. **15**. Therefore, the 3D modeling/rendering and animation package is able to keep a texture map locked to the surface that is output by the motion capture system.

In addition, correlation can be performed on subsequent time frame captures from the same camera in order to track points on the cloth as they move. For example, FIG. **22** illustrates the overlapping of FIGS. **21***a* and **21***b*, which were captured at different times. Regions **2102** and **2106** of FIG. **21***a* are correlated to regions **2112** and **2116** of FIG. **21***b*, respectively, as shown by regions **2202** and **2206**/**2216**, respectively, in FIG. **22**. Region **2104** has no mated region in FIG. **21***b* because the region is hidden from the camera's view by the fold in the cloth, as shown by corresponding region **2204** in FIG. **22** in red, for which there is no mated green region. For illustrative purposes, the uniformly yellow regions of the frame in FIG. **22** correspond to non-moving regions of the frames in FIGS. **21***a* and **21***b* and the regions of FIG. **22** that are either a medley of red/green/yellow or are of a solid red or green color indicate areas that have moved from the frame captured in FIG. **21***a* and the frame captured in FIG. **21***b*. Thus, movement can be noticed because of the shifting of region **2106**/**2206** to region **2116**/**2216** and the disappearance of region **2104** of the cloth between FIGS. **21***a* and **21***b*, leaving only a solid red region **2204**.

The cloth capture techniques described herein can also facilitate a simulated cloth animation, which may be created by cloth animation packages such as those available within Maya from Alias Systems Corp. of Toronto, Ontario Canada. A performer may wear a garment similar to the one being simulated by the cloth animation package. The performer may then perform movements desired by the animation director while being captured by the motion capture system. The motion capture system of the present invention then outputs the cloth surface each frame, as previously described, along with a mapping of the position of the regions on the cloth surface (as correlated with the previously captured region database of the entire surface of the cloth). The data is then used by the cloth simulation package to establish constraints on the movement of the cloth.

For example, suppose an animation director has a character in an animation that is wearing a cloak. The animation director wishes the cloak to billow in the wind with a certain dramatic effect. Prior art cloth simulation packages would require the animation director to try establish physical conditions in the simulation (e.g. the speed, direction and turbulence of the wind, the weight and flexibility of the cloth, the mechanical constraints of where the cloth is attached to the performer's body, the shape and flexibility of any objects the cloth comes into contact with, seams or other stiff elements in the cape, etc.). And, even with very fast computers, a high-resolution cloth simulation could easily take hours, or even days, to complete, before the animation director will know whether the resulting billowing cloak look corresponds to the dramatic effect he or she is trying to achieve. If it doesn't, then it will be a matter of adjusting the physical conditions of the simulation again, and then waiting for the simulation to complete again. This adds enormous cost to animations involving cloth animation and limits the degree of dramatic expression.

Given the same example as the previous paragraph, but using one embodiment of the present invention (i.e. applying a random pattern of paint to the cloth and capturing it as described previously), if the animation director desires a character to have a cloak to billow in the wind with a certain dramatic effect, then the animation director just attaches a cloak of the desired weight and flexibility on a performer in the environment of the scene, and then adjusts a fan blowing on the performer until the billowing of the cloak achieves the desired dramatic effect. Then, this billowing cloak is captured using the techniques previous described. Now, when the cloth for the cloak is simulated by the cloth simulation package, the cloth simulation package can be configured with only very approximate physical conditions, but to only allow the cloak to move within some range of motion (e.g. plus or minus 5 pixels in x, y, or z) relative to the motion of the captured cloak. Then, when the cloth animation package simulates the cloak, its motion will very closely follow the motion of the captured cloak due to the constrained motion, and the animation director will achieve the desired dramatic effect. Thus, compared to prior art cloth simulation techniques, the method of the present invention dramatically reduces the time and effort needed to achieve a desired dramatic effect with simulated cloth, which allows the director far more creative control. In one embodiment of the present invention (as illustrated in the preceding example), the captured cloth surface may be used to establish a general set of boundaries for the cloth simulation, so that each region simulated cloth may not veer further than a certain distance from each region of the captured cloth. In another embodiment, the captured cloth surface may be used for rigid parts of a garment (e.g. the rigid parts like the collar or seams), and the simulated cloth may be used for the non-rigid parts of the garment (e.g., the sleeves). Likewise, another embodiment is that the captured cloth surface may be used for the non-rigid parts of the garment (e.g. the sleeves), and the simulated cloth may be used for the rigid parts of a garment (e.g., collar, seams).

The present invention is not constrained to capturing or using only specific portions of a captured cloth surface. The captured cloth surface can be used to fully specify the cloth surface for an animation, or it can be used partially to specify the cloth surface, or it can be used as a constraint for a simulation of a cloth surface. The above embodiments are only for illustrative purposes.

Camera Positioning for a Motion Capture System

Because motion capture with random patterns allows for higher resolution capture, the system may employ camera positioning which is different from existing camera configurations in current motion capture systems. The unique configuration yields motion capture at higher resolution than motion capture produced by previously existing camera configurations with the same type of cameras. Another of the many advantages of the unique camera configuration is that large-scale camera shots can capture relatively low-resolution background objects and skeletal motion of performers and still motion capture at high resolution critical motions of performers such as faces and hands.

FIG. **23** illustrates one embodiment of the camera positioning for motion capturing the performer **2302**. In the current embodiment, the performer is wearing a crown **2400** with markers attached (e.g., **2406**, **2408**). FIG. **24** shows the markers of the crown **2400** worn by the performer **2302** at varying heights from one another. For example, marker **2406** is lower than marker **2408**, which is lower than marker **2410**. With varying heights placed on the markers, the motion capture system can determine in which direction the performer **2302** is orientated. Orientation can also be determined by other embodiments of the present invention, such as markers placed on the body, or identifiable random patterns applied to certain regions of the performer **2302**.

In FIG. **24**, a random pattern is applied to the entire performer **2302**, but alternate embodiments have the random pattern applied to a portion of the performer **2302**, such as the face. In an additional embodiment, filming without motion capture using the unique camera configuration allows higher resolution capture of portions of a larger shot (e.g., close up capture of two performers having a dialogue in a larger scene).

In FIG. **23**, a ring of cameras (e.g., cameras **2310** and **2312**) close to the performer **2302** is used. In one embodiment of the present invention, the cameras capture the areas of the performer **2302** for which a high resolution is desired. For example, a random pattern applied to the face of a performer **2302** may be captured at a high resolution because of the close proximity of the cameras **2310-2312**. Any number of cameras can circle the performer **2302**, and the cameras can be positioned any reasonable distance away from the performer **2302**.

FIG. **25** illustrates the performer **2302** encircled by the ring of cameras **2310-2312** from FIG. **23**. In one embodiment of the present invention, persons control the cameras circling the performer **2302**. For example, person **2504** controls camera **2310**. Human control of a camera allows the person to focus on important and/or critical areas of the performer **2302** for high resolution motion capture. In alternate embodiments, the cameras may be machine-controlled and/or stabilized.

Referring back to FIG. **23**, a second ring of cameras (e.g., cameras **2318-2322**) encircles the first ring of cameras and the performer **2302**. Any number of cameras may form the second ring of cameras **2318-2322**. In one embodiment, the outer ring of cameras capture wide shots including a lower resolution capture of the performer **2302** than the cameras **2310-2312**, which are in closer proximity to the performer **2302**.

In order to create a wide shot with a high resolution capture of the performer **2302**, the motion captures of the inner ring of cameras **2310-2312** must be integrated into the wide captures of the outer ring of cameras **2318-2322**. In order to integrate the captures, the Data Processing Unit **610** of the motion capture system must know the camera position and orientation for each of the cameras comprising the inner ring of cameras **2310-2312**. Determining the positioning of the cameras comprising the inner ring may be of more importance and difficulty with the use of persons **2504** to control the cameras **2310-2312** because of random human movement.

In one embodiment, markers (e.g., **2314** and **2316**) are attached to the cameras **2310-2312**. The markers **2314-2316** are captured by the outer ring of cameras **2318-2322**. The position and orientation of the markers **2314-2316** identified in the frame captures of the outer ring of cameras **2318-2322** allow the data processing unit to determine the position and orientation of each camera of the inner ring of cameras **2310-2312**. Therefore, the Data Processing Unit **610** can correlate the desired frame captures from an inner ring camera with the frame captures of an outer ring camera so as to match the orientation and positioning of the inner ring camera's frame captures with the outer ring camera's frame captures. In this way, a combined capture of both high-resolution and low-resolution captured data can be achieved in the same motion capture session.

FIG. **25** illustrates the cameras' field of view (e.g., camera **2310** has field of view **2510** and camera **2312** has field of view **2512**). When two cameras have overlapping fields of view, 3D rendering can be performed on the streams of frame captures (as previously discussed).

In order to correlate images as described in the process illustrated in FIG. **15**, the data processing unit must know the orientations and positions of the two cameras. For example, the Data Processing Unit **610** may have to correct the tilt of a frame because of the person controlling the camera holding the camera at a tilted angle in comparison to the other camera. In one embodiment, the position and orientation of the markers attached to the cameras are used by the Data Processing Unit **610** to calculate corrections to offset the orientation differences between the two cameras. The Data Processing Unit **610** can also correct the difference in distance the two cameras are positioned away from the performer **2302**.

Once corrections are performed by the Data Processing Unit **610**, the Data Processing Unit **610** may correlate the streams of capture data from the two cameras in order to render a 3D surface. Correlations can also be performed on the streams of frame captures from two outer ring cameras **2318-2322**, and then all correlations can be combined to render a volume from the captures. Correlations can then be performed on the sequence of volumes to render the motion of a volume.

In an alternative embodiment, the outer ring of cameras **2318-2322** are prior art retroreflective marker-based motion capture cameras and the inner ring of cameras **2310-2312** are random-pattern motion capture cameras of the present invention. In this embodiment, when phosphorescent random pattern paint is used, the LED rings around the marker-based cameras **2318-2322** (shown as LED rings **130-132** in FIG. **1**) are switched on and off synchronously with the light panels (e.g. **608** and **609** of FIG. **6**) so that the outer ring marker capture occurs when the LED rings **130-132** are on (e.g. during interval **713** of FIG. **7**) and the inner ring random pattern capture occurs when the LED rings **130-132** are off (e.g. during interval **715** of FIG. **7**).

In another embodiment, the outer ring of cameras **2318-2322** are prior art marker-based motion capture cameras and the inner ring of cameras **2310-2312** are random-pattern motion capture cameras of the present invention, but instead of using retroreflective balls for markers, phosphorescent balls are used for markers. In this embodiment, when phosphorescent random paint is used, the inner and outer cameras capture their frames at the same time (e.g. interval **715** of FIG. **7**).

In another embodiment, utilizing either of the capture synchronization methods described in the preceding two paragraphs, the outer ring of cameras **2318-2322** capture lower-resolution marker-based motion (e.g. skeletal motion) and the inner ring of cameras **2310-2312** capture high-resolution surface motion (e.g. faces, hands and cloth). In one embodiment the outer ring of cameras **2318-2322** are in fixed positions (e.g. on tripods) while the inner ring of cameras **2310-2312** are handheld and move to follow the performer. Markers **2314-2316** on the inner ring cameras are tracked by the outer ring cameras **2318-2322** to establish their position in the capture volume (x, y, z, yaw, pitch roll). This positioning information is then used by the software correlating the data from the inner ring cameras **2310-2312** using the methods described above (e.g. FIG. **15**). Also, this positioning information is used to establish a common coordinate space for the marker-based motion data captured by the outer ring cameras **2318-2322** and the random-pattern based motion data captured by the inner ring cameras **2310-2312** so that the captured objects can be integrated into the same 3D scene with appropriate relative placement.

In another embodiment, using either outer- and inner-ring synchronization method, an outer ring of marker-based cameras **2318-2322** tracks the crown of markers **2400** and determines the position of the markers in the capture volume, and an inner ring of random pattern-based cameras **2310-2310** determines their position relative to one another and to the crown **2400** by tracking the markers on the crown **2400**. And in yet another embodiment, the outer ring of marker-based cameras **2318-2322** tracks both the crown of markers **2400** and markers **2314-2316** on the inner ring of random pattern-based cameras **2310-2312**, and determines the position of whatever markers are visible, while the inner ring of cameras **2310-2312** tracks whatever markers on the crown **2400** are visible. Both methods (tracking the crown of markers **2400** and tracking the markers on the cameras) are used to determine the position of the inner cameras **2310-2312** in the capture volume, so that if for a given frame one method fails to determine an inner camera's **2310-1212** position (e.g. if markers are obscured) the other method is used if it is available.

In an alternate embodiment of the camera positioning, each group of cameras may be placed in an arc, line, or any other geometric configuration, and are not limited to circles or circular configurations. In addition, more than two groups of cameras may be used. For example, if the application requires it, four rings of cameras may be configured for the motion capture system.

Hardware and/or Software Implementation of the Present Invention

Embodiments of the invention may include various steps as set forth above. The steps may be embodied in machine-executable instructions which cause a general-purpose or special-purpose processor to perform certain steps. Various elements which are not relevant to the underlying principles of the invention such as computer memory, hard drive, input devices, have been left out of the figures to avoid obscuring the pertinent aspects of the invention.

Alternatively, in one embodiment, the various functional modules illustrated herein and the associated steps may be performed by specific hardware components that contain hardwired logic for performing the steps, such as an application-specific integrated circuit ("ASIC") or by any combination of programmed computer components and custom hardware components.

Elements of the present invention may also be provided as a machine-readable medium for storing the machine-executable instructions. The machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of machine-readable media suitable for storing electronic instructions. For example, the present invention may be downloaded as a computer program which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Throughout the foregoing description, for the purposes of explanation, numerous specific details were set forth in order to provide a thorough understanding of the present system and method. It will be apparent, however, to one skilled in the art that the system and method may be practiced without some of these specific details. Accordingly, the scope and spirit of the present invention should be judged in terms of the claims which follow.

What is claimed is:

1. A method comprising:

applying a random pattern of material to specified regions of a performer's face, body and/or clothing;

capturing sequences of images of the random pattern with a first plurality of cameras as the performer moves and/or changes facial expressions during a motion capture session;

correlating the random pattern across two or more images captured from two or more different cameras to create a 3-dimensional surface of the specified regions of the performer's face, body, and/or clothing;

generating motion data representing the movement of the 3-dimensional surface across the sequence of images;

strobing a light source on and off, the light source charging the random pattern when on; and

strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture the sequences of images of the random pattern ("glow frames") as the performer moves or changes facial expressions during a performance, wherein the shutters of the first plurality of cameras are open when the light source is off and the shutters are closed when the light source is on.

2. The method as in claim **1** wherein the material is phosphorescent paint.

3. The method as in claim **1** further comprising:

strobing the shutters of a second plurality of cameras synchronously with the strobing of the light source to capture images of the performer ("lit frames"), wherein the shutters of the second plurality of cameras are open when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

4. The method as in claim **3** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

5. The method as in claim **3** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

6. The method as in claim **3** wherein cameras capturing the lit frames have a sensitivity which is different from cameras capturing the glow frames.

7. The method as in claim **3** wherein color cameras are used to capture the lit frames and grayscale cameras are used to capture the glow frames.

8. The method as in claim **7** wherein the grayscale cameras have a relatively higher sensitivity than the color cameras.

9. The method as in claim **7** wherein two different synchronization signals are used to control the shutters of the color and grayscale cameras.

10. The method as in claim **9** wherein the different synchronization signals are 180 degrees out of phase.

11. The method as in claim **1** wherein the light source comprises a light emitting diode (LED) array.

12. The method as in claim **1** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

13. The method as in claim **12** wherein the first period of time is longer than the second period of time.

14. The method as in claim **1** wherein the camera shutters are controlled by synchronization signals from a computer system.

15. The method as in claim **1** further comprising:

opening the shutters for a first period of time when the light source is on; and

opening the shutters for a second period of time when the light source is off;

wherein the first and second periods of time are unequal.

16. The method as in claim **1** wherein strobing the shutters further comprises:

opening the shutters for a period of time when the light source is on to capture images of the performers face, body, and/or clothing ("lit frame").

17. The method as in claim **16** wherein after being opened to capture a lit frame, the shutters are closed and then opened again when the light source is off to capture a glow frame, and then closed and then opened again when the light source is on to capture the next lit frame.

18. The method as in claim **16** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time wherein the first period of time is not equal to the second period of time.

19. The method as in claim **18** further comprising:

opening the shutters for a relatively shorter period of time when the light source is on; and

opening the shutters for a relatively longer period of time when the light source is off.

20. The method as in claim **16** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

21. The method as in claim **16** further comprising:

alternating sensitivity, of the cameras between capturing the lit frames and the glow frames.

22. The method as in claim **1** wherein correlating the random pattern further comprises:

performing a first correlation at a first resolution for each of the two or more images using overlapping fields of view of the two or more cameras.

23. The method as in claim **22** wherein correlating the random pattern further comprises:

performing a second correlation at a second resolution for each of the two or more images to render the 3-dimensional surface, wherein the first resolution is lower than the second resolution.

24. The method as in claim **1** wherein the two or more images are captured at substantially the same point in time.

25. The method as in claim **1** wherein the two or more images are captured in sequence at different points in time.

26. The method as in claim **1** further comprising:

capturing a series of images of the performer's face, body, and/or clothing; and

using the images as a texture map corresponding to regions of the random pattern.

27. The method as in claim **1** wherein applying the random pattern comprises:

applying phosphorescent material to a sponge; and

applying the sponge upon the performer's face, body, and/or clothing.

28. The method as in claim **1** wherein applying the random pattern comprises:

spraying the random pattern of material on the performer's face, body, and/or clothing with an airbrush.

29. The method as in claim **1** wherein applying the random pattern comprises:

applying paint to the performer's face, body, and/or clothing through a stencil.

30. The method as in claim **1** wherein applying the random pattern comprises:

flicking a wire brush containing paint such that droplets of paint are splattered onto the surface to be captured.

31. The method as in claim **1** wherein the random pattern is applied with paint viewable in visible light.

32. The method as in claim **31** wherein visible light is used in capturing the images.

33. A method comprising:

applying a random pattern of phosphorescent material to specified regions of a performer's face, body and/or clothing;

strobing a light source on and off, the light source charging the random pattern when on; and

strobing the shutters of the first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the random pattern ("glow frames") as the performer moves or changes facial expressions during a performance, wherein the shutters of the first plurality of cameras are open when the light source is off and the shutters are closed when the light source is on.

34. The method as in claim **33** wherein the phosphorescent material is phosphorescent paint.

35. The method as in claim **33** further comprising:

tracking the motion of the phosphorescent paint over time; and

generating motion data representing the movement of the performer's face and/or body using the tracked movement of the phosphorescent paint.

36. The method as in claim **33** wherein the phosphorescent paint is applied as a series of curves on the performer's face.

37. The method as in claim **33** wherein the phosphorescent paint is applied as a series of markers at specified areas of the performer's body.

38. The method as in claim **33** further comprising:

strobing the shutters of a second plurality of cameras synchronously with the strobing of the light source to capture images of the performer ("lit frames"), wherein the shutters of the second plurality of cameras are open when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

39. The method as in claim **38** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

40. The method as in claim **38** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

41. The method as in claim **38** wherein cameras capturing the lit frames have a sensitivity which is different from cameras capturing the glow frames.

42. The method as in claim **38** further comprising:

opening the shutters for a first period of time when the light source is on; and opening the shutters for a second period of time when the light source is off;

wherein the first and second periods of time are unequal.

43. The method as in claim **38** wherein color cameras are used to capture the lit frames and grayscale cameras are used to capture the glow frames.

44. The method as in claim **43** wherein the grayscale cameras have a relatively higher sensitivity than the color cameras.

45. The method as in claim **43** wherein two different synchronization signals are used to control the shutters of the color and grayscale cameras.

46. The method as in claim **45** wherein the different synchronization signals are 180 degrees out of phase.

47. The method as in claim **33** wherein the light source comprises a light emitting diode (LED) array.

48. The method as in claim **33** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

49. The method as in claim **48** wherein the first period of time is longer than the second period of time.

50. The method as in claim **33** wherein the camera shutters are controlled by synchronization signals from a computer system.

51. The method as in claim **33** wherein strobing the shutters further comprises:

opening the shutters for a period of time when the light source is on to capture images of the performers face and/or body.

52. The method as in claim **51** wherein after being opened to capture a lit frame, the shutters are closed and then opened again when the light source is off to capture the next glow frame, and then closed and then opened again when the light source is on to capture the next lit frame.

53. The method as in claim **52** further comprising:

generating motion data representing the movement of the 3-dimensional surface across the sequence of images.

54. The method as in claim **51** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time wherein the first period of time is not equal to the second period of time.

55. The method as in claim **54** further comprising:

opening the shutters for a relatively shorter period of time when the light source is on; and

opening the shutters for a relatively longer period of time when the light source is off.

56. The method as in claim **51** further comprising:

separating the lit frames from the glow frames to generate two separate sets of image data.

57. The method as in claim **51** further comprising:

alternating sensitivity, of the cameras between capturing the lit frames and the glow frames.

58. The method as in claim **33** further comprising:

correlating the random pattern across two or more images captured from the first plurality of cameras to create a 3-dimensional surface of the specified regions of the performer's face, body, and/or clothing.

* * * * *

Exhibit 4

US007548272B2

(12) **United States Patent**
Perlman et al.

(10) **Patent No.: US 7,548,272 B2**
(45) **Date of Patent: Jun. 16, 2009**

(54) **SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE USING PHOSPHOR APPLICATION TECHNIQUES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 449 days.

(21) Appl. No.: **11/449,127**

(22) Filed: **Jun. 7, 2006**

(65) **Prior Publication Data**

US 2007/0285514 A1 Dec. 13, 2007

(51) **Int. Cl.**

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H04N 5/225	(2006.01)
H04N 5/228	(2006.01)
H04N 5/222	(2006.01)

(52) **U.S. Cl.** **348/371**; 348/77; 348/169; 348/208.14; 348/370

(58) **Field of Classification Search** 348/370, 348/371, 218.1, 77, 157
See application file for complete search history.

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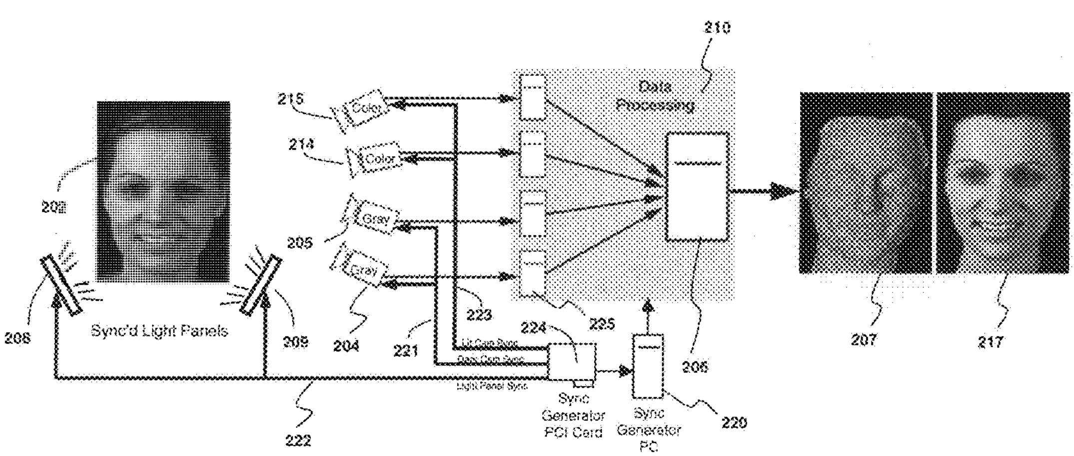
Primary Examiner—David L Ometz
Assistant Examiner—Richard M Bemben
(74) *Attorney, Agent, or Firm*—Blakely Sokoloff Taylor & Zafman LLP

(57) **ABSTRACT**

A system and method are described for performing motion capture on a subject. For example, a method according to one embodiment of the invention comprises: mixing phosphorescent makeup with a makeup base; applying the mixture of phosphorescent makeup and makeup base to surface regions of a motion capture subject; strobing a light source on and off, the light source charging phosphor within the phosphorescent makeup when on; and strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture images of the phosphorescent makeup, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

24 Claims, 27 Drawing Sheets
(6 of 27 Drawing Sheet(s) Filed in Color)



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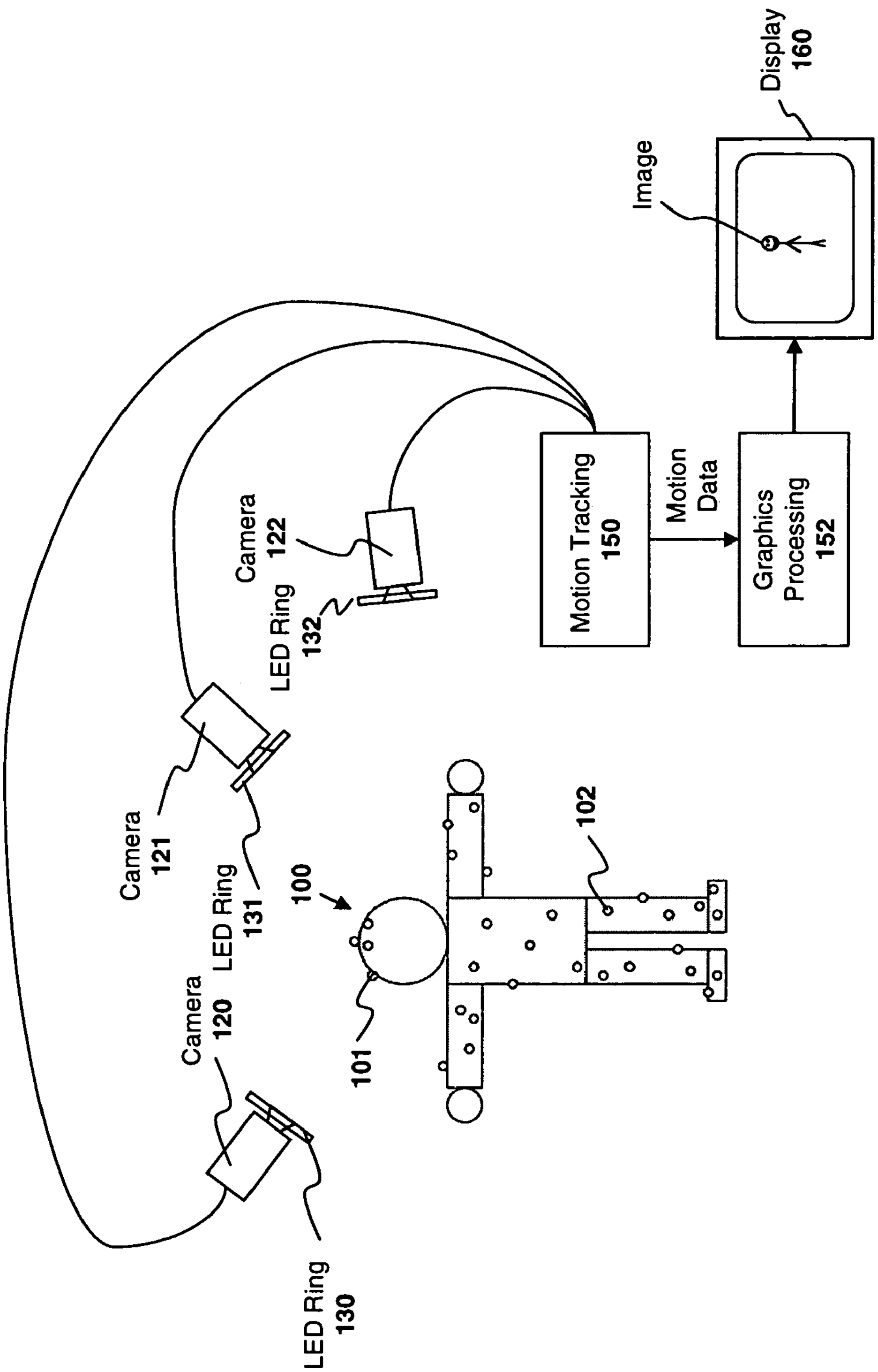
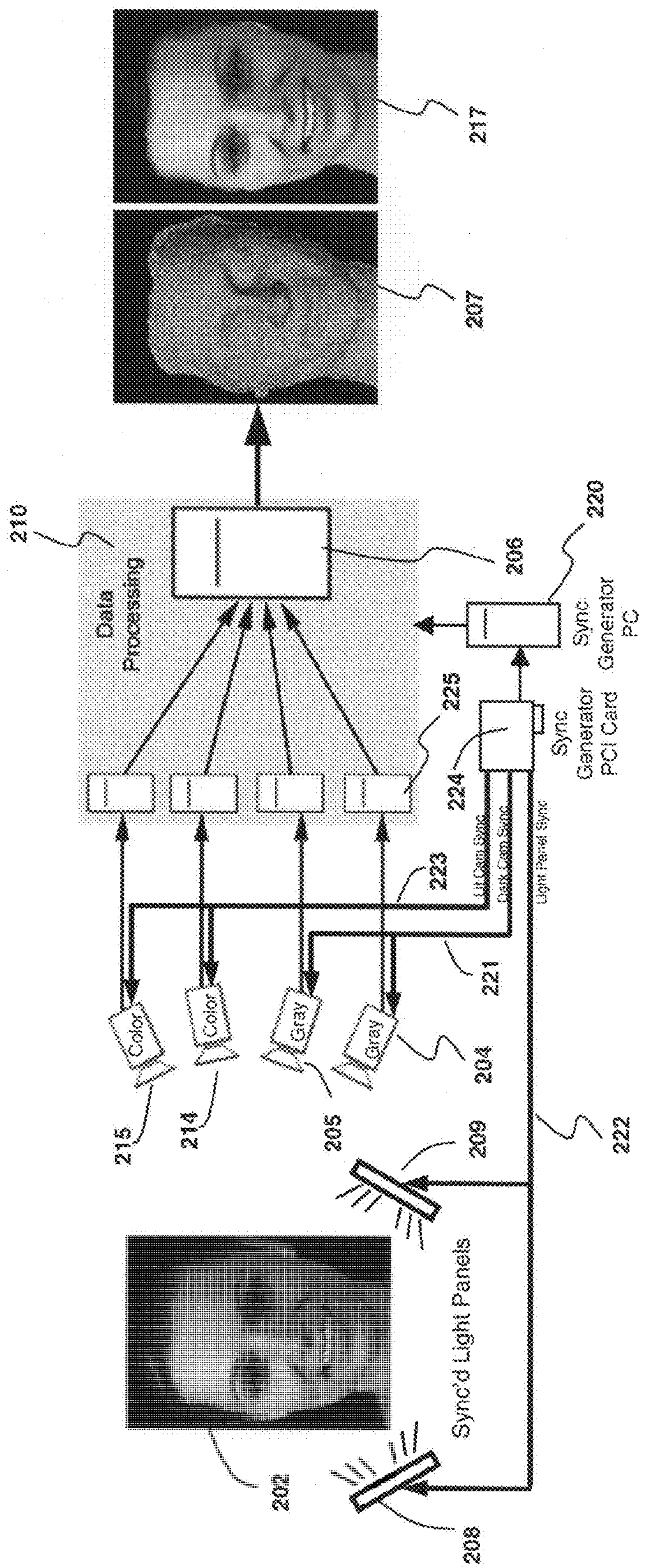


Fig. 1
(prior art)



217
207
210
Data Processing
206
220
Sync Generator PC
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Sync Generator PCI Card
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223
Lit Cam Sync
Dark Cam Sync
Light Panel Sync
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Color
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Gray
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214
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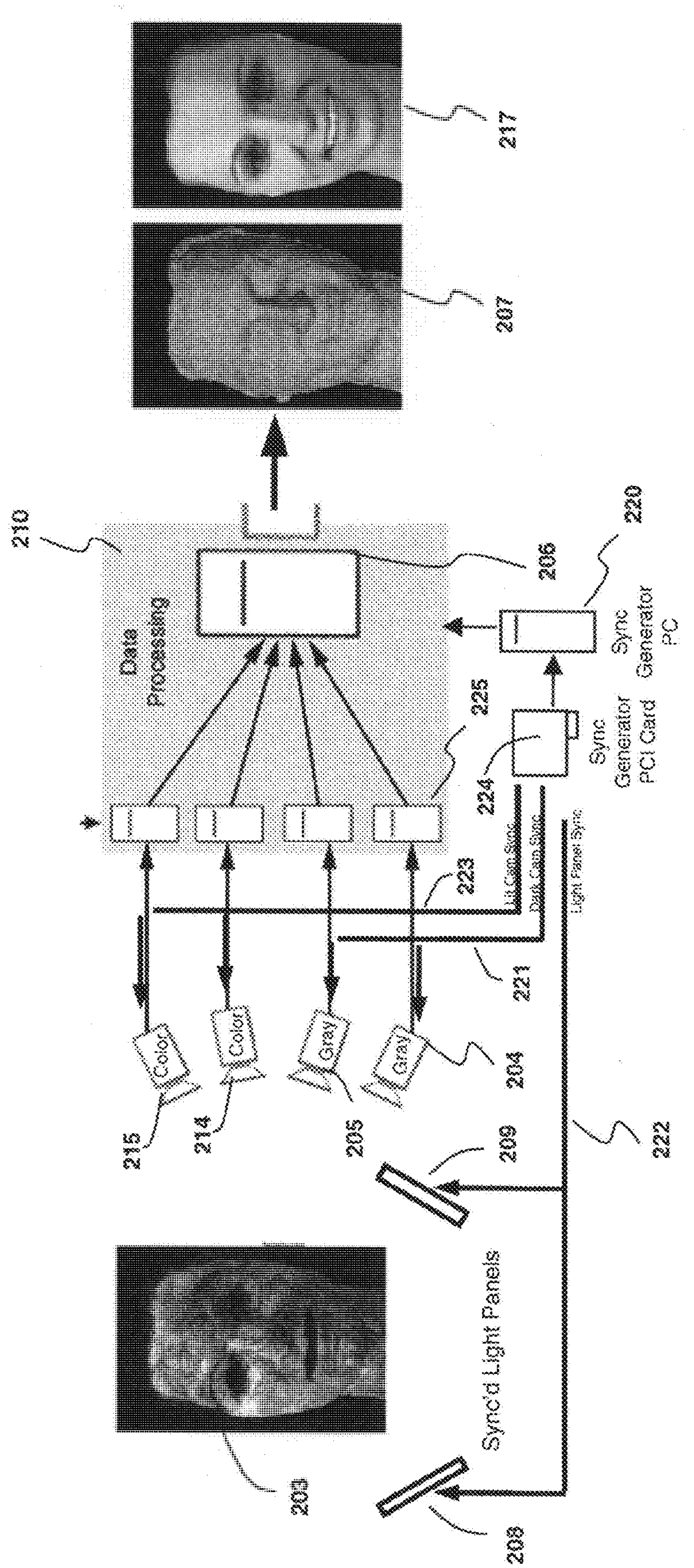
222
Sync'd Light Panels
202
208

Fig. 2a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Dark Cam Sync
Light Panel Sync
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Color
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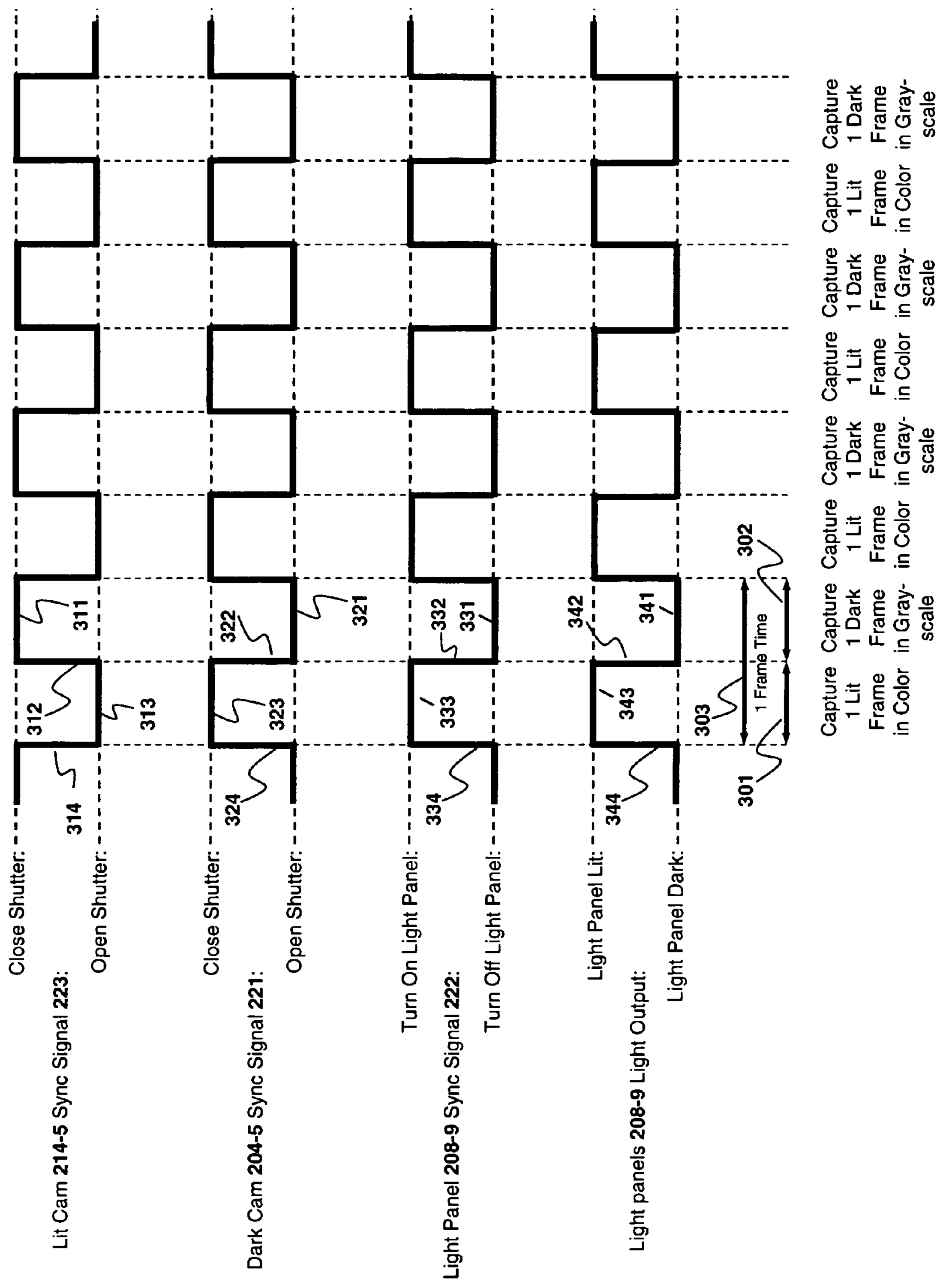
222
203
Sync'd Light Panels
208

Fig. 2b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Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
301
302
303
311
312
313
314
321
322
323
324
331
332
333
334
341
342
343
344

Fig. 3

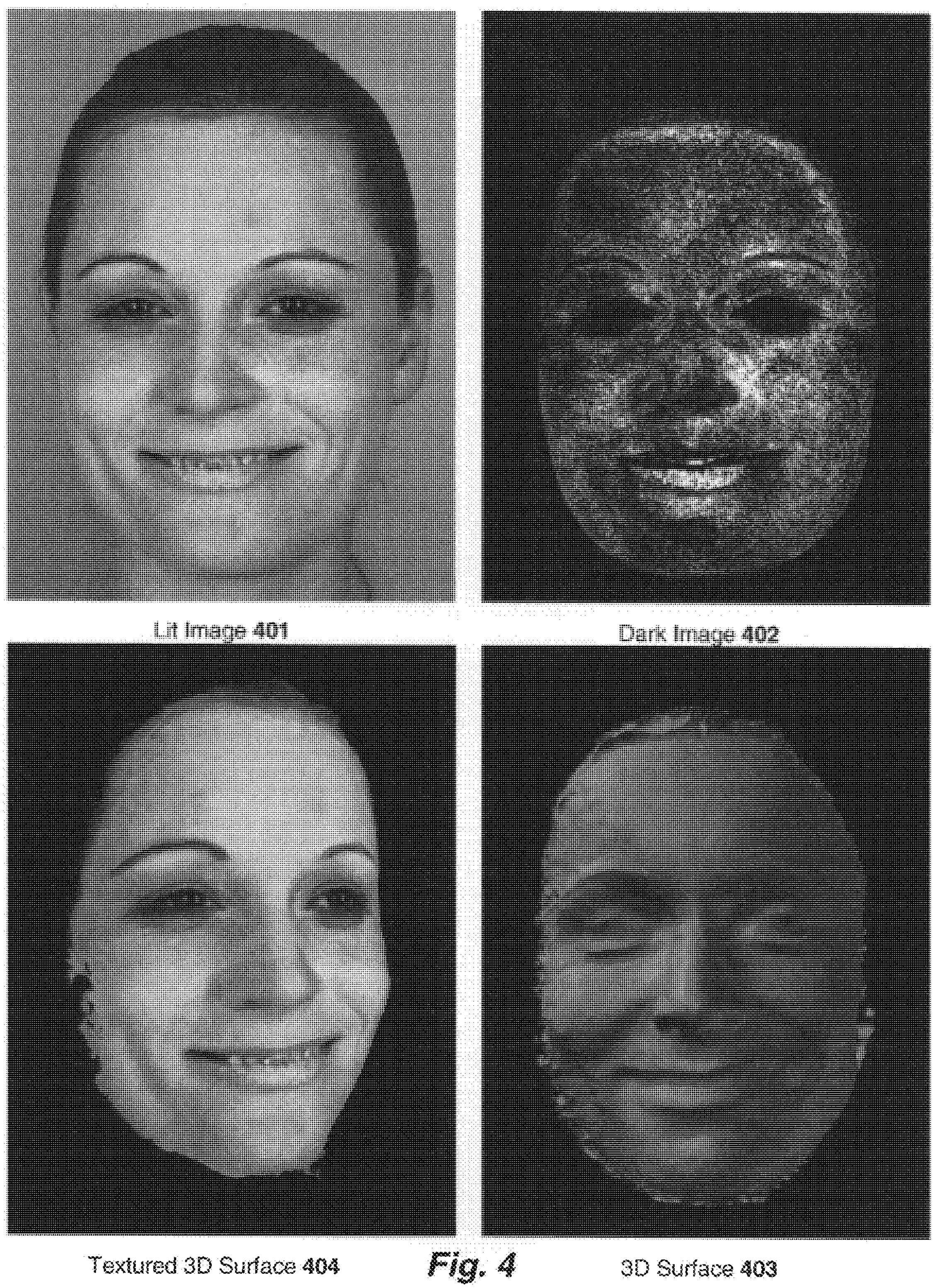

Lit Image 401
Dark Image 402
Textured 3D Surface 404
3D Surface 403

Fig. 4

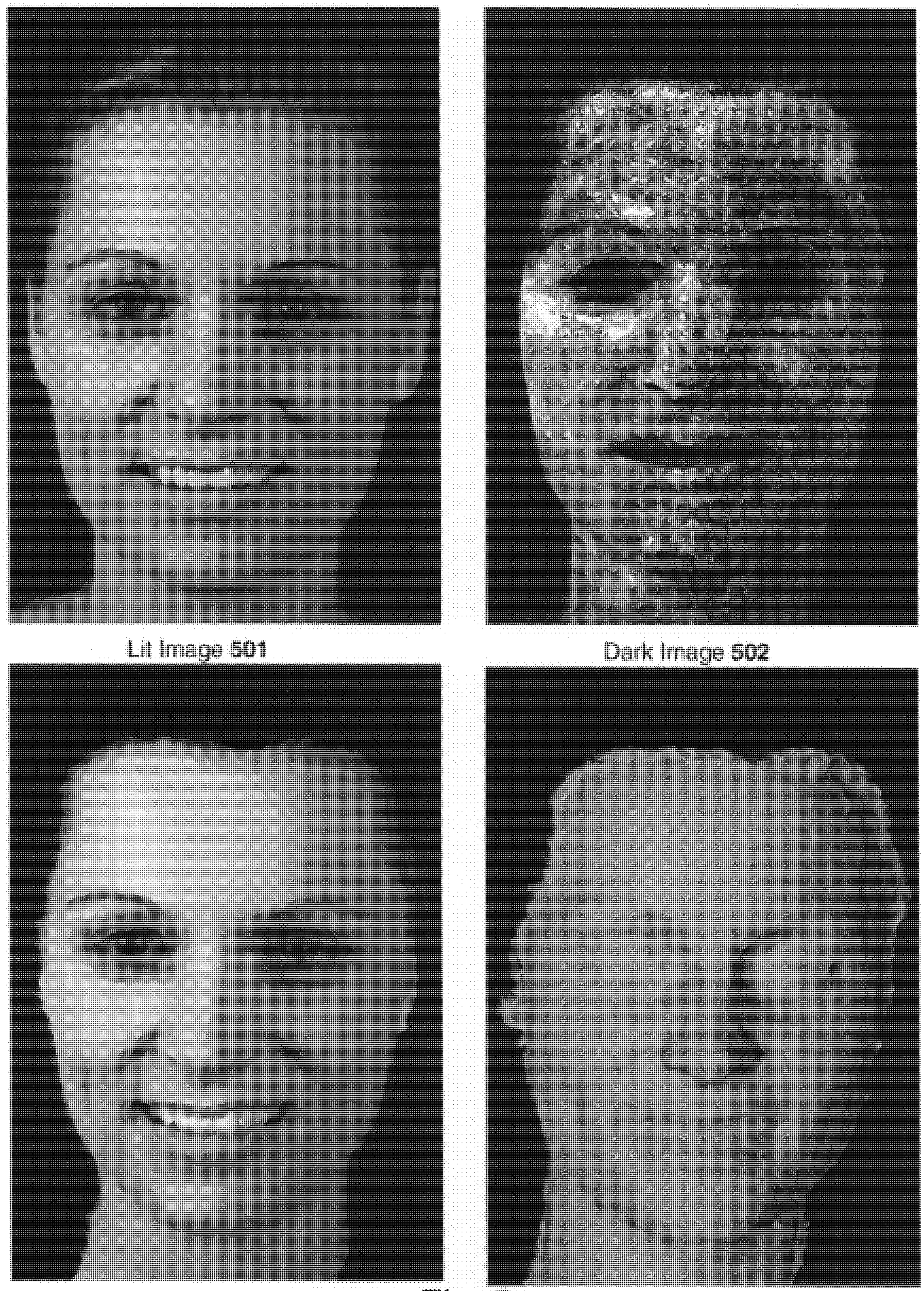

Lit Image 501
Dark Image 502
Textured 3D Surface 504
3D Surface 503

Fig. 5

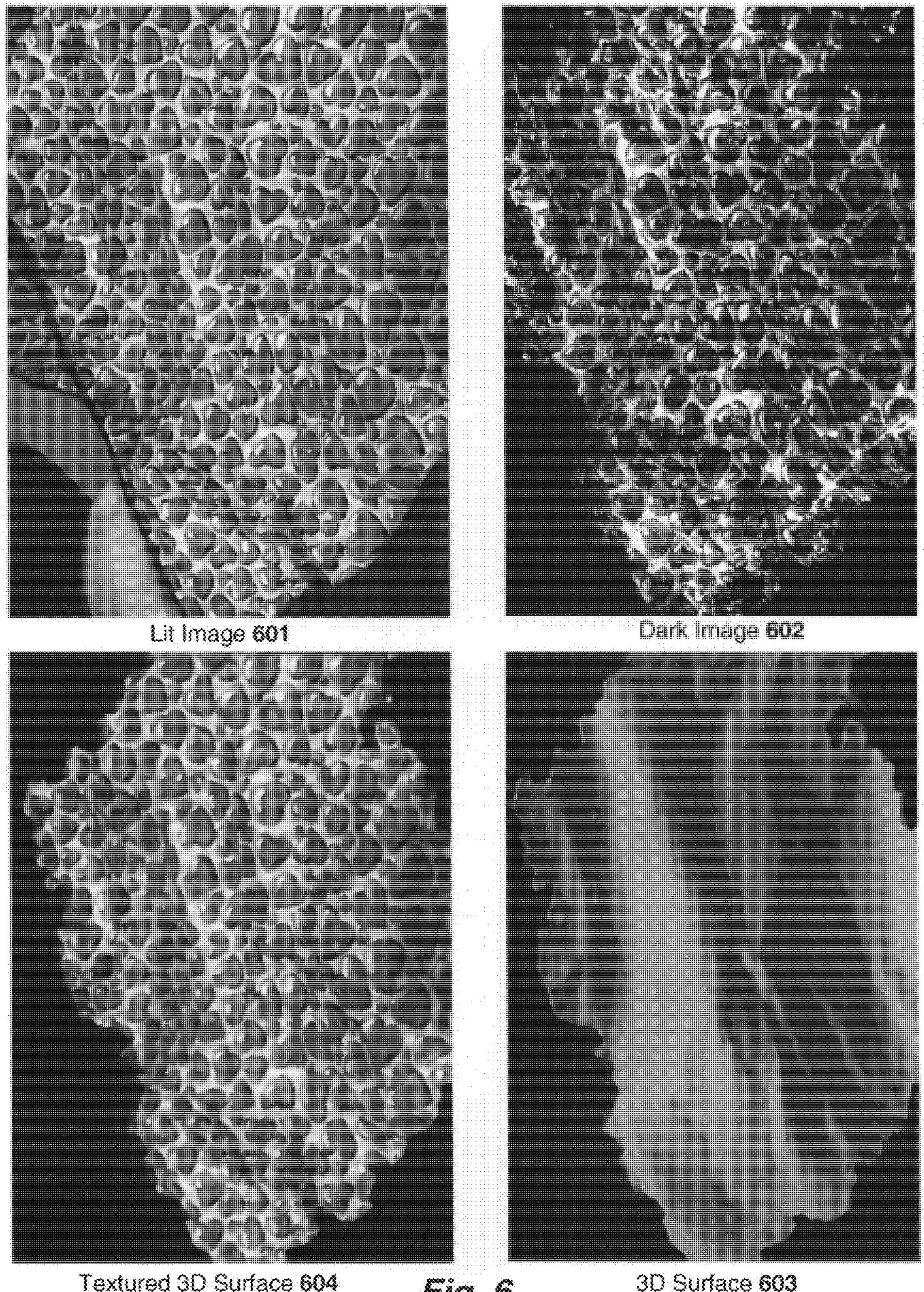

Lit Image 601
Dark Image 602
Textured 3D Surface 604
3D Surface 603

Fig. 6

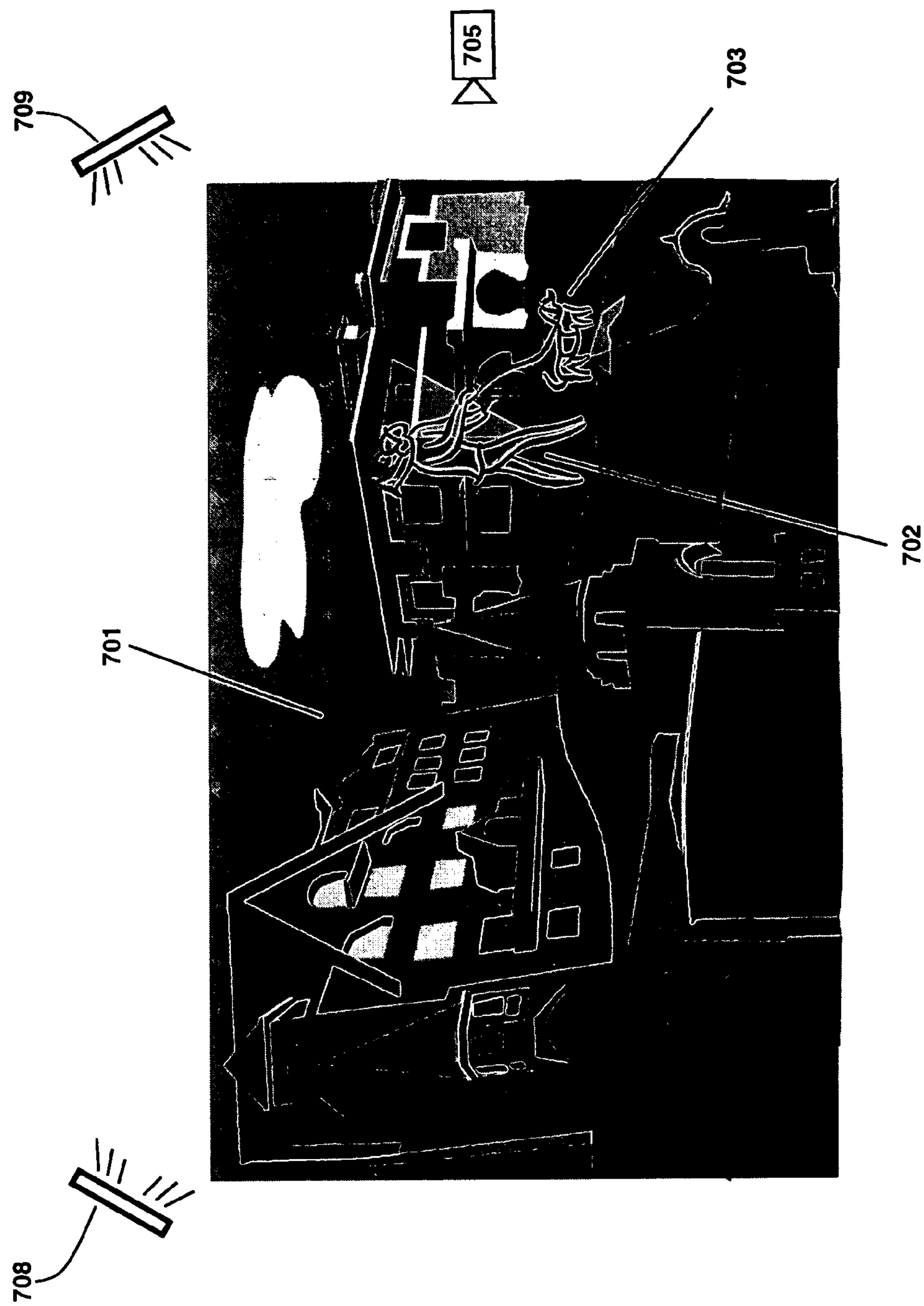


Fig. 7a
(prior art)

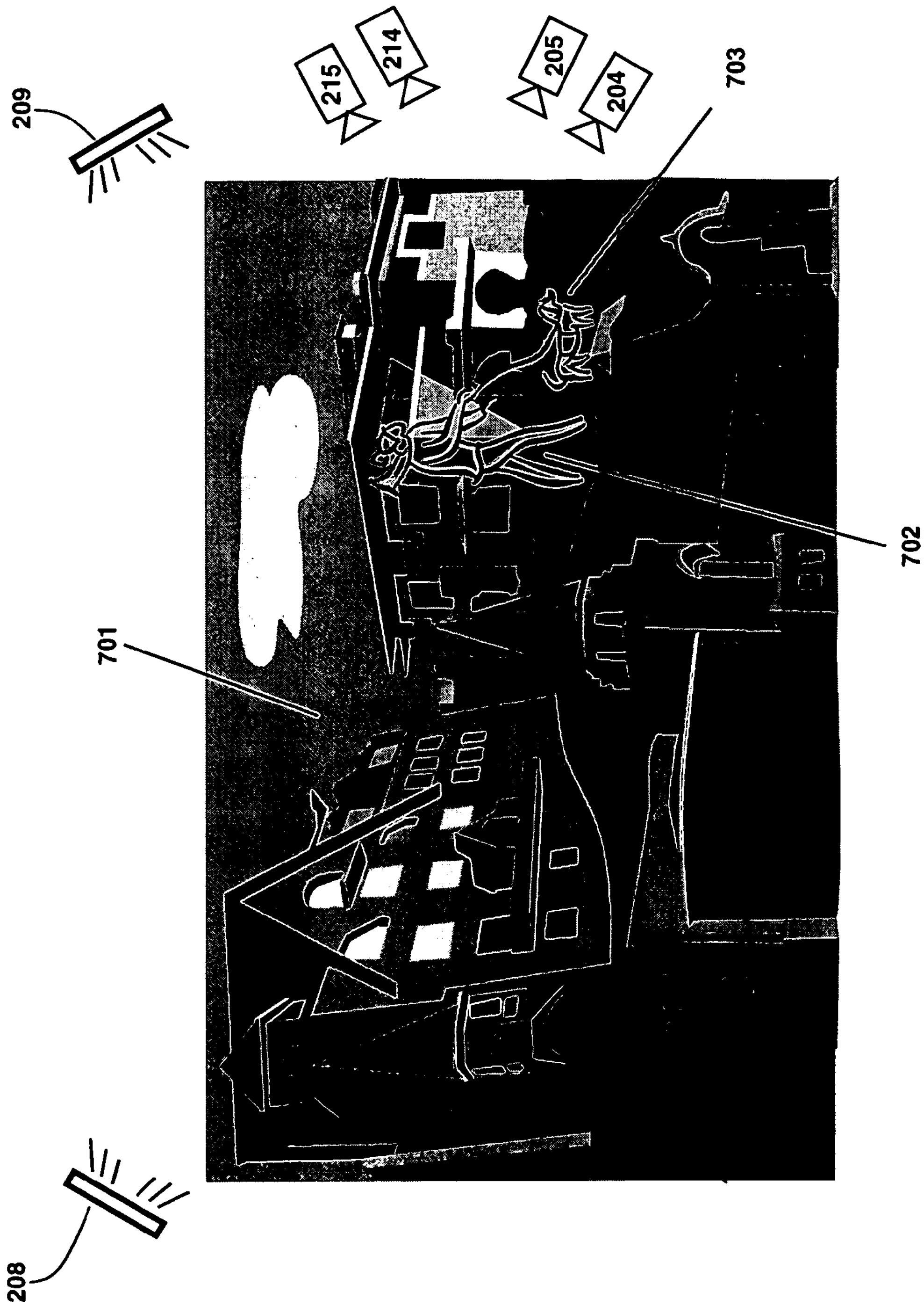


Fig. 7b

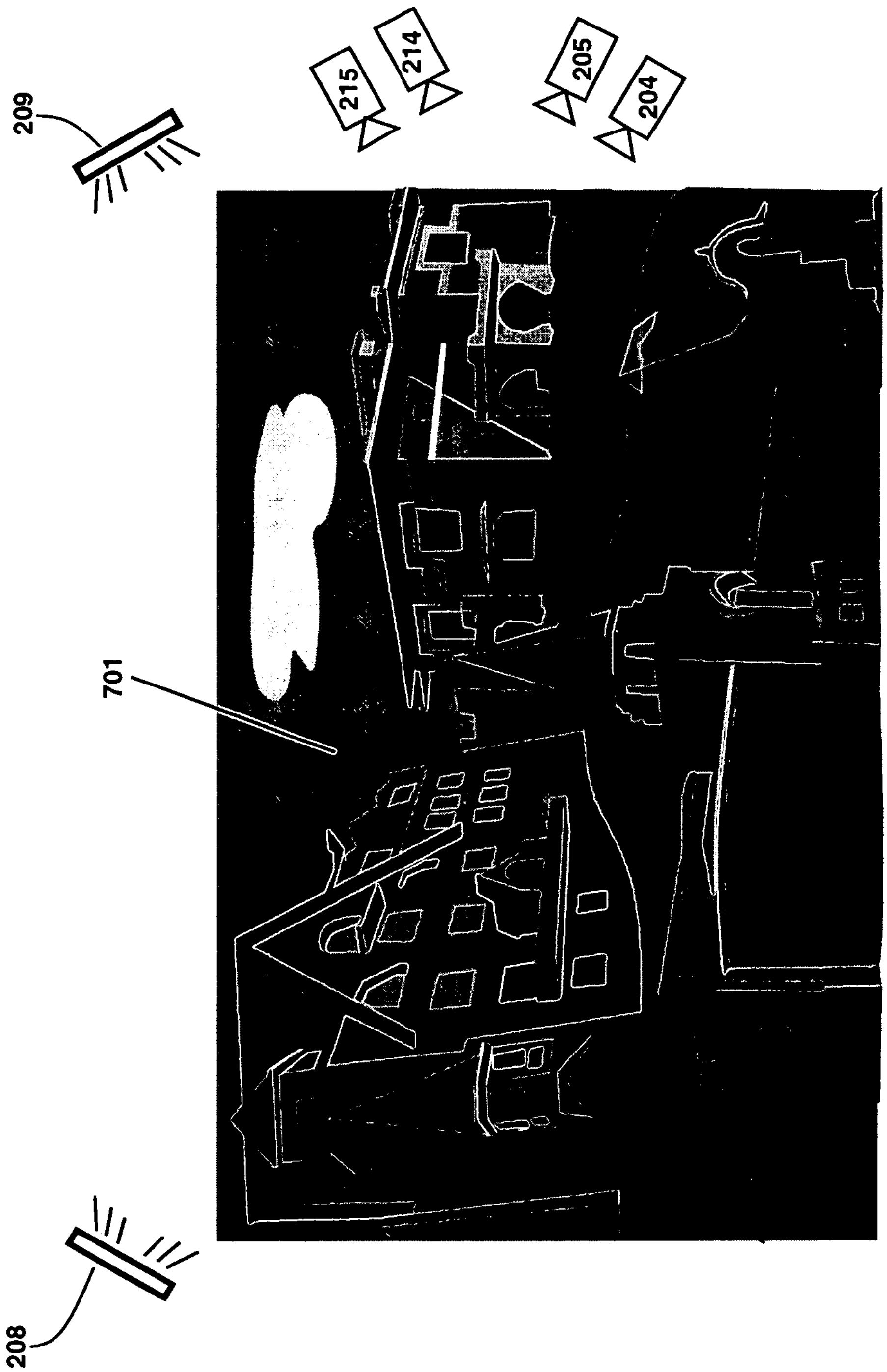


Fig. 7c

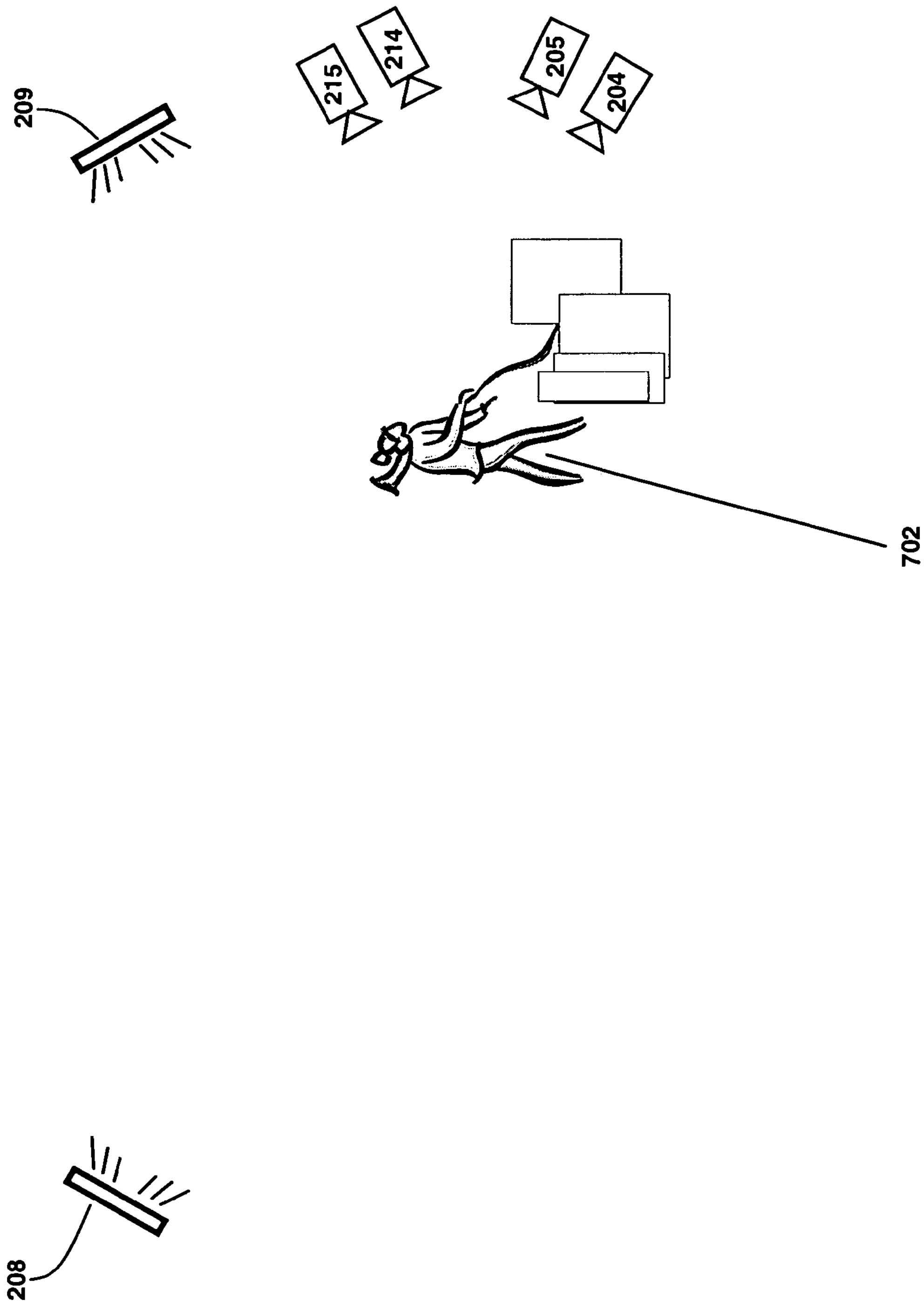


Fig. 7d

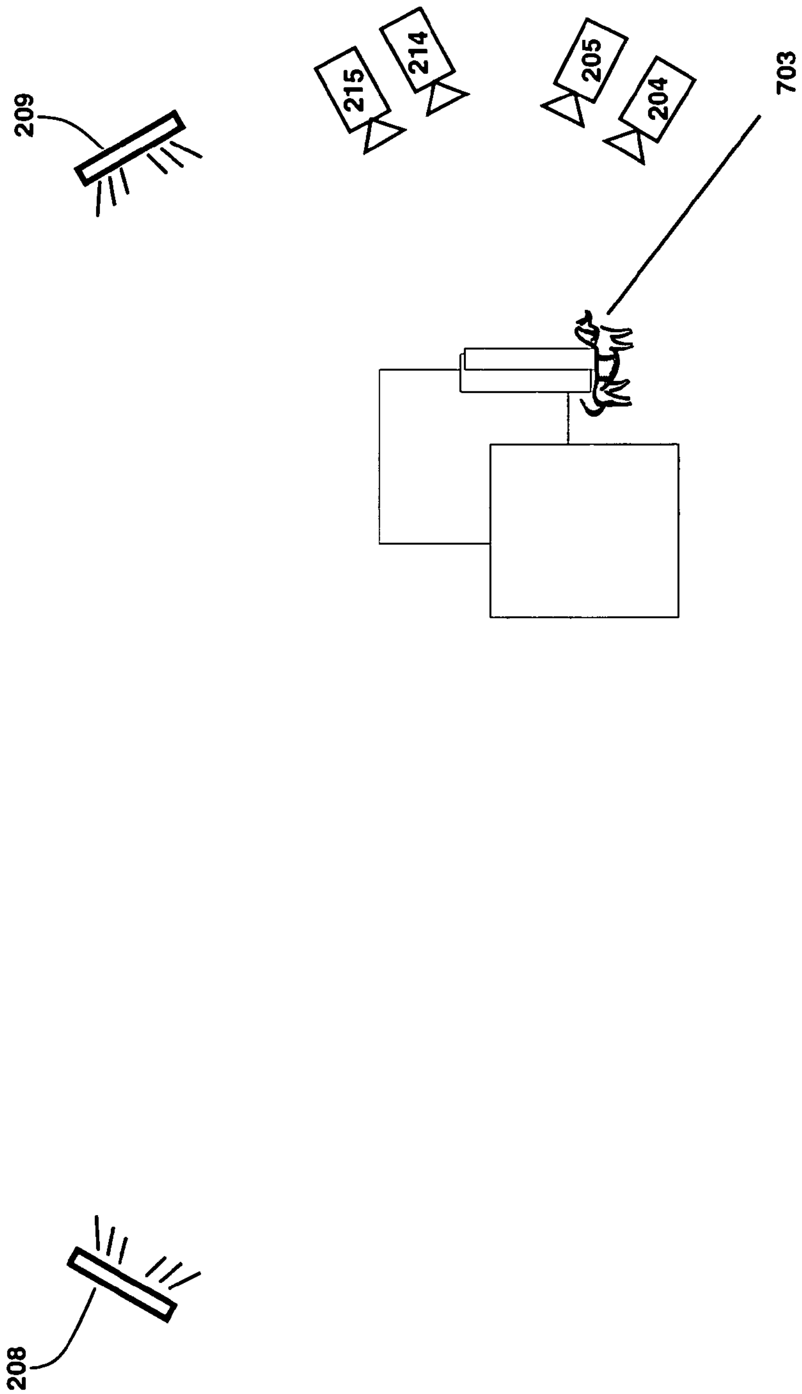
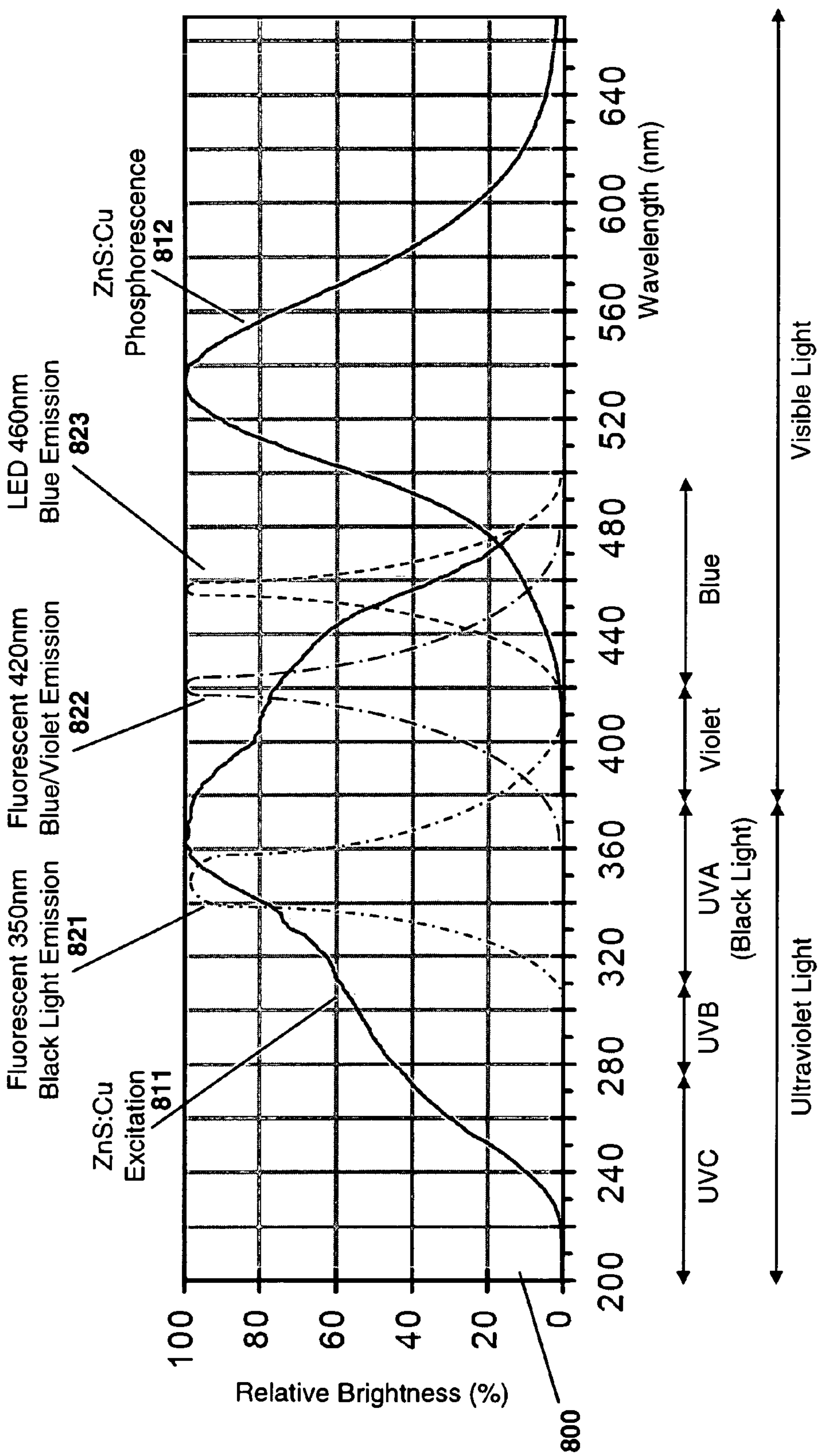


Fig. 7e



ZnS:Cu
Phosphorescence
812
LED 460nm
Blue Emission
823
Fluorescent 420nm
Blue/Violet Emission
822
Fluorescent 350nm
Black Light Emission
821
ZnS:Cu
Excitation
811
100
80
60
40
20
0
Relative Brightness (%)
800
200
240
280
320
360
400
440
480
520
560
600
640
Wavelength (nm)
UVC
UVB
UVA
(Black Light)
Violet
Blue
Ultraviolet Light
Visible Light

Fig. 8

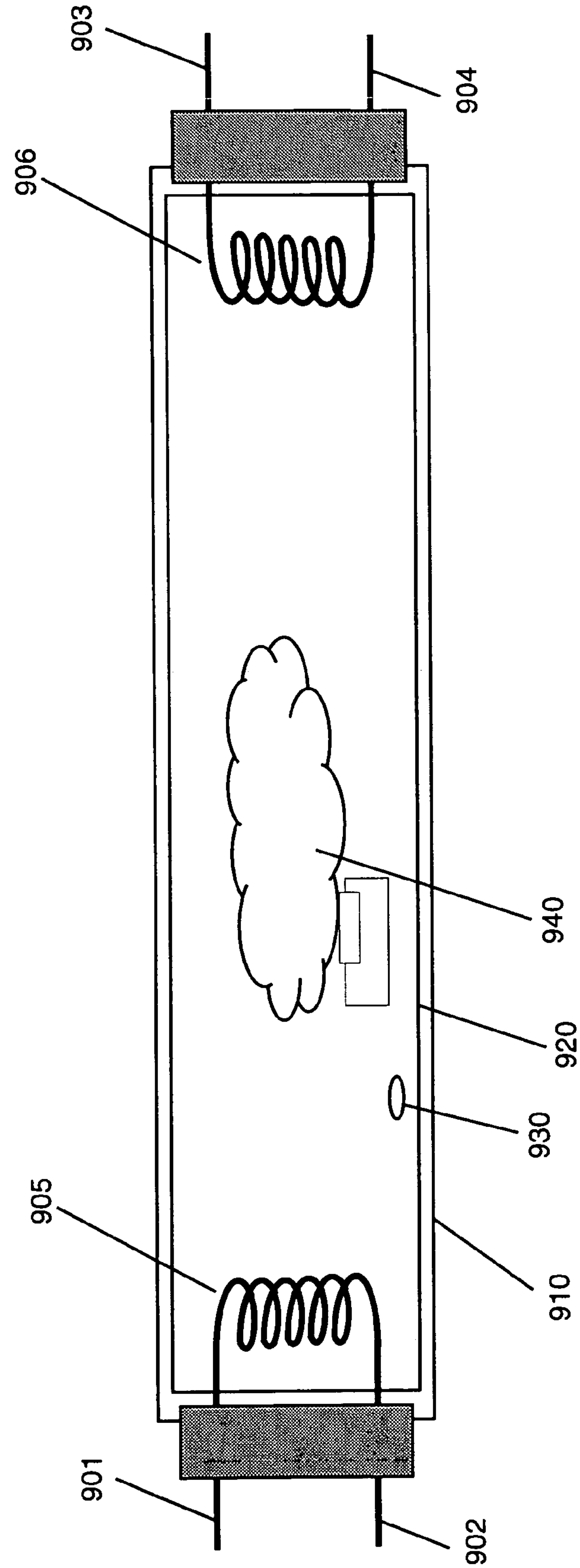


FIG. 9
(Prior Art)

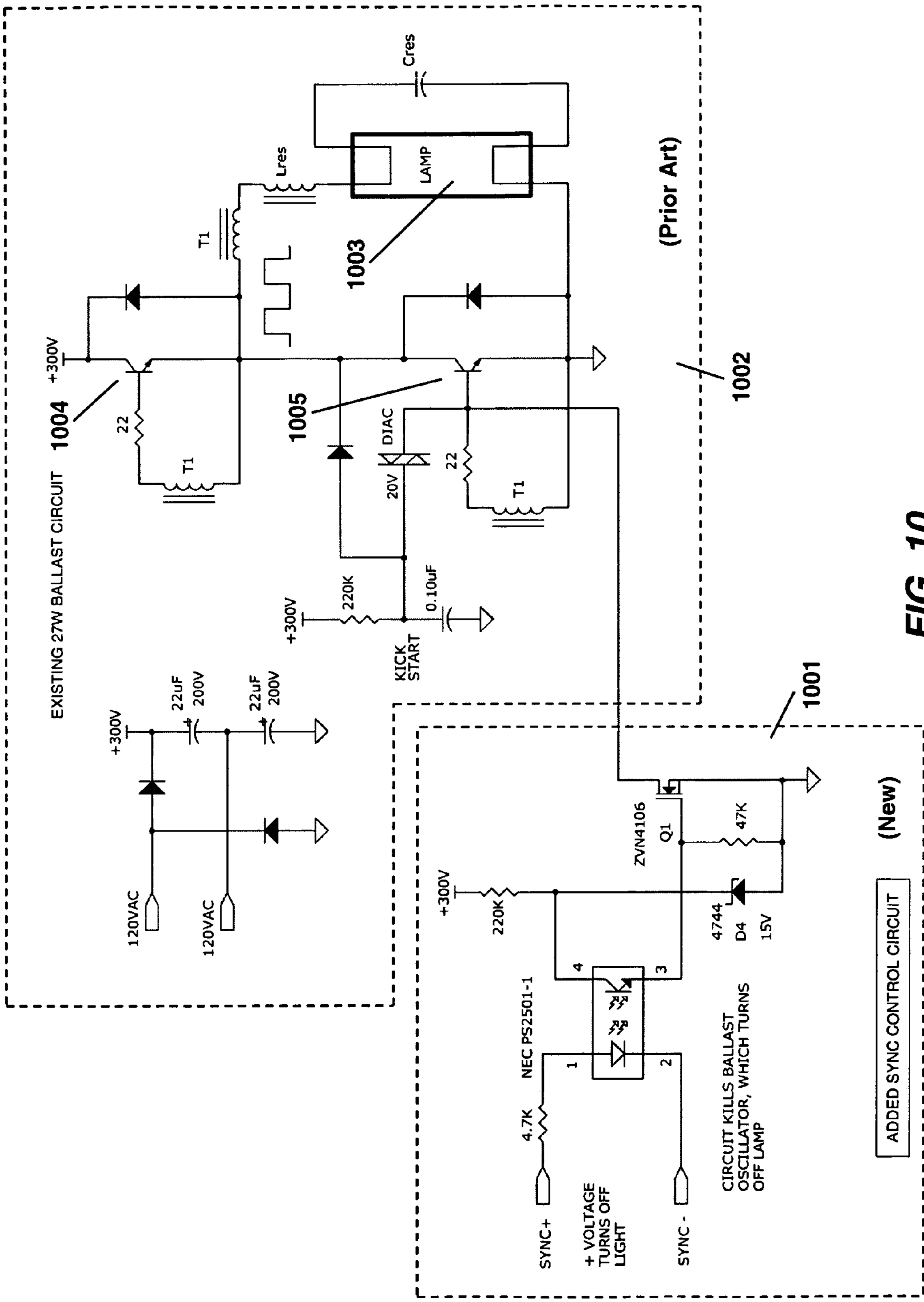
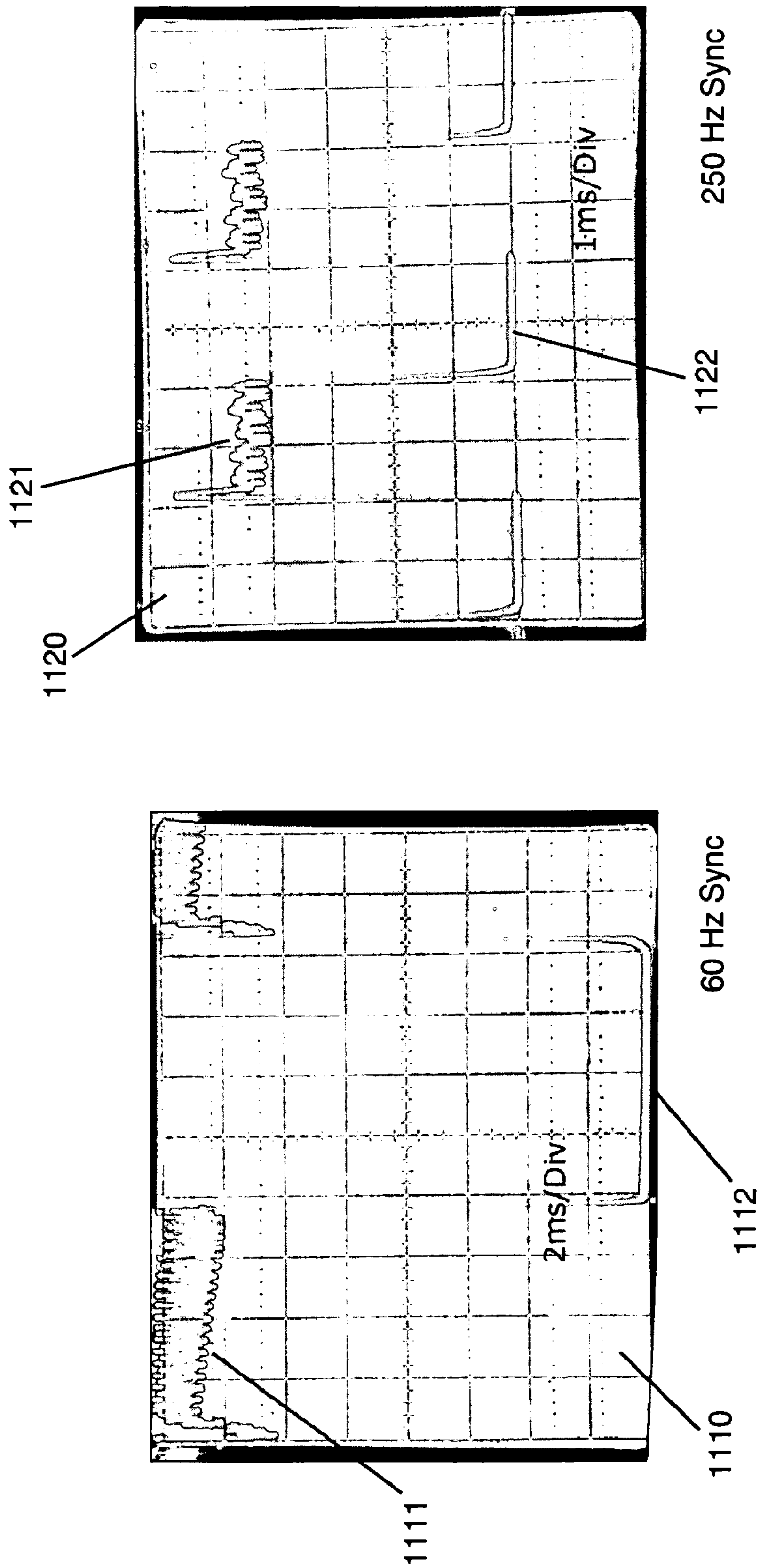

EXISTING 27W BALLAST CIRCUIT
1004
+300V
22
T1
Lres
Cres
LAMP
1003
1005
DIAC
20V
22
T1
220K
+300V
0.10uF
KICK START
+300V
22uF 200V
22uF 200V
120VAC
120VAC
(Prior Art)
1002
1001
ZVN4106
Q1
47K
+300V
220K
4744
D4
15V
NEC PS2501-1
4
3
1
2
4.7K
SYNC+
+ VOLTAGE TURNS OFF LIGHT
SYNC -
CIRCUIT KILLS BALLAST OSCILLATOR, WHICH TURNS OFF LAMP
ADDED SYNC CONTROL CIRCUIT
(New)

FIG. 10



250 Hz Sync
1ms/Div
1120
1121
1122
60 Hz Sync
2ms/Div
1110
1111
1112

FIG. 11

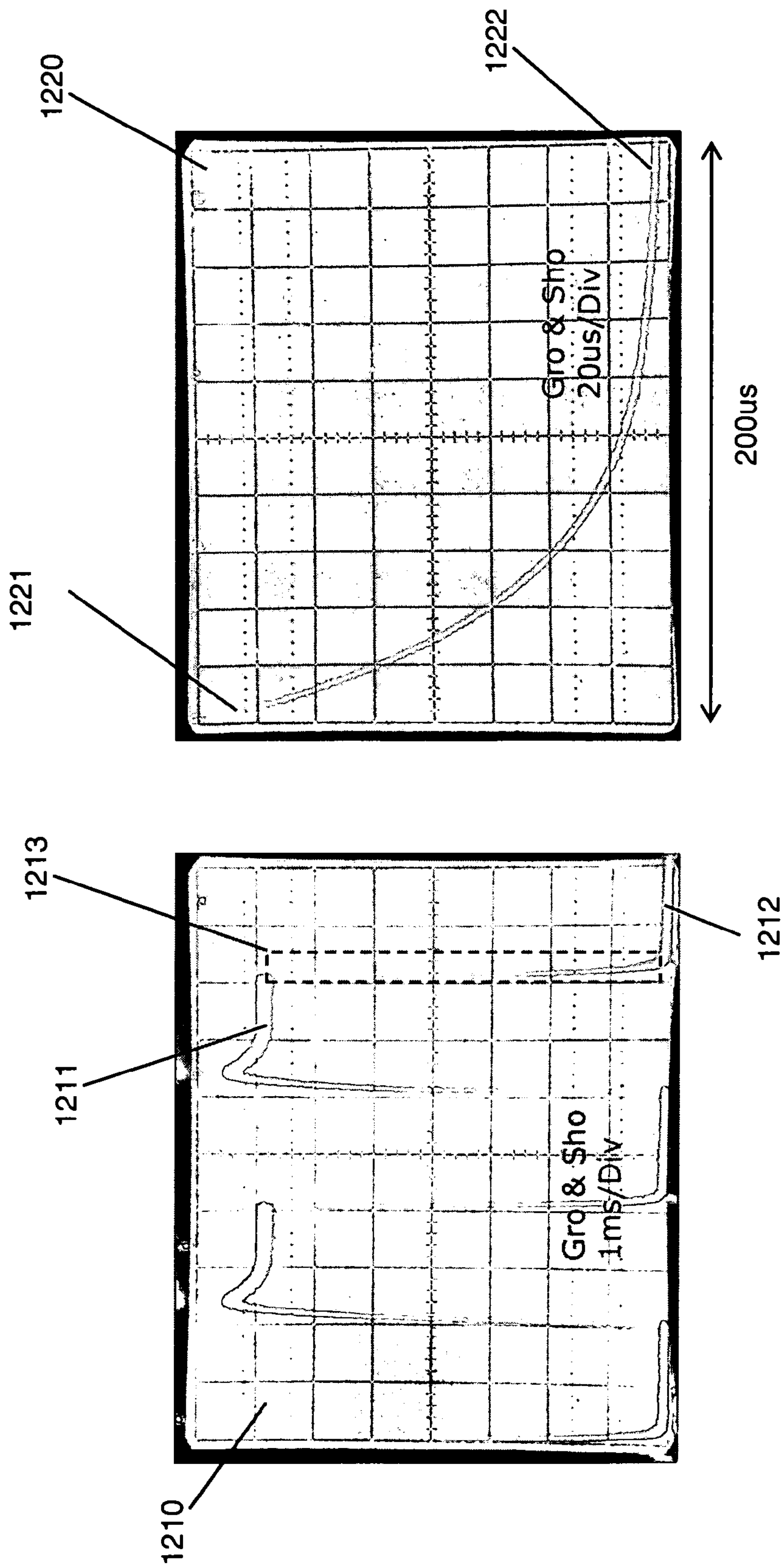

1220
1222
1221
Gro & Sho
20us/Div
200us
1213
1212
1211
Gro & Sho
1ms/Div
1210

FIG. 12

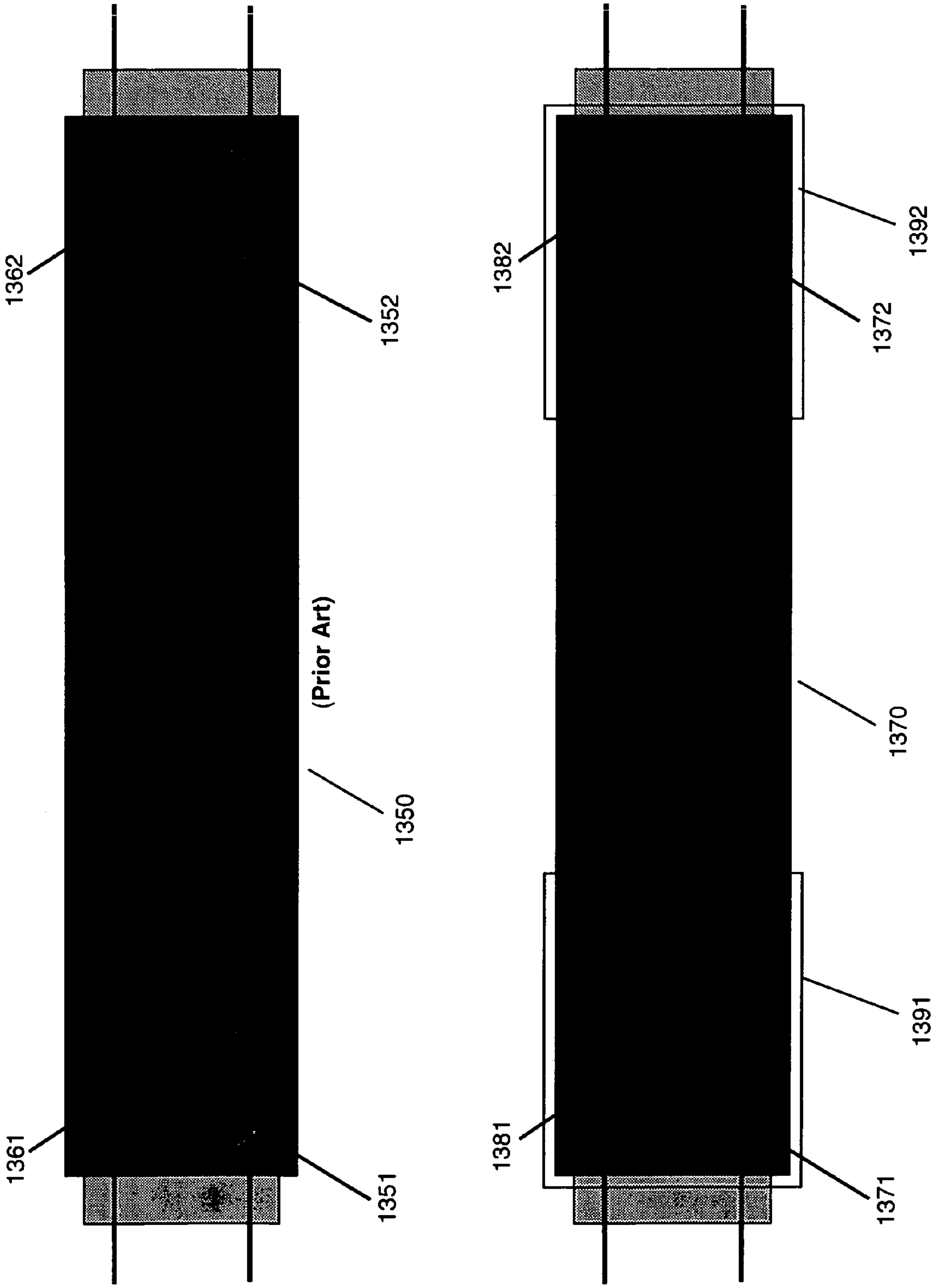

1362
1352
(Prior Art)
1350
1361
1351
1382
1392
1372
1370
1391
1381
1371

FIG. 13

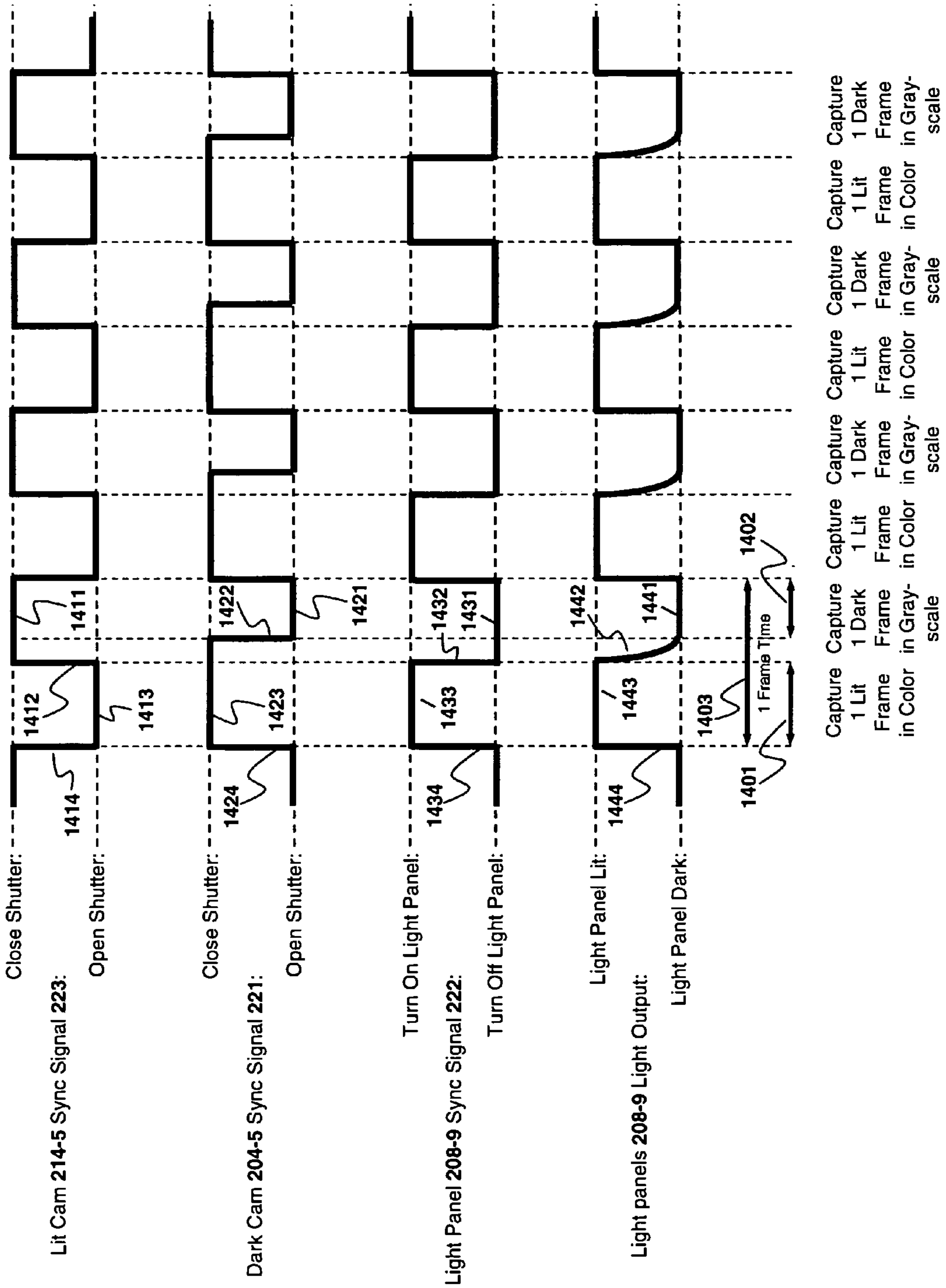

Close Shutter:
Lit Cam 214-5 Sync Signal 223:
Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
1411
1412
1413
1414
1421
1422
1423
1424
1431
1432
1433
1434
1441
1442
1443
1444
1401
1402
1403
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 14

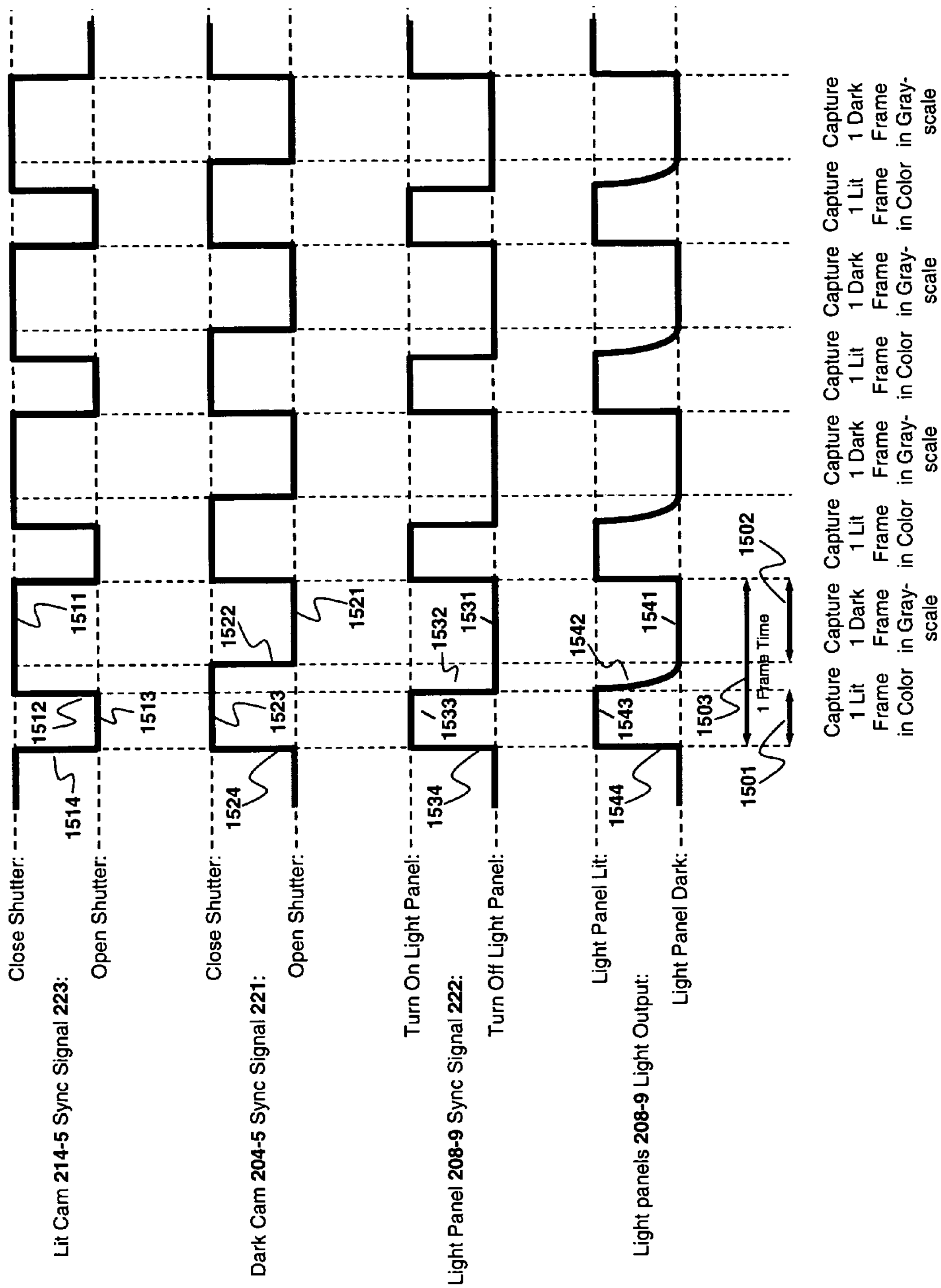

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
1511
1512
1513
1514
1521
1522
1523
1524
1531
1532
1533
1534
1541
1542
1543
1544
1501
1502
1503
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 15

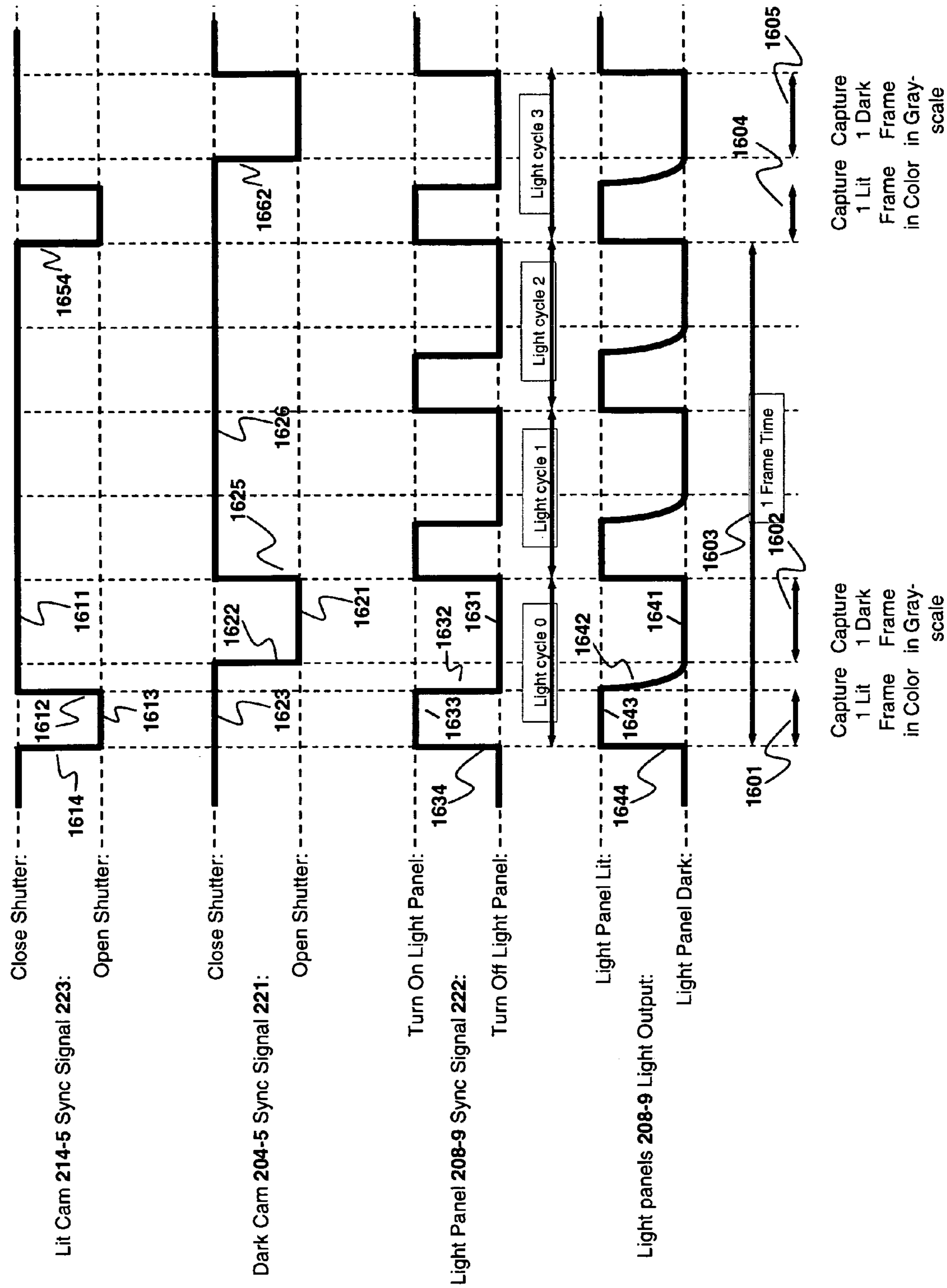
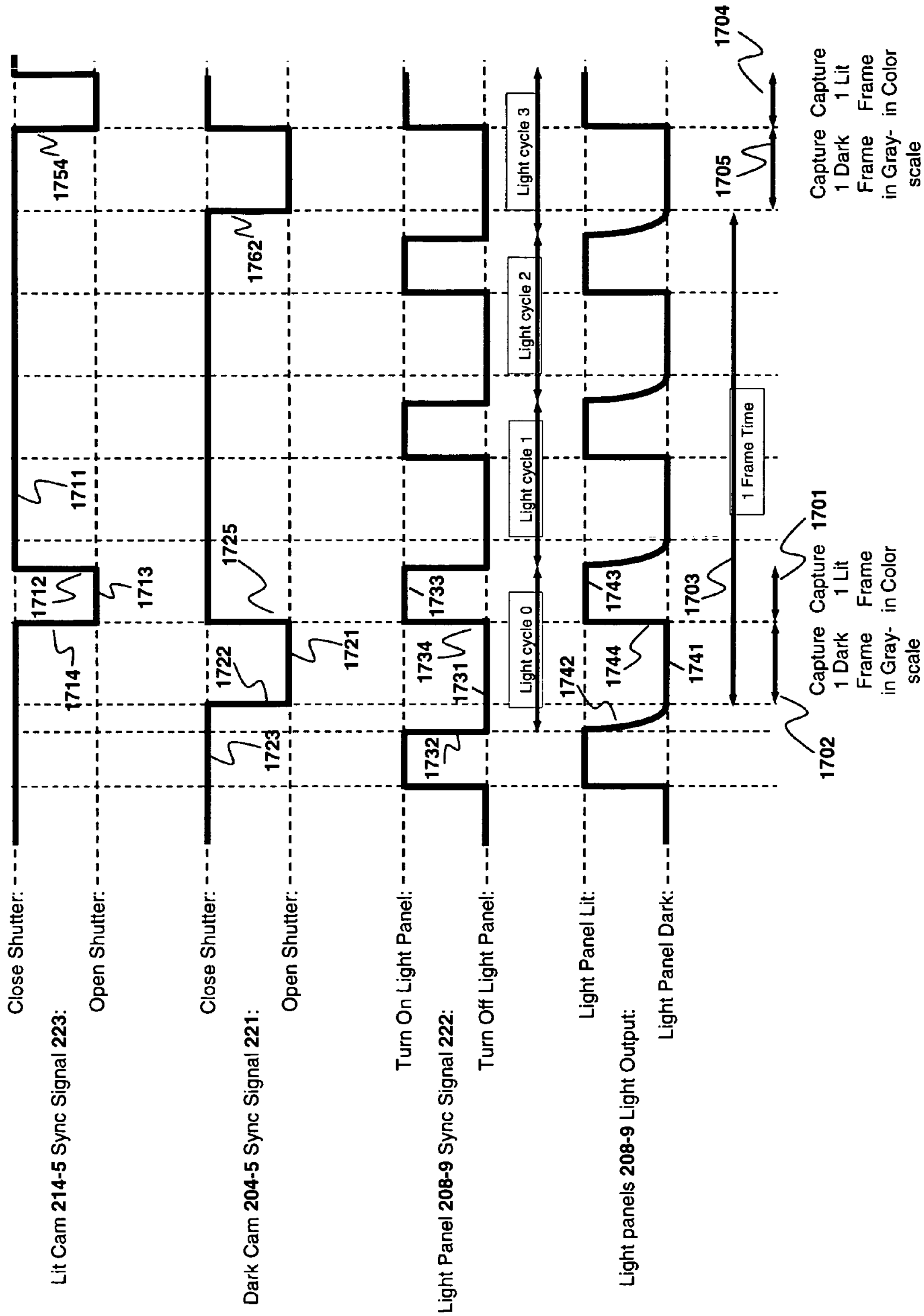

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
1601
1602
1603
1604
1605
1611
1612
1613
1614
1621
1622
1623
1625
1626
1631
1632
1633
1634
1641
1642
1643
1644
1654
1662

Fig. 16



Close Shutter:
Lit Cam 214-5 Sync Signal 223:
Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
1754
1711
1712
1713
1714
1762
1725
1722
1721
1723
1733
1734
1731
1732
Light cycle 3
Light cycle 2
Light cycle 1
Light cycle 0
1743
1744
1742
1741
1703
1 Frame Time
1704
1705
1701
1702
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 17

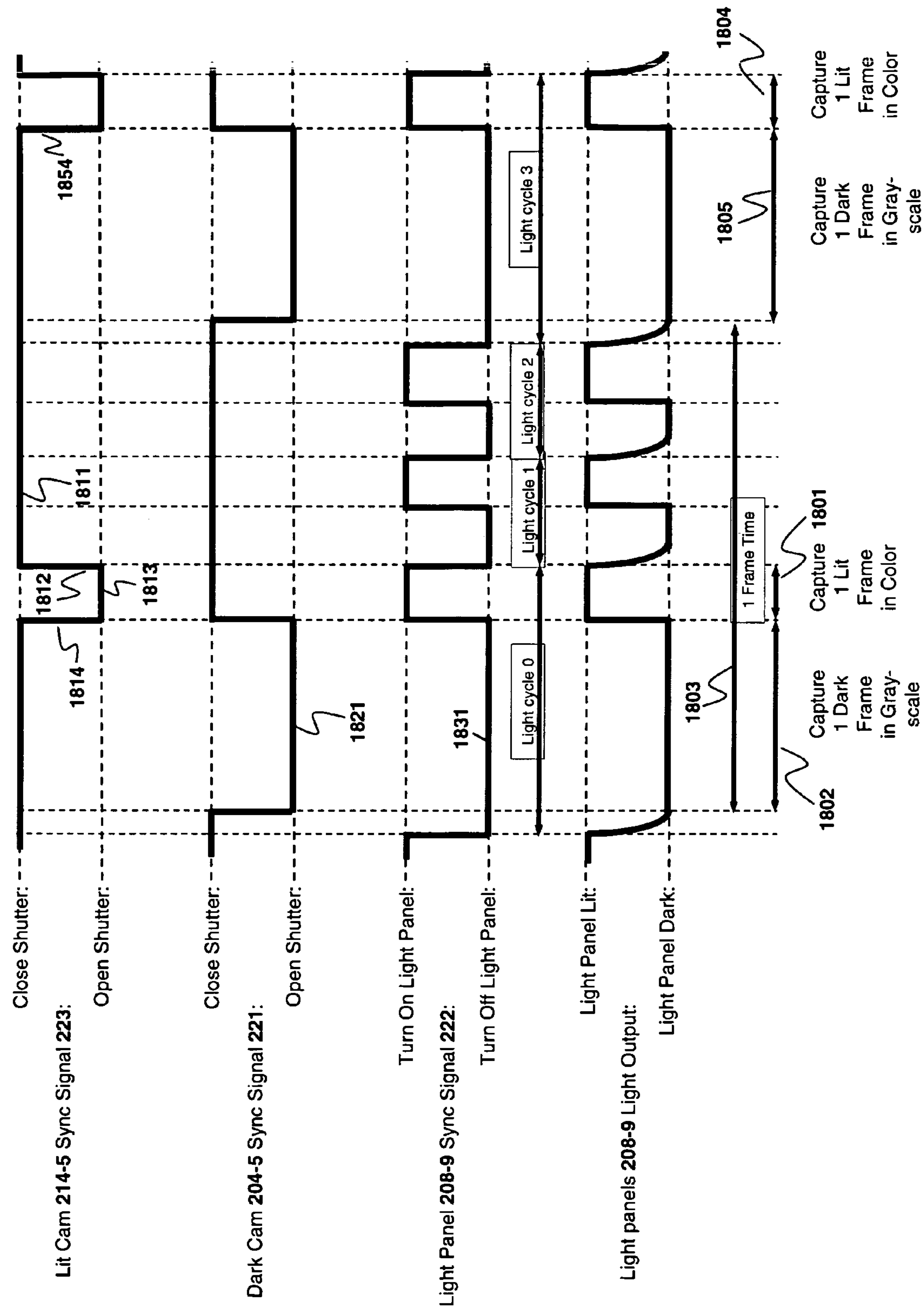

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
1854
1811
1812
1813
1814
1821
1831
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
1803
1805
1804
1801
1802
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color

Fig. 18

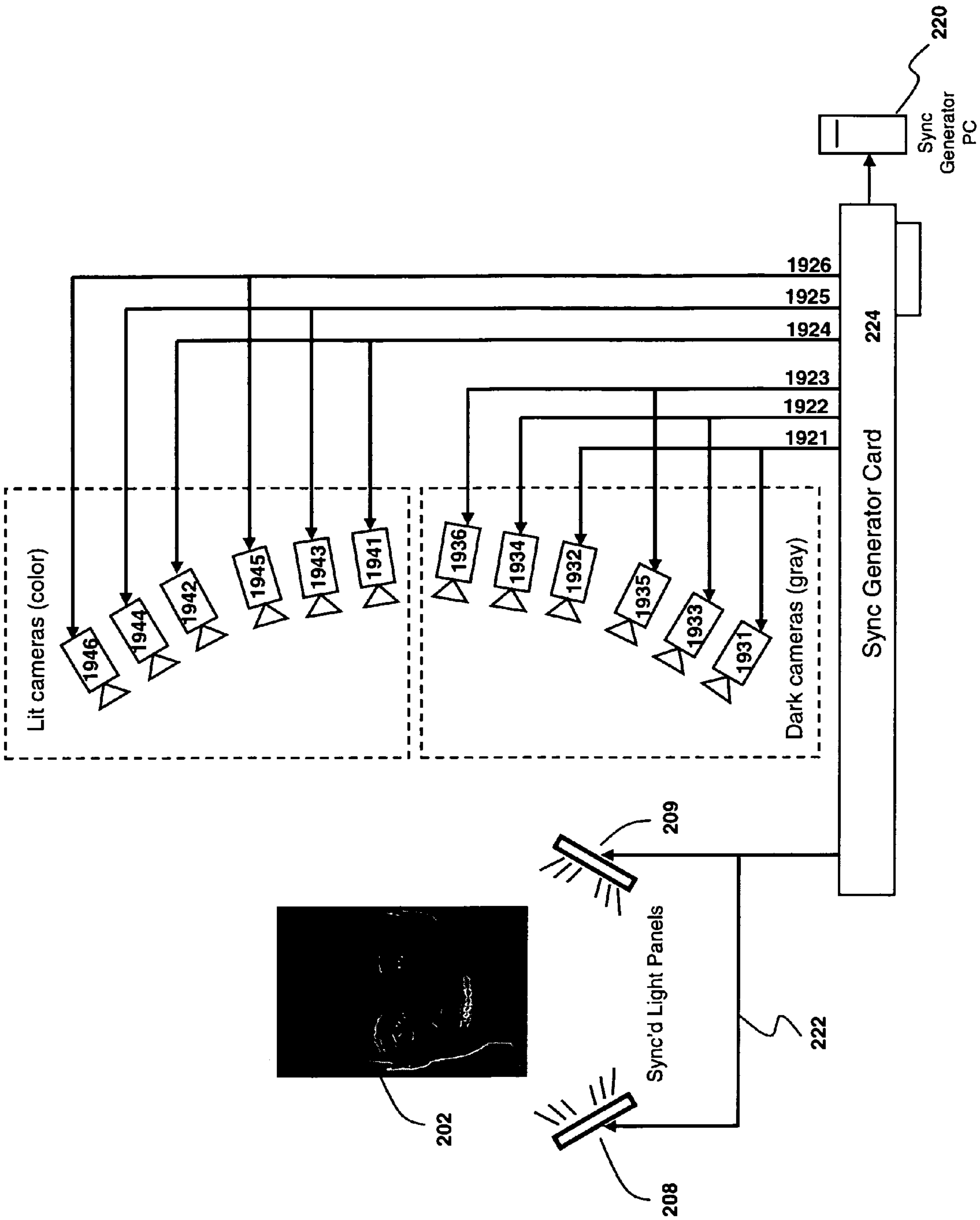
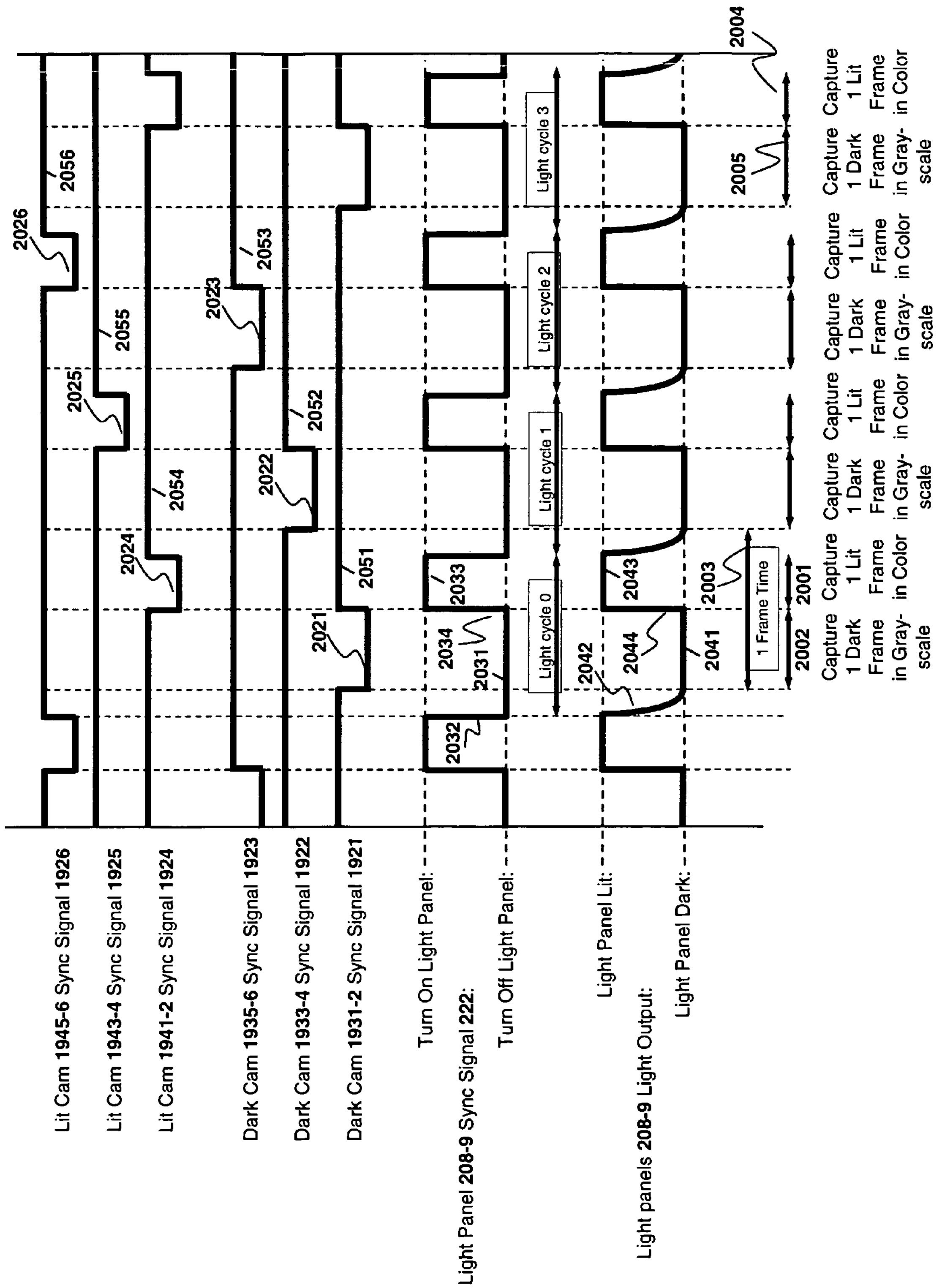
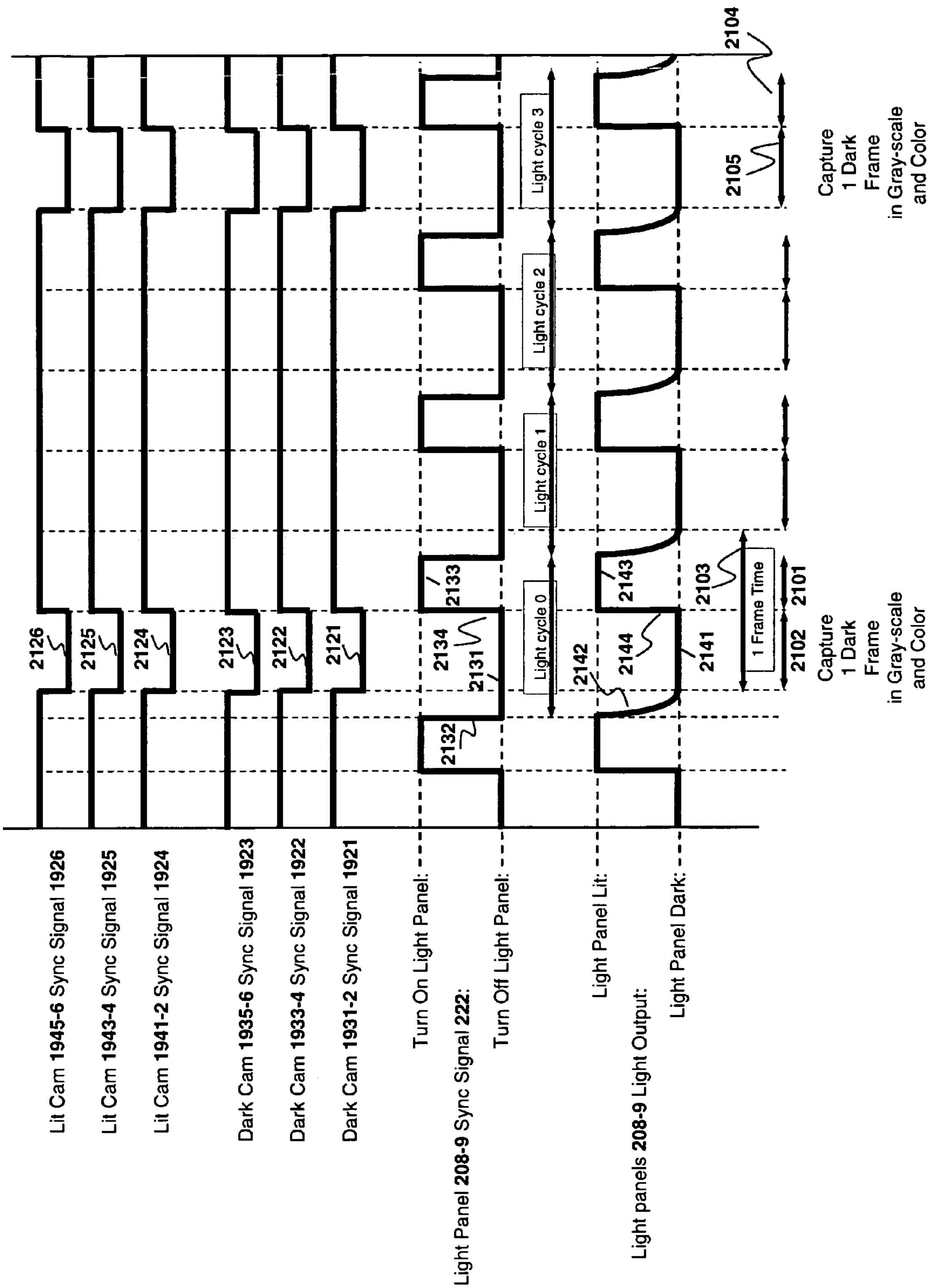

220
Sync Generator PC
224
Sync Generator Card
1926
1925
1924
1923
1922
1921
Lit cameras (color)
1946
1944
1942
1945
1943
1941
Dark cameras (gray)
1936
1934
1932
1935
1933
1931
209
Sync'd Light Panels
222
202
208

Fig. 19



Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
2001
2002
2003
2004
2005
2021
2022
2023
2024
2025
2026
2031
2032
2033
2034
2041
2042
2043
2044
2051
2052
2053
2054
2055
2056

Fig. 20



Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
2126
2125
2124
2123
2122
2121
2132
2134
2131
2133
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
2142
2144
2143
2141
2103
1 Frame Time
2102
2101
2104
2105
Capture
1 Dark
Frame
in Gray-scale
and Color
Capture
1 Dark
Frame
in Gray-scale
and Color

Fig. 21

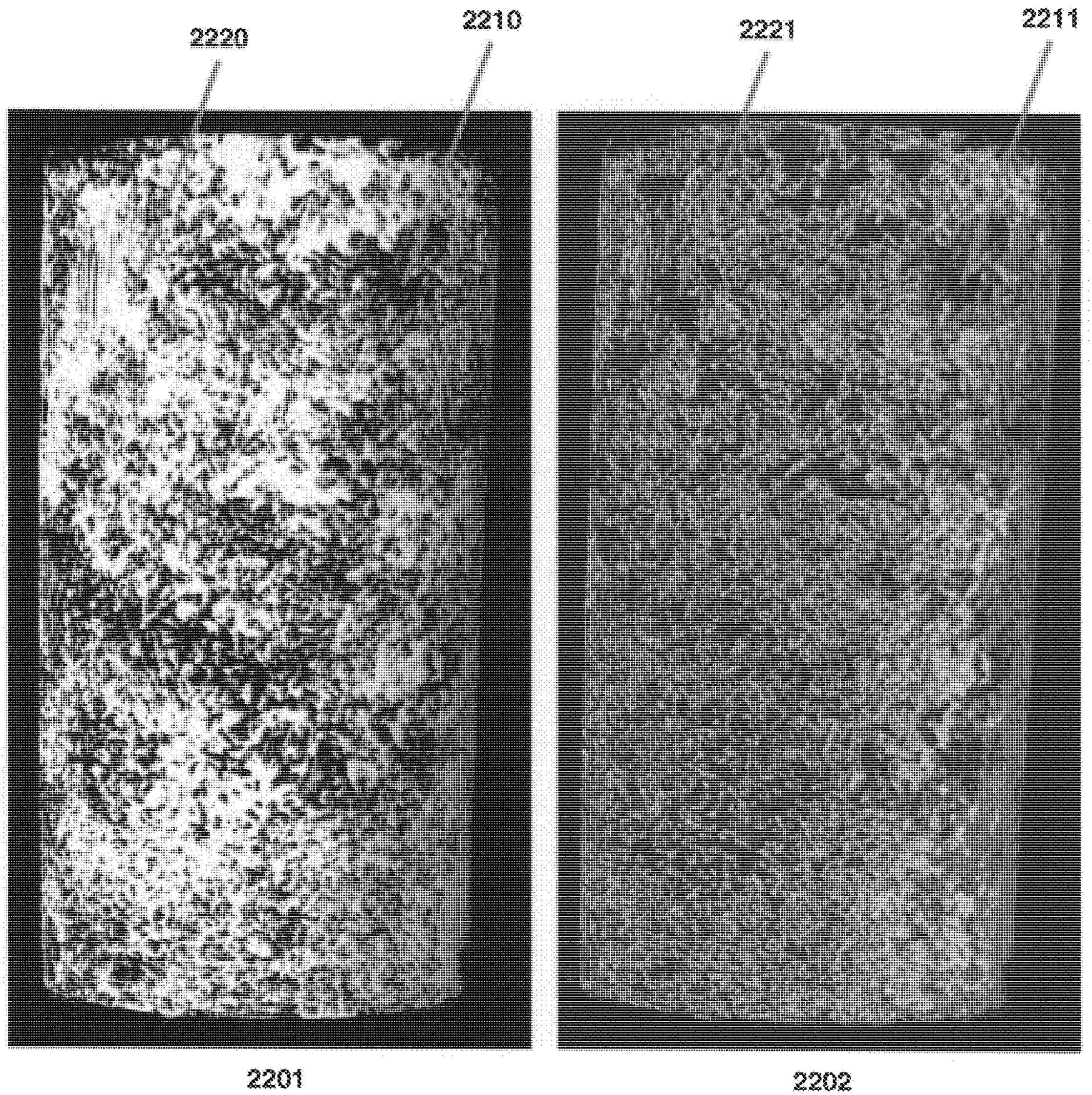


Fig. 22

SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE USING PHOSPHOR APPLICATION TECHNIQUES

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of motion capture. More particularly, the invention relates to an improved apparatus and method for performing motion capture using phosphor application techniques.

2. Description of the Related Art

"Motion capture" refers generally to the tracking and recording of human and animal motion. Motion capture systems are used for a variety of applications including, for example, video games and computer-generated movies. In a typical motion capture session, the motion of a "performer" is captured and translated to a computer-generated character.

As illustrated in FIG. **1** in a motion capture system, a plurality of motion tracking "markers" (e.g., markers **101**, **102**) are attached at various points on a performer's **100**'s body. The points are selected based on the known limitations of the human skeleton. Different types of motion capture markers are used for different motion capture systems. For example, in a "magnetic" motion capture system, the motion markers attached to the performer are active coils which generate measurable disruptions x, y, z and yaw, pitch, roll in a magnetic field.

By contrast, in an optical motion capture system, such as that illustrated in FIG. **1**, the markers **101**, **102** are passive spheres comprised of retro-reflective material, i.e., a material which reflects light back in the direction from which it came, ideally over a wide range of angles of incidence. A plurality of cameras **120**, **121**, **122**, each with a ring of LEDs **130**, **131**, **132** around its lens, are positioned to capture the LED light reflected back from the retro-reflective markers **101**, **102** and other markers on the performer. Ideally, the retro-reflected LED light is much brighter than any other light source in the room. Typically, a thresholding function is applied by the cameras **120**, **121**, **122** to reject all light below a specified level of brightness which, ideally, isolates the light reflected off of the reflective markers from any other light in the room and the cameras **120**, **121**, **122** only capture the light from the markers **101**, **102** and other markers on the performer.

A motion tracking unit **150** coupled to the cameras is programmed with the relative position of each of the markers **101**, **102** and/or the known limitations of the performer's body. Using this information and the visual data provided from the cameras **120-122**, the motion tracking unit **150** generates artificial motion data representing the movement of the performer during the motion capture session.

A graphics processing unit **152** renders an animated representation of the performer on a computer display **160** (or similar display device) using the motion data. For example, the graphics processing unit **152** may apply the captured motion of the performer to different animated characters and/or to include the animated characters in different computer-generated scenes. In one implementation, the motion tracking unit **150** and the graphics processing unit **152** are programmable cards coupled to the bus of a computer (e.g., such as the PCI and AGP buses found in many personal computers). One well known company which produces motion capture systems is Motion Analysis Corporation (see, e.g., www.motionanalysis.com).

SUMMARY

A system and method are described for performing motion capture on a subject. For example, a method according to one embodiment of the invention comprises: mixing phosphorescent makeup with a makeup base; applying the mixture of phosphorescent makeup and makeup base to surface regions of a motion capture subject; strobing a light source on and off, the light source charging phosphor within the phosphorescent makeup when on; and strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture images of the phosphorescent makeup, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent publication with color drawing(s) will be provided by the U.S. Patent and Trademark Office upon request and payment of the necessary fee.

A better understanding of the present invention can be obtained from the following detailed description in conjunction with the drawings, in which:

FIG. **1** illustrates a prior art motion tracking system for tracking the motion of a performer using retro-reflective markers and cameras.

FIG. **2***a* illustrates one embodiment of the invention during a time interval when the light panels are lit.

FIG. **2***b* illustrates one embodiment of the invention during a time interval when the light panels are dark.

FIG. **3** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **4** is images of heavily-applied phosphorescent makeup on a model during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **5** is images of phosphorescent makeup mixed with base makeup on a model both during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **6** is images of phosphorescent makeup applied to cloth during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **7***a* illustrates a prior art stop-motion animation stage.

FIG. **7***b* illustrates one embodiment of the invention where stop-motion characters and the set are captured together.

FIG. **7***c* illustrates one embodiment of the invention where the stop-motion set is captured separately from the characters.

FIG. **7***d* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **7***e* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **8** is a chart showing the excitation and emission spectra of ZnS:Cu phosphor as well as the emission spectra of certain fluorescent and LED light sources.

FIG. **9** is an illustration of a prior art fluorescent lamp.

FIG. **10** is a circuit diagram of a prior art fluorescent lamp ballast as well as one embodiment of a synchronization control circuit to modify the ballast for the purposes of the present invention.

FIG. **11** is oscilloscope traces showing the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **12** is oscilloscope traces showing the decay curve of the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **13** is a illustration of the afterglow of a fluorescent lamp filament and the use of gaffer's tape to cover the filament.

FIG. **14** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **15** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **16** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **17** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **18** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **19** illustrates one embodiment of the camera, light panel, and synchronization subsystems of the invention during a time interval when the light panels are lit.

FIG. **20** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **21** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **22** illustrates one embodiment of the invention where color is used to indicate phosphor brightness.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Described below is an improved apparatus and method for performing motion capture using shutter synchronization and/or phosphorescent makeup, paint or dye. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form to avoid obscuring the underlying principles of the invention.

The assignee of the present application previously developed a system for performing color-coded motion capture and a system for performing motion capture using a series of reflective curves painted on a performer's face. These systems are described in the co-pending applications entitled "Apparatus and Method for Capturing the Motion and/or Expression of a Performer," Ser. No. 10/942,609, and Ser. No. 10/942,413, Filed Sep. 15, 2004. These applications are assigned to the assignee of the present application and are incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture of random patterns applied to surfaces. This system is described in the co-pending applications entitled "Apparatus and Method for Performing Motion Capture Using A Random Pattern On Capture Surfaces," Ser. No. 11/255,854, Filed Oct. 20, 2005. This application is assigned to the assignee of the present application and is incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture using shutter synchronization and phosphorescent paint. This system is described in the co-pending application entitled "Apparatus and Method for Performing Motion Capture Using Shutter Synchronization," Ser. No. 11/077,628, Filed Mar. 10, 2005 (hereinafter "Shutter Synchronization" application). Briefly, in the Shutter Synchronization application, the efficiency of the motion capture system is improved by using phosphorescent paint or makeup and by precisely controlling synchronization between the motion capture cameras' shutters and the illumination of the painted curves. This application is assigned to the assignee of the present application and is incorporated herein by reference.

SYSTEM OVERVIEW

As described in these co-pending applications, by analyzing curves or random patterns applied as makeup on a performer's face rather than discrete marked points or markers on a performer's face, the motion capture system is able to generate significantly more surface data than traditional marked point or marker-based tracking systems. The random patterns or curves are painted on the face of the performer using retro-reflective, non-toxic paint or theatrical makeup. In one embodiment of the invention, non-toxic phosphorescent makeup is used to create the random patterns or curves. By utilizing phosphorescent paint or makeup combined with synchronized lights and camera shutters, the motion capture system is able to better separate the patterns applied to the performer's face from the normally-illuminated image of the face or other artifacts of normal illumination such as highlights and shadows.

FIGS. **2***a* and **2***b* illustrate an exemplary motion capture system described in the co-pending applications in which a random pattern of phosphorescent makeup is applied to a performer's face and motion capture is system is operated in a light-sealed space. When the synchronized light panels **208-209** are on as illustrated FIG. **2***a*, the performers' face looks as it does in image **202** (i.e. the phosphorescent makeup is only slightly visible). When the synchronized light panels **208-209** (e.g. LED arrays) are off as illustrated in FIG. **2***b*, the performers' face looks as it does in image **203** (i.e. only the glow of the phosphorescent makeup is visible).

Grayscale dark cameras **204-205** are synchronized to the light panels **208-209** using the synchronization signal generator PCI Card **224** (an exemplary PCI card is a PCI-6601 manufactured by National Instruments of Austin, Tex.) coupled to the PCI bus of synchronization signal generator PC **220** that is coupled to the data processing system **210** and so that all of the systems are synchronized together. Light Panel Sync signal **222** provides a TTL-level signal to the light panels **208-209** such that when the signal **222** is high (i.e. ≧2.0V), the light panels **208-209** turn on, and when the signal **222** is low (i.e. ≦0.8V), the light panels turn off. Dark Cam Sync signal **221** provides a TTL-level signal to the grayscale dark cameras **204-205** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller PCs **205**. The synchronization timing (explained in detail below) is such that the camera **204-205** shutters open to capture a frame when the light panels **208-209** are off (the "dark" interval). As a result, grayscale dark cameras **204-205** capture images of only the output of the phosphorescent makeup. Similarly, Lit Cam Sync **223** provides TTL-level signal to color lit cameras **214-215** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller computers **225**. Color lit cameras **214-215** are synchronized (as explained in detail below) such that their shutters open to capture a frame when the light panels **208-209** are on (the "lit" interval). As a result, color lit cameras **214-215** capture images of the performers' face illuminated by the light panels.

As used herein, grayscale cameras **204-205** may be referenced as "dark cameras" or "dark cams" because their shutters normally only when the light panels **208-209** are dark. Similarly, color cameras **214-215** may be referenced as "lit cameras" or "lit cams" because normally their shutters are only open when the light panels **208-209** are lit. While grayscale and color cameras are used specifically for each lighting phase in one embodiment, either grayscale or color cameras can be used for either light phase in other embodiments.

In one embodiment, light panels **208-209** are flashed rapidly at 90 flashes per second (as driven by a 90 Hz square wave from Light Panel Sync signal **222**), with the cameras **204-205** and **214-205** synchronized to them as previously described. At 90 flashes per second, the light panels **208-209** are flashing at a rate faster than can be perceived by the vast majority of humans, and as a result, the performer (as well as any observers of the motion capture session) perceive the room as being steadily illuminated and are unaware of the flashing, and the performer is able to proceed with the performance without distraction from the flashing light panels **208-209**.

As described in detail in the co-pending applications, the images captured by cameras **204-205** and **214-215** are recorded by camera controllers **225** (coordinated by a centralized motion capture controller **206**) and the images and images sequences so recorded are processed by data processing system **210**. The images from the various grayscale dark cameras are processed so as to determine the geometry of the 3D surface of the face **207**. Further processing by data processing system **210** can be used to map the color lit images captured onto the geometry of the surface of the face **207**. Yet further processing by the data processing system **210** can be used to track surface points on the face from frame-to-frame.

In one embodiment, each of the camera controllers **225** and central motion capture controller **206** is implemented using a separate computer system. Alternatively, the camera controllers and motion capture controller may be implemented as software executed on a single computer system or as any combination of hardware and software. In one embodiment, the camera controller computers **225** are rack-mounted computers, each using a 945GT Speedster-A4R motherboard from MSI Computer Japan Co., Ltd. (C&K Bldg. 6F 1-17-6, Higashikanda, Chiyoda-ku, Tokyo 101-0031 Japan) with 2 Gbytes of random access memory (RAM) and a 2.16 GHz Intel Core Duo central processing unit from Intel Corporation, and a 300 GByte SATA hard disk from Western Digital, Lake Forest Calif. The cameras **204-205** and **214-215** interface to the camera controller computers **225** via IEEE 1394 cables.

In another embodiment the central motion capture controller **206** also serves as the synchronization signal generator PC **220**. In yet another embodiment the synchronization signal generator PCI card **224** is replaced by using the parallel port output of the synchronization signal generator PC **220**. In such an embodiment, each of the TTL-level outputs of the parallel port are controlled by an application running on synchronization signal generator PC **220**, switching each TTL-level output to a high state or a low state in accordance with the desired signal timing. For example, bit **0** of the PC **220** parallel port is used to drive synchronization signal **221**, bit **1** is used to drive signal **222**, and bit **2** is used to drive signal **224**. However, the underlying principles of the invention are not limited to any particular mechanism for generating the synchronization signals.

The synchronization between the light sources and the cameras employed in one embodiment of the invention is illustrated in FIG. **3**. In this embodiment, the Light Panel and Dark Cam Sync signals **221** and **222** are in phase with each other, while the Lit Cam Sync Signal **223** is the inverse of signals **221/222**. In one embodiment, the synchronization signals cycle between 0 to 5 Volts. In response to the synchronization signal **221** and **223**, the shutters of the cameras **204-205** and **214-215**, respectively, are periodically opened and closed as shown in FIG. **3**. In response to sync signal **222**, the light panels are periodically turned off and on, respectively as shown in FIG. **3**. For example, on the falling edge **314** of sync signal **223** and on the rising edges **324** and **334** of sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are opened and the dark camera **204-215** shutters are closed and the light panels are illuminated as shown by rising edge **344**. The shutters remain in their respective states and the light panels remain illuminated for time interval **301**. Then, on the rising edge **312** of sync signal **223** and falling edges **322** and **332** of the sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are closed, the dark camera **204-215** shutters are opened and the light panels are turned off as shown by falling edge **342**. The shutters and light panels are left in this state for time interval **302**. The process then repeats for each successive frame time interval **303**.

As a result, during the first time interval **301**, a normally-lit image is captured by the color lit cameras **214-215**, and the phosphorescent makeup is illuminated (and charged) with light from the light panels **208-209**. During the second time interval **302**, the light is turned off and the grayscale dark cameras **204-205** capture an image of the glowing phosphorescent makeup on the performer. Because the light panels are off during the second time interval **302**, the contrast between the phosphorescent makeup and any surfaces in the room without phosphorescent makeup is extremely high (i.e., the rest of the room is pitch black or at least quite dark, and as a result there is no significant light reflecting off of surfaces in the room, other than reflected light from the phosphorescent emissions), thereby improving the ability of the system to differentiate the various patterns applied to the performer's face. In addition, because the light panels are on half of the time, the performer will be able to see around the room during the performance, and also the phosphorescent makeup is constantly recharged. The frequency of the synchronization signals is 1/(time interval **303**) and may be set at such a high rate that the performer will not even notice that the light panels are being turned on and off. For example, at a flashing rate of 90 Hz or above, virtually all humans are unable to perceive that a light is flashing and the light appears to be continuously illuminated. In psychophysical parlance, when a high frequency flashing light is perceived by humans to be continuously illuminated, it is said that "fusion" has been achieved. In one embodiment, the light panels are cycled at 120 Hz; in another embodiment, the light panels are cycled at 140 Hz, both frequencies far above the fusion threshold of any human.

However, the underlying principles of the invention are not limited to any particular frequency.

SURFACE CAPTURE OF SKIN USING PHOSPHORESCENT RANDOM PATTERNS

FIG. **4** shows images captured using the methods described above and the 3D surface and textured 3D surface reconstructed from them. Prior to capturing the images, a phosphorescent makeup was applied to a Caucasian model's face with an exfoliating sponge. Luminescent zinc sulfide with a copper activator (ZnS:Cu) is the phosphor responsible for the makeup's phosphorescent properties. This particular formulation of luminescent Zinc Sulfide is approved by the FDA color additives regulation 21 CFR Part 73 for makeup preparations. The particular brand is Fantasy F/XT Tube Makeup; Product #: FFX; Color Designation: GL; manufactured by Mehron Inc. of 100 Red Schoolhouse Rd. Chestnut Ridge, N.Y. 10977. The motion capture session that produced these images utilized 8 grayscale dark cameras (such as cameras **204-205**) surrounding the model's face from a plurality of angles and 1 color lit camera (such as cameras **214-215**) pointed at the model's face from an angle to provide the view seen in Lit Image **401**. The grayscale cameras were model A311f from Basler AG, An der Strusbek 60-62, 22926 Ahrensburg, Germany, and the color camera was a Basler model A311fc. The light panels **208-209** were flashed at a rate of 72 flashes per second.

Lit Image **401** shows an image of the performer captured by one of the color lit cameras **214-215** during lit interval **301**, when the light panels **208-209** are on and the color lit camera **214-215** shutters are open. Note that the phosphorescent makeup is quite visible on the performer's face, particularly the lips.

Dark Image **402** shows an image of the performer captured by one of the grayscale dark cameras **204-205** during dark interval **302**, when the light panels **208-209** are off and the grayscale dark camera **204-205** shutters are open. Note that only random pattern of phosphorescent makeup is visible on the surfaces where it is applied. All other surfaces in the image, including the hair, eyes, teeth, ears and neck of the performer are completely black.

3D Surface **403** shows a rendered image of the surface reconstructed from the Dark Images **402** from grayscale dark cameras **204-205** (in this example, 8 grayscale dark cameras were used, each producing a single Dark Image **402** from a different angle) pointed at the model's face from a plurality of angles. One reconstruction process which may be used to create this image is detailed in co-pending application Apparatus and Method for Performing Motion Capture Using A Random Pattern On Capture Surfaces, Ser. No. 11/255,854, Filed Oct. 20, 2005. Note that 3D Surface **403** was only reconstructed from surfaces where there was phosphorescent makeup applied. Also, the particular embodiment of the technique that was used to produce the 3D Surface **403** fills in cavities in the 3D surface (e.g., the eyes and the mouth in this example) with a flat surface.

Textured 3D Surface **404** shows the Lit Image **401** used as a texture map and mapped onto 3D Surface **403** and rendered at an angle. Although Textured 3D Surface **404** is a computer-generated 3D image of the model's face, to the human eye it appears real enough that when it is rendered at an angle, such as it is in image **404**, it creates the illusion that the model is turning her head and actually looking at an angle. Note that no phosphorescent makeup was applied to the model's eyes and teeth, and the image of the eyes and teeth are mapped onto flat surfaces that fill those cavities in the 3D surface. Nonetheless, the rest of the 3D surface is reconstructed so accurately, the resulting Textured 3D Surface **404** approaches photorealism. When this process is applied to create successive frames of Textured 3D Surfaces **404**, when the frames are played back in real-time, the level of realism is such that, to the untrained eye, the successive frames look like actual video of the model, even though it is a computer-generated 3D image of the model viewed from side angle.

Since the Textured 3D Surfaces **404** produces computer-generated 3D images, such computer-generated images can manipulated with far more flexibility than actual video captured of the model. With actual video it is often impractical (or impossible) to show the objects in the video from any camera angles other than the angle from which the video was shot. With computer-generated 3D, the image can be rendered as if it is viewed from any camera angle. With actual video it is generally necessary to use a green screen or blue screen to separate an object from its background (e.g. so that a TV meteorologist can be composited in front of a weather map), and then that green- or blue-screened object can only be presented from the point of view of the camera shooting the object. With the technique just described, no green/blue screen is necessary. Phosphorescent makeup, paint, or dye is applied to the areas desired to be captured (e.g. the face, body and clothes of the meteorologist) and then the entire background will be separated from the object. Further, the object can be presented from any camera angle. For example, the meteorologist can be shown from a straight-on shot, or from an side angle shot, but still composited in front of the weather map.

Further, a 3D generated image can be manipulated in 3D. For example, using standard 3D mesh manipulation tools (such as those in Maya, sold by Autodesk, Inc.) the nose can be shortened or lengthened, either for cosmetic reasons if the performer feels her nose would look better in a different size, or as a creature effect, to make the performer look like a fantasy character like Gollum of "Lord of the Rings." More extensive 3D manipulations could add wrinkles to the performers face to make her appear to be older, or smooth out wrinkles to make her look younger. The face could also be manipulated to change the performer's expression, for example, from a smile to a frown. Although some 2D manipulations are possible with conventional 2D video capture, they are generally limited to manipulations from the point of view of the camera. If the model turns her head during the video sequence, the 2D manipulations applied when the head is facing the camera would have to be changed when the head is turned. 3D manipulations do not need to be changed, regardless of which way the head is turned. As a result, the techniques described above for creating successive frames of Textured 3D Surface **404** in a video sequence make it possible to capture objects that appear to look like actual video, but nonetheless have the flexibility of manipulation as computer-generated 3D objects, offering enormous advantages in production of video, motion pictures, and also video games (where characters may be manipulated by the player in 3D).

Note that in FIG. **4** the phosphorescent makeup is visible on the model's face in Lit Image **401** and appears like a yellow powder has been spread on her face. It is particularly prominent on her lower lip, where the lip color is almost entirely changed from red to yellow. These discolorations appear in Textured 3D Surface **404**, and they would be even more prominent on a dark-skinned model who is, for example, African in race. Many applications (e.g. creating a fantasy 3D character like Gollum) only require 3D Surface **403**, and Textured 3D Surface **404** would only serve as a reference to the director of the motion capture session or as a reference to

3D animators manipulating the 3D Surface **403**. But in some applications, maintaining the actual skin color of the model's skin is important and the discolorations from the phosphorescent makeup are not desirable.

SURFACE CAPTURE USING PHOSPHORESCENT MAKEUP MIXED WITH BASE

FIG. **5** shows a similar set of images as FIG. **4**, captured and created under the same conditions: with 8 grayscale dark cameras (such as **204-205**), 1 color camera (such as **214-215**), with the Lit Image **501** captured by the color lit camera during the time interval when the Light Array **208-9** is on, and the Dark Image **502** captured by one of the 8 grayscale dark cameras when the Light Array **208-9**. 3D Surface **503** is reconstructed from the **8** Dark Images **502** from the 8 grayscale dark cameras, and Textured 3D Surface **504** is a rendering of the Lit Image **501** texture-mapped onto 3D Surface **503** (and unlike image **404**, image **504** is rendered from a camera angle similar to the camera angle of the color lit camera that captured Lit Image **501**).

However, there is a notable differences between the images of FIG. **5** and FIG. **4**: The phosphorescent makeup that is noticeably visible in Lit Image **401** and Textured 3D Surface **404** is almost invisible in Lit Image **501** and Textured 3D Surface **504**. The reason for this is that, rather than applying the phosphorescent makeup to the model in its pure form, as was done in the motion capture session of FIG. **4**, in the embodiment illustrated in FIG. **5** the phosphorescent makeup was mixed with makeup base and was then applied to the model. The makeup base used was "Clean Makeup" in "Buff Beige" color manufactured by Cover Girl, and it was mixed with the same phosphorescent makeup used in the FIG. **4** shoot in a proportion of 80% phosphorescent makeup and 20% base makeup.

Note that mixing the phosphorescent makeup with makeup base does reduce the brightness of the phosphorescence during the Dark interval **302**. Despite this, the phosphorescent brightness is still sufficient to produce Dark Image **502**, and there is enough dynamic range in the dark images from the 8 grayscale dark cameras to reconstruct 3D Surface **503**. As previously noted, some applications do not require an accurate capture of the skin color of the model, and in that case it is advantageous to not mix the phosphorescent makeup with base, and then get the benefit of higher phosphorescent brightness during the Dark interval **302** (e.g. higher brightness allows for a smaller aperture setting on the camera lens, which allows for larger depth of field). But some applications do require an accurate capture of the skin color of the model. For such applications, it is advantageous to mix the phosphorescent makeup with base (in a color suited for the model's skin tone) makeup, and work within the constraints of lower phosphorescent brightness. Also, there are applications where some phosphor visibility is acceptable, but not the level of visibility seen in Lit Image **401**. For such applications, a middle ground can be found in terms of skin color accuracy and phosphorescent brightness by mixing a higher percentage of phosphorescent makeup relative to the base.

In another embodiment, luminescent zinc sulfide ($ZnS:Cu$) in its raw form is mixed with base makeup and applied to the model's face.

SURFACE CAPTURE OF FABRIC WITH PHOSPHORESCENT RANDOM PATTERNS

In another embodiment, the techniques described above are used to capture cloth. FIG. **6** shows a capture of a piece of cloth (part of a silk pajama top) with the same phosphorescent makeup used in FIG. **4** sponged onto it. The capture was done under the exact same conditions with 8 grayscale dark cameras (such as **204-205**) and 1 color lit camera (such as **214-215**). The phosphorescent makeup can be seen slightly discoloring the surface of Lit Frame **601**, during lit interval **301**, but it can be seen phosphorescing brightly in Dark Frame **602**, during dark interval **302**. From the 8 cameras of Dark Frame **602**, 3D Surface **603** is reconstructed using the same techniques used for reconstructing the 3D Surfaces **403** and **503**. And, then Lit Image **601** is texture-mapped onto 3D Surface **603** to produce Textured 3D Surface **604**.

FIG. **6** shows a single frame of captured cloth, one of hundreds of frames that were captured in a capture session while the cloth was moved, folded and unfolded. And in each frame, each area of the surface of the cloth was captured accurately, so long as at least 2 of the 8 grayscale cameras had a view of the area that was not overly oblique (e.g. the camera optical axis was within 30 degrees of the area's surface normal). In some frames, the cloth was contorted such that there were areas within deep folds in the cloth (obstructing the light from the light panels **208-209**), and in some frames the cloth was curved such that there were areas that reflected back the light from the light panels **208-209** so as to create a highlight (i.e. the silk fabric was shiny). Such lighting conditions would make it difficult, if not impossible, to accurately capture the surface of the cloth using reflected light during lit interval **301** because shadow areas might be too dark for an accurate capture (e.g. below the noise floor of the camera sensor) and some highlights might be too bright for an accurate capture (e.g. oversaturating the sensor so that it reads the entire area as solid white). But, during the dark interval **302**, such areas are readily captured accurately because the phosphorescent makeup emits light quite uniformly, whether deep in a fold or on an external curve of the cloth.

Because the phosphor charges from any light incident upon it, including diffused or reflected light that is not directly from the light panels **208-209**, even phosphor within folds gets charged (unless the folds are so tightly sealed no light can get into them, but in such cases it is unlikely that the cameras can see into the folds anyway). This illustrates a significant advantage of utilizing phosphorescent makeup (or paint or dye) for creating patterns on (or infused within) surfaces to be captured: the phosphor is emissive and is not subject to highlights and shadows, producing a highly uniform brightness level for the patterns seen by the grayscale dark cameras **204-205**, that neither has areas too dark nor areas too bright.

Another advantage of dyeing or painting a surface with phosphorescent dye or paint, respectively, rather than applying phosphorescent makeup to the surface is that with dye or paint the phosphorescent pattern on the surface can be made permanent throughout a motion capture session. Makeup, by its nature, is designed to be removable, and a performer will normally remove phosphorescent makeup at the end of a day's motion capture shoot, and if not, almost certainly before going to bed. Frequently, motion capture sessions extend across several days, and as a result, normally a fresh application of phosphorescent makeup is applied to the performer each day prior to the motion capture shoot. Typically, each fresh application of phosphorescent makeup will result in a different random pattern. One of the techniques disclosed in co-pending applications is the tracking of vertices ("vertex tracking") of the captured surfaces. Vertex tracking is accomplished by correlating random patterns from one captured frame to the next. In this way, a point on the captured surface can be followed from frame-to-frame. And, so long as the random patterns on the surface stay the same, a point on a captured surface even can be tracked from shot-to-shot. In the case of random patterns made using phosphorescent makeup, it is typically practical to leave the makeup largely undisturbed (although it is possible for some areas to get smudged, the bulk of the makeup usually stays unchanged until removed) during one day's-worth of motion capture shooting, but as previously mentioned it normally is removed at the end of the day. So, it is typically impractical to maintain the same phosphorescent random pattern (and with that, vertex tracking based on tracking a particular random pattern) from day-to-day. But when it comes to non-skin objects like fabric, phosphorescent dye or paint can be used to create a random pattern. Because dye and paint are essentially permanent, random patterns will not get smudged during the motion capture session, and the same random patterns will be unchanged from day-to-day. This allows vertex tracking of dyed or painted objects with random patterns to track the same random pattern through the duration of a multi-day motion capture session (or in fact, across multiple motion capture sessions spread over long gaps in time if desired).

Skin is also subject to shadows and highlights when viewed with reflected light. There are many concave areas (e.g., eye sockets) that often are shadowed. Also, skin may be shiny and cause highlights, and even if the skin is covered with makeup to reduce its shininess, performers may sweat during a physical performance, resulting in shininess from sweaty skin. Phosphorescent makeup emits uniformly both from shiny and matte skin areas, and both from convex areas of the body (e.g. the nose bridge) and concavities (e.g. eye sockets). Sweat has little impact on the emission brightness of phosphorescent makeup. Phosphorescent makeup also charges while folded up in areas of the body that fold up (e.g. eyelids) and when it unfolds (e.g. when the performer blinks) the phosphorescent pattern emits light uniformly.

Returning back to FIG. **6**, note that the phosphorescent makeup can be seen on the surface of the cloth in Lit Frame **601** and in Textured 3D Surface **604**. Also, while this is not apparent in the images, although it may be when the cloth is in motion, the phosphorescent makeup has a small impact on the pliability of the silk fabric. In another embodiment, instead of using phosphorescent makeup (which of course is formulated for skin application) phosphorescent dye is used to create phosphorescent patterns on cloth. Phosphorescent dyes are available from a number of manufacturers. For example, it is common to find t-shirts at novelty shops that have glow-in-the-dark patterns printed onto them with phosphorescent dyes. The dyes can also can be formulated manually by mixing phosphorescent powder (e.g. ZnS:Cu) with off-the-shelf clothing dyes, appropriate for the given type of fabric. For example, Dharma Trading Company with a store at 1604 Fourth Street, San Rafael, Calif. stocks a large number of dyes, each dye designed for certain fabrics types (e.g. Dharma Fiber Reactive Procion Dye is for all natural fibers, Sennelier Tinfix Design—French Silk Dye is for silk and wool), as well as the base chemicals to formulate such dyes. When phosphorescent powder is used as the pigment in such formulations, then a dye appropriate for a given fabric type is produced and the fabric can be dyed with phosphorescent pattern while minimizing the impact on the fabric's pliability.

SURFACE CAPTURE OF STOP-MOTION ANIMATION CHARACTERS WITH PHOSPHORESCENT RANDOM PATTERNS

In another embodiment, phosphor is embedded in silicone or a moldable material such as modeling clay in characters, props and background sets used for stop-motion animation. Stop-motion animation is a technique used in animated motion pictures and in motion picture special effects. An exemplary prior art stop-motion animation stage is illustrated in FIG. **7***a*. Recent stop-motion animations are feature films *Wallace & Gromit in The Curse of the Were-Rabbit* (Academy Award-winning best animated feature film released in 2005) (hereafter referenced as WG) and *Corpse Bride* (Academy Award-nominated best animated feature film released in 2005) (hereafter referred to as CB). Various techniques are used in stop-motion animation. In WG the characters **702**-**703** are typically made of modeling clay, often wrapped around a metal armature to give the character structural stability. In CB the characters **702**-**703** are created from puppets with mechanical armatures which are then covered with molded silicone (e.g. for a face), or some other material (e.g. for clothing). The characters **702**-**703** in both films are placed in complex sets **701** (e.g. city streets, natural settings, or in buildings), the sets are lit with lights such as **708**-**709**, a camera such as **705** is placed in position, and then one frame is shot by the camera **705** (in modern stop-motion animation, typically, a digital camera). Then the various characters (e.g. the man with a leash **702** and the dog **703**) that are in motion in the scene are moved very slightly. In the case of WB, often the movement is achieved by deforming the clay (and potentially the armature underneath it) or by changing a detailed part of a character **702**-**703** (e.g. for each frame swapping in a different mouth shape on a character **702**-**703** as it speaks). In the case of CB, often motion is achieved by adjusting the character puppet **702**-**703** armature (e.g. a screwdriver inserted in a character puppet's **702**-**703** ear might turn a screw that actuates the armature causing the character's **702**-**703** mouth to open). Also, if the camera **705** is moving in the scene, then the camera **705** is placed on a mechanism that allows it to be moved, and it is moved slightly each frame time. After all the characters **702**-**703** and the camera **705** in a scene have been moved, another frame is captured by the camera **705**. This painstaking process continues frame-by-frame until the shot is completed.

There are many difficulties with the stop-motion animation process that both limit the expressive freedom of the animators, limit the degree of realism in motion, and add to the time and cost of production. One of these difficulties is animating many complex characters **702**-**703** within a complex set **701** on a stop-motion animation stage such as that shown in FIG. **7***a*. The animators often need to physically climb into the sets, taking meticulous care not to bump anything inadvertently, and then make adjustments to character **702**-**703** expressions, often with sub-millimeter precision. When characters **702**-**703** are very close to each other, it gets even more difficult. Also, sometimes characters **702**-**703** need to be placed in a pose where a character **702**-**703** can easily fall over (e.g. a character **702**-**703** is doing a hand stand or a character **702**-**703** is flying). In these cases the character **702**-**703** requires some support structure that may be seen by the camera **705**, and if so, needs to be erased from the shot in post-production.

In one embodiment illustrated by the stop-motion animation stage in FIG. **7***b*, phosphorescent phosphor (e.g. zinc sulfide) in powder form can be mixed (e.g. kneaded) into modeling clay resulting in the clay surface phosphorescing in darkness with a random pattern. Zinc sulfide powder also can be mixed into-liquid silicone before the silicone is poured into a mold, and then when the silicone dries and solidifies, it has zinc sulfide distributed throughout. In another embodiment, zinc sulfide powder can be spread onto the inner surface of a mold and then liquid silicone can be poured into the mold to solidify (with the zinc sulfide embedded on the surface). In yet another embodiment, zinc sulfide is mixed in with paint that is applied to the surface of either modeling clay or silicone. In yet another embodiment, zinc sulfide is dyed into fabric worn by characters **702-703** or mixed into paint applied to props or sets **701**. In all of these embodiments the resulting effect is that the surfaces of the characters **702-703**, props and sets **701** in the scene phosphoresce in darkness with random surface patterns.

At low concentrations of zinc sulfide in the various embodiments described above, the zinc sulfide is not significantly visible under the desired scene illumination when light panels **208-208** are on. The exact percentage of zinc sulfide depends on the particular material it is mixed with or applied to, the color of the material, and the lighting circumstances of the character **702-703**, prop or set **701**. But, experimentally, the zinc sulfide concentration can be continually reduced until it is no longer visually noticeable in lighting situations where the character **702-703**, prop or set **701** is to be used. This may result in a very low concentration of zinc sulfide and very low phosphorescent emission. Although this normally would be a significant concern with live action frame capture of dim phosphorescent patterns, with stop-motion animation, the dark frame capture shutter time can be extremely long (e.g. 1 second or more) because by definition, the scene is not moving. With a long shutter time, even very dim phosphorescent emission can be captured accurately.

Once the characters **702-703**, props and the set **701** in the scene are thus prepared, they look almost exactly as they otherwise would look under the desired scene illumination when light panels **208-209** are on, but they phosphoresce in random patterns when the light panels **208-209** are turned off. At this point all of the characters **702-703**, props and the set **701** of the stop-motion animation can now be captured in 3D using a configuration like that illustrated in FIGS. **2***a* and **2***b* and described in the co-pending applications. (FIGS. **7***b*-**7***e* illustrate stop-motion animation stages with light panels **208-209**, dark cameras **204-205** and lit cameras **214-215** from FIGS. **2***a* and **2***b* surrounding the stop-motion animation characters **702-703** and set **701**. For clarity, the connections to devices **208-209**, **204-205** and **214-215** have been omitted from FIGS. **7***b*-**7***e*, but in they would be hooked up as illustrated in FIGS. **2***a* and **2***b*.) Dark cameras **204-205** and lit cameras **214-215** are placed around the scene illustrated in FIG. **7***b* so as to capture whatever surfaces will be needed to be seen in the final animation. And then, rather than rapidly switching sync signals **221-223** at a high capture frame rate (e.g. 90 fps), the sync signals are switched very slowly, and in fact may be switched by hand.

In one embodiment, the light panels **208-209** are left on while the animators adjust the positions of the characters **702-703**, props or any changes to the set **701**. Note that the light panels **208-209** could be any illumination source, including incandescent lamps, because there is no requirement in stop-motion animation for rapidly turning on and off the illumination source. Once the characters **702-703**, props and set **701** are in position for the next frame, lit cam sync signal **223** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the lit cameras **214-215** capture a frame for a specified duration based on the desired exposure time for the captured frames. In other embodiments, different cameras may have different exposure times based on individual exposure requirements.

Next, light panels **208-209** are turned off (either by sync signal **222** or by hand) and the lamps are allowed to decay until the scene is in complete darkness (e.g. incandescent lamps may take many seconds to decay). Then, dark cam sync signal **221** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the dark cameras **208-209** capture a frame of the random phosphorescent patterns for a specified duration based on the desired exposure time for the captured frames. Once again, different cameras have different exposure times based on individual exposure requirements. As previously mentioned, in the case of very dim phosphorescent emissions, the exposure time may be quite long (e.g., a second or more). The upper limit of exposure time is primarily limited by the noise accumulation of the camera sensors. The captured dark frames are processed by data processing system **210** to produce 3D surface **207** and then to map the images captured by the lit cameras **214-215** onto the 3D surface **207** to create textured 3D surface **217**. Then, the light panels, **208-9** are turned back on again, the characters **702-703**, props and set **701** are moved again, and the process described in this paragraph is repeated until the entire shot is completed.

The resulting output is the successive frames of textured 3D surfaces of all of the characters **702-703**, props and set **701** with areas of surfaces embedded or painted with phosphor that are in view of at least 2 dark cameras **204-205** at a non-oblique angle (e.g., <30 degrees from the optical axis of a camera). When these successive frames are played back at the desired frame rate (e.g., 24 fps), the animated scene will come to life, but unlike frames of a conventional stop-motion animation, the animation will be able to be viewed from any camera position, just by rendering the textured 3D surfaces from a chosen camera position. Also, if the camera position of the final animation is to be in motion during a frame sequence (e.g. if a camera is following a character **702-703**), it is not necessary to have a physical camera moving in the scene. Rather, for each successive frame, the textured 3D surfaces of the scene are simply rendered from the desired camera position for that frame, using a 3D modeling/animation application software such as Maya (from Autodesk, Inc.).

In another embodiment, illustrated in FIGS. **7***c*-**7***e*, some or all of the different characters **702-703**, props, and/or sets **701** within a single stop-motion animation scene are shot separately, each in a configuration such as FIGS. **2***a* and **2***b*. For example, if a scene had man with leash **702** and his dog **703** walking down a city street set **701**, the city street set **701**, the man with leash **702**, and the dog **703** would be shot individually, each with separate motion capture systems as illustrated in FIG. **1***c* (for city street set **701**, FIG. **7***d* (for man with leash **702**) and FIG. **7***e* (for dog **703**)*a*. The stop-motion animation of the 2 characters **702-703** and 1 set **701** would each then be separately captured as individual textured 3D surfaces **217**, in the manner described above. Then, with a 3D modeling and/or animation application software the **2** characters **702-703** and 1 set **701** would be rendered together into a 3D scene. In one embodiment, the light panel **208-209** lighting the characters **702-703** and the set **701** could be configured to be the same, so the man with leash **702** and the dog **703** appear to be illuminated in the same environment as the set **701**. In another embodiment, flat lighting (i.e. uniform lighting to minimize shadows and highlights) is used, and then lighting (including shadows and highlights) is simulated by the 3D modeling/animation application software. Through the 3D modeling/animation application software the animators will be able to see how the characters **702-703** look relative to each other and the set **701**, and will also be able to look at the characters **702-703** and set **701** from any camera angle they wish, without having to move any of the physical cameras **204-205** or **214-215** doing the capture.

This approach provides significant advantages to stop-motion animation. The following are some of the advantages of this approach: (a) individual characters **702-703** may be manipulated individually without worrying about the animator bumping into another character **702-703** or the characters **702-703** bumping into each other, (b) the camera position of the rendered frames may be chosen arbitrarily, including having the camera position move in successive frames, (c) the rendered camera position can be one where it would not be physically possible to locate a camera **705** in a conventional stop-motion configuration (e.g. directly between 2 characters **702-703** that are close together, where there is no room for a camera **705**), (d) the lighting, including highlights and shadows can be controlled arbitrarily, including creating lighting situations that are not physically possible to realize (e.g. making a character glow), (e) special effects can be applied to the characters **702-703** (e.g. a ghost character **702-703** can be made translucent when it is rendered into the scene), (f) a character **702-703** can remain in a physically stable position on the ground while in the scene it is not (e.g. a character **702-703** can be captured in an upright position, while it is rendered into the scene upside down in a hand stand, or rendered into the scene flying above the ground), (g) parts of the character **702-703** can be held up by supports that do not have phosphor on them, and as such will not be captured (and will not have to be removed from the shot later in post-production), (h) detail elements of a character **702-703**, like mouth positions when the character **702-703** is speaking, can be rendered in by the 3D modeling/animation application, so they do not have be attached and then removed from the character **702-703** during the animation, (i) characters **702-703** can be rendered into computer-generated 3D scenes (e.g. the man with leash **702** and dog **703** can be animated as clay animations, but the city street set **701** can be a computer-generated scene), (j) 3D motion blur can be applied to the objects as they move (or as the rendered camera position moves), resulting in a smoother perception of motion to the animation, and also making possible faster motion without the perception of jitter.

ADDITIONAL PHOSPHORESCENT PHOSPHORS

In another embodiment, different phosphors other than ZnS:Cu are used as pigments with dyes for fabrics or other non-skin objects. ZnS:Cu is the preferred phosphor to use for skin applications because it is FDA-approved as a cosmetic pigment. But a large variety of other phosphors exist that, while not approved for use on the skin, are in some cases approved for use within materials handled by humans. One such phosphor is $SrAl_2O_4:Eu^{2+},Dy^{3+}$. Another is $SrAl_2O_4:Eu^{2+}$. Both phosphors have a much longer afterglow than ZnS:Cu for a given excitation.

OPTIMIZING PHOSPHORESCENT EMISSION

Many phosphors that phosphoresce in visible light spectra are charged more efficiently by ultraviolet light than by visible light. This can be seen in chart **800** of FIG. **8** which show approximate excitation and emission curves of ZnS:Cu (which we shall refer to hereafter as "zinc sulfide") and various light sources. In the case of zinc sulfide, its excitation curve **811** spans from about 230 nm to 480 nm, with its peak at around 360 nm. Once excited by energy in this range, its phosphorescence curve **812** spans from about 420 nm to 650 nm, producing a greenish glow. The zinc sulfide phosphorescence brightness **812** is directly proportional to the excitation energy **811** absorbed by the zinc sulfide. As can be seen by excitation curve **811**, zinc sulfide is excited with varying degrees of efficiency depending on wavelength. For example, at a given brightness from an excitation source (i.e. in the case of the presently preferred embodiment, light energy from light panels **208-209**) zinc sulfide will absorb only 30% of the energy at 450 nm (blue light) that it will absorb at 360 nm (UVA light, commonly called "black light"). Since it is desirable to get the maximum phosphorescent emission **812** from the zinc sulfide (e.g. brighter phosphorescence will allow for smaller lens apertures and longer depth of field), clearly it is advantageous to excite the zinc sulfide with as much energy as possible. The light panels **208-209** can only produce up to a certain level of light output before the light becomes uncomfortable for the performers. So, to maximize the phosphorescent emission output of the zinc sulfide, ideally the light panels **208-209** should output light at wavelengths that are the most efficient for exciting zinc sulfide.

Other phosphors that may be used for non-skin phosphorescent use (e.g. for dyeing fabrics) also are excited best by ultraviolet light. For example, $SrAl_2O_4:Eu^{2+},Dy^{3+}$ and $SrAl_2O_4:Eu^{2+}$ are both excited more efficiently with ultraviolet light than visible light, and in particular, are excited quite efficiently by UVA (black light).

As can be seen in FIG. **3**, a requirement for a light source used for the light panels **208-209** is that the light source can transition from completely dark to fully lit very quickly (e.g. on the order of a millisecond or less) and from fully lit to dark very quickly (e.g. also on the order of a millisecond or less). Most LEDs fulfill this requirement quite well, typically turning on an off on the order of microseconds. Unfortunately, though, current LEDs present a number of issues for use in general lighting. For one thing, LEDs currently available have a maximum light output of approximately 35 W. The BL-43F0-0305 from Lamina Ceramics, 120 Hancock Lane, Westampton, N.J. 08060 is one such RGB LED unit. For another, currently LEDs have special power supply requirements (in the case of the BL-43F0-0305, different voltage supplies are need for different color LEDs in the unit). In addition, current LEDs require very large and heavy heatsinks and produce a great deal of heat. Each of these issues results in making LEDs expensive and somewhat unwieldy for lighting an entire motion capture stage for a performance. For example, if 3500 Watts were needed to light a stage, 100 35 W LED units would be needed.

But, in addition to these disadvantages, the only very bright LEDs currently available are white or RGB LEDs. In the case of both types of LEDs, the wavelengths of light emitted by the LED does not overlap with wavelengths where the zinc sulfide is efficiently excited. For example, in FIG. **8** the emission curve **823** of the blue LEDs in the BL-43F0-0305 LED unit is centered around 460 nm. It only overlaps with the tail end of the zinc sulfide excitation curve **811** (and the Red and Green LEDs don't excite the zinc sulfide significantly at all). So, even if the blue LEDs are very bright (to the point where they are as bright as is comfortable to the performer), only a small percentage of that light energy will excite the zinc sulfide, resulting in a relatively dim phosphorescence. Violet and UVA ("black light") LEDs do exist, which would excite the zinc sulfide more efficiently; but they only currently are available at very low power levels, on the order of 0.1 Watts. To achieve 3500 Watts of illumination would require 35,000 such 0.1 Watt LEDs, which would be quite impractical and prohibitively expensive.

FLUORESCENT LAMPS AS A FLASHING ILLUMINATION SOURCE

Other lighting sources exist that output light at wavelengths that are more efficiently absorbed by zinc sulfide. For example, fluorescent lamps (e.g. 482-S9 from Kino-Flo, Inc.

2840 North Hollywood Way, Burbank, Calif. 91505) are available that emit UVA (black light) centered around 350 nm with an emission curve similar to **821**, and Blue/violet fluorescent lamps (e.g. 482-S10-S from Kino-Flo) exist that emit bluish/violet light centered around 420 nm with an emission curve similar to **822**. The emission curves **821** and **822** are much closer to the peak of the zinc sulfide excitation curve **811**, and as a result the light energy is far more efficiently absorbed, resulting in a much higher phosphorescent emission **812** for a given excitation brightness. Such fluorescent bulbs are quite inexpensive (typically $15/bulb for a 48" bulb), produce very little heat, and are very light weight. They are also available in high wattages. A typical 4-bulb fluorescent fixture produces 160 Watts or more. Also, theatrical fixtures are readily available to hold such bulbs in place as staging lights. (Note that UVB and UVC fluorescent bulbs are also available, but UVB and UVC exposure is known to present health hazards under certain conditions, and as such would not be appropriate to use with human or animal performers without suitable safety precautions.)

The primary issue with using fluorescent lamps is that they are not designed to switch on and off quickly. In fact, ballasts (the circuits that ignite and power fluorescent lamps) typically turn the lamps on very slowly, and it is common knowledge that fluorescent lamps may take a second or two until they are fully illuminated.

FIG. **9** shows a diagrammatic view of a prior art fluorescent lamp. The elements of the lamp are contained within a sealed glass bulb **910** which, in this example, is in the shape of a cylinder (commonly referred to as a "tube"). The bulb contains an inert gas **940**, typically argon, and a small amount of mercury **930**. The inner surface of the bulb is coated with a phosphor **920**. The lamp has 2 electrodes **905-906**, each of which is coupled to a ballast through connectors **901-904**. When a large voltage is applied across the electrodes **901-904**, some of the mercury in the tube changes from a liquid to a gas, creating mercury vapor, which, under the right electrical circumstances, emits ultraviolet light. The ultraviolet light excites the phosphor coating the inner surface of the bulb. The phosphor then fluoresces light at a higher wavelength than the excitation wavelength. A wide range of phosphors are available for fluorescent lamps with different wavelengths. For example, phosphors that are emissive at UVA wavelengths and all visible light wavelengths are readily available off-the-shelf from many suppliers.

Standard fluorescent ballasts are not designed to switch fluorescent lamps on and off quickly, but it is possible to modify an existing ballast so that it does. FIG. **10** is a circuit diagram of a prior art 27 Watt fluorescent lamp ballast **1002** modified with an added sync control circuit **1001** of the present invention.

For the moment, consider only the prior art ballast circuit **1002** of FIG. **10** without the modification **1001**. Prior art ballast **1002** operates in the following manner: A voltage doubler circuit converts 120 VAC from the power line into 300 volts DC. The voltage is connected to a half bridge oscillator/driver circuit, which uses two NPN power transistors **1004-1005**. The half bridge driver, in conjunction with a multi-winding transformer, forms an oscillator. Two of the transformer windings provide high drive current to the two power transistors **1004-1005**. A third winding of the transformer is in line with a resonant circuit, to provide the needed feedback to maintain oscillation. The half bridge driver generates a square-shaped waveform, which swings from +300 volts during one half cycle, to zero volts for the next half cycle. The square wave signal is connected to an "LC" (i.e. inductor-capacitor) series resonant circuit. The frequency of the circuit is determined by the inductance Lres and the capacitance Cres. The fluorescent lamp **1003** is connected across the resonant capacitor. The voltage induced across the resonant capacitor from the driver circuit provides the needed high voltage AC to power the fluorescent lamp **1003**. To kick the circuit into oscillation, the base of the power transistor **1005** is connected to a simple relaxation oscillator circuit. Current drawn from the 300 v supply is routed through a resistor and charges up a 0.1 uF capacitor. When the voltage across the capacitor reaches about 20 volts, a DIAC (a bilateral trigger diode) quickly switches and supplies power transistor **1005** with a current spike. This spike kicks the circuit into oscillation.

Synchronization control circuit **1001** is added to modify the prior art ballast circuit **1002** described in the previous paragraph to allow rapid on-and-off control of the fluorescent lamp **1003** with a sync signal. In the illustrated embodiment in FIG. **10**, a sync signal, such as sync signal **222** from FIG. **2**, is electrically coupled to the SYNC+ input. SYNC− is coupled to ground. Opto-isolator NEC PS2501-1 isolates the SYNC+ and SYNC− inputs from the high voltages in the circuit. The opto-isolator integrated circuit consists of a light emitting diode (LED) and a phototransistor. The voltage differential between SYNC+ and SYNC− when the sync signal coupled to SYNC+ is at a high level (e.g. ≧2.0V) causes the LED in the opto-isolator to illuminate and turn on the phototransistor in the opto-isolator. When this phototransistor is turned on, voltage is routed to the gate of an n-channel MOSFET Q1 (Zetex Semiconductor ZVN4106F DMOS FET). MOSFET Q1 functions as a low resistance switch, shorting out the base-emitter voltage of power transistor **1005** to disrupt the oscillator, and turn off fluorescent lamp **1003**. To turn the fluorescent lamp back on, the sync signal (such as **222**) is brought to a low level (e.g. <0.8V), causing the LED in the opto-isolator to turn off, which turns off the opto-isolator phototransistor, which turns off MOSFET Q1 so it no longer shorts out the base-emitter voltage of power transistor **1005**. This allows the kick start circuit to initialize ballast oscillation, and the fluorescent lamp **1003** illuminates.

This process repeats as the sync signal coupled to SYNC+ oscillates between high and low level. The synch control circuit **1001** combined with prior art ballast **1002** will switch fluorescent lamp **1003** on and off reliably, well in excess of 120 flashes per second. It should be noted that the underlying principles of the invention are not limited to the specific set of circuits illustrated in FIG. **10**.

FIG. **11** shows the light output of fluorescent lamp **1003** when synch control circuit **1001** is coupled to prior art ballast **1002** and a sync signal **222** is coupled to circuit **1001** as described in the previous paragraph. Traces **1110** and **1120** are oscilloscope traces of the output of a photodiode placed on the center of the bulb of a fluorescent lamp using the prior art ballast circuit **1002** modified with the sync control circuit **1001** of the present invention. The vertical axis indicates the brightness of lamp **1003** and the horizontal axis is time. Trace **1110** (with 2 milliseconds/division) shows the light output of fluorescent lamp **1003** when sync signal **222** is producing a 60 Hz square wave. Trace **1120** (with the oscilloscope set to 1 millisecond/division and the vertical brightness scale reduced by 50%) shows the light output of lamp **1003** under the same test conditions except now sync signal **222** is producing a 250 Hz square wave. Note that the peak **1121** and minimum **1122** (when lamp **1003** is off and is almost completely dark) are still both relatively flat, even at a much higher switching frequency. Thus, the sync control circuit **1001** modification to prior art ballast **1002** produces dramatically different light output than the unmodified ballast **1002**, and makes it possible to achieve on and off switching of fluorescent lamps at high frequencies as required by the motion capture system illustrated in FIG. **2** with timing similar to that of FIG. **3**.

Although the modified circuit shown in FIG. **10** will switch a fluorescent lamp **1003** on and off rapidly enough for the requirements of a motion capture system such as that illustrated in FIG. **2**, there are certain properties of fluorescent lamps that may be modified for use in a practical motion capture system.

FIG. **12** illustrates one of these properties. Traces **1210** and **1220** are the oscilloscope traces of the light output of a General Electric Gro and Sho fluorescent lamp **1003** placed in circuit **1002** modified by circuit **1001**, using a photodiode placed on the center of the bulb. Trace **1210** shows the light output at 1 millisecond/division, and Trace **1220** shows the light output at 20 microseconds/division. The portion of the waveform shown in Trace **1220** is roughly the same as the dashed line area **1213** of Trace **1210**. Sync signal **222** is coupled to circuit **1002** as described previously and is producing a square wave at 250 Hz. Peak level **1211** shows the light output when lamp **1003** is on and minimum **1212** shows the light output when lamp **1003** is off. While Trace **1210** shows the peak level **1211** and minimum **1212** as fairly flat, upon closer inspection with Trace **1220**, it can be seen that when the lamp **1003** is turned off, it does not transition from fully on to completely off instantly. Rather, there is a decay curve of approximately 200 microseconds (0.2 milliseconds) in duration. This is apparently due to the decay curve of the phosphor coating the inside of the fluorescent bulb (i.e. when the lamp **1003** is turned off, the phosphor continues to fluoresce for a brief period of time). So, when sync signal **222** turns off the modified ballast **1001-1002**, unlike LED lights which typically switch off within a microsecond, fluorescent lamps take a short interval of time until they decay and become dark.

There exists a wide range of decay periods for different brands and types of fluorescent lamps, from as short as 200 microseconds, to as long as over a millisecond. To address this property of fluorescent lamps, one embodiment of the invention adjusts signals **221-223**. This embodiment will be discussed shortly.

Another property of fluorescent lamps that impacts their usability with a motion capture system such as that illustrated in FIG. **2** is that the electrodes within the bulb are effectively incandescent filaments that glow when they carry current through them, and like incandescent filaments, they continue to glow for a long time (often a second or more) after current is removed from them. So, even if they are switched on and off rapidly (e.g. at 90 Hz) by sync signal **222** using ballast **1002** modified by circuit **1001**, they continue to glow for the entire dark interval **302**. Although the light emitted from the fluorescent bulb from the glowing electrodes is very dim relative to the fully illuminated fluorescent bulb, it is still is a significant amount of light, and when many fluorescent bulbs are in use at once, together the electrodes add up to a significant amount of light contamination during the dark interval **302**, where it is advantageous for the room to be as dark as possible.

FIG. **13** illustrates one embodiment of the invention which addresses this problem. Prior art fluorescent lamp **1350** is shown in a state 10 milliseconds after the lamp as been shut off. The mercury vapor within the lamp is no longer emitting ultraviolet light and the phosphor lining the inner surface of the bulb is no longer emitting a significant amount of light. But the electrodes **1351-1352** are still glowing because they are still hot. This electrode glowing results in illuminated regions **1361-1362** near the ends of the bulb of fluorescent lamp **1350**.

Fluorescent lamp **1370** is a lamp in the same state as prior art lamp **1350**, 10 milliseconds after the bulb **1370** has been shut off, with its electrodes **1371-1372** still glowing and producing illuminated regions **1381-1382** near the ends of the bulb of fluorescent lamp **1370**, but unlike prior art lamp **1350**, wrapped around the ends of lamp **1370** is opaque tape **1391** and **1392** (shown as see-through with slanted lines for the sake of illustration). In the presently preferred embodiment black gaffers' tape is used, such as 4" P-665 from Permacel, A Nitto Denko Company, US Highway No. 1, P.O. Box 671, New Brunswick, N.J. 08903. The opaque tape **1391-1392** serves to block almost all of the light from glowing electrodes **1371-1372** while blocking only a small amount of the overall light output of the fluorescent lamp when the lamp is on during lit interval **301**. This allows the fluorescent lamp to become much darker during dark interval **302** when being flashed on and off at a high rate (e.g. 90 Hz). Other techniques can be used to block the light from the glowing electrodes, including other types of opaque tape, painting the ends of the bulb with an opaque paint, or using an opaque material (e.g. sheets of black metal) on the light fixtures holding the fluorescent lamps so as to block the light emission from the parts of the fluorescent lamps containing electrodes.

Returning now to the light decay property of fluorescent lamps illustrated in FIG. **12**, if fluorescent lamps are used for light panels **208-209**, the synchronization signal timing shown in FIG. **3** will not produce optimal results because when Light Panel sync signal **222** drops to a low level on edge **332**, the fluorescent light panels **208-209** will take time to become completely dark (i.e. edge **342** will gradually drop to dark level). If the Dark Cam Sync Signal triggers the grayscale cameras **204-205** to open their shutters at the same time as edge **322**, the grayscale camera will capture some of the scene lit by the afterglow of light panels **208-209** during its decay interval. Clearly, FIG. **3**'s timing signals and light output behavior is more suited for light panels **208-209** using a lighting source like LEDs that have a much faster decay than fluorescent lamps.

SYNCHRONIZATION TIMING FOR FLUORESCENT LAMPS

FIG. **14** shows timing signals which are better suited for use with fluorescent lamps and the resulting light panel **208-209** behavior (note that the duration of the decay curve **1442** is exaggerated in this and subsequent timing diagrams for illustrative purposes). The rising edge **1434** of sync signal **222** is roughly coincident with rising edge **1414** of lit cam sync signal **223** (which opens the lit camera **214-215** shutters) and with falling edge **1424** of dark cam sync signal **223** (which closes the dark camera **204-205** shutters). It also causes the fluorescent lamps in the light panels **208-209** to illuminate quickly. During lit time interval **1401**, the lit cameras **214-215** capture a color image illuminated by the fluorescent lamps, which are emitting relatively steady light as shown by light output level **1443**.

At the end of lit time interval **1401**, the falling edge **1432** of sync signal **222** turns off light panels **208-209** and is roughly coincident with the rising edge **1412** of lit cam sync signal **223**, which closes the shutters of the lit cameras **214-215**. Note, however, that the light output of the light panels **208-209** does not drop from lit to dark immediately, but rather slowly drops to dark as the fluorescent lamp phosphor decays as shown by edge **1442**. When the light level of the fluorescent lamps finally reaches dark level **1441**, dark cam sync signal **221** is dropped from high to low as shown by edge **1422**, and this opens the shutters of dark cameras **204-205**. This way the dark cameras **204-205** only capture the emissions from the phosphorescent makeup, paint or dye, and do not capture the reflection of light from any objects illuminated by the fluorescent lamps during the decay interval **1442**. So, in this embodiment the dark interval **1402** is shorter than the lit interval **1401**, and the dark camera **204-205** shutters are open for a shorter period of time than the lit camera **214-205** shutters.

Another embodiment is illustrated in FIG. **15** where the dark interval **1502** is longer than the lit interval **1501**. The advantage of this embodiment is it allows for a longer shutter time for the dark cameras **204-205**. In this embodiment, light panel sync signal **222** falling edge **1532** occurs earlier which causes the light panels **208-209** to turn off. Lit cam sync signal **223** rising edge **1512** occurs roughly coincident with falling edge **1532** and closes the shutters on the lit cameras **214-5**. The light output from the light panel **208-209** fluorescent lamps begins to decay as shown by edge **1542** and finally reaches dark level **1541**. At this point dark cam sync signal **221** is transitions to a low state on edge **1522**, and the dark cameras **204-205** open their shutters and capture the phosphorescent emissions.

Note that in the embodiments shown in both FIGS. **14** and **15** the lit camera **214-215** shutters were only open while the light output of the light panel **208-209** fluorescent lamps was at maximum. In another embodiment, the lit camera **214-215** shutters can be open during the entire time the fluorescent lamps are emitting any light, so as to maximize the amount of light captured. In this situation, however, the phosphorescent makeup, paint or dye in the scene will become more prominent relative to the non-phosphorescent areas in the scene because the phosphorescent areas will continue to emit light fairly steadily during the fluorescent lamp decay while the non-phosphorescent areas will steadily get darker. The lit cameras **214-215** will integrate this light during the entire time their shutters are open.

In yet another embodiment the lit cameras **214-215** leave their shutters open for some or all of the dark time interval **1502**. In this case, the phosphorescent areas in the scene will appear very prominently relative to the non-phosphorescent areas since the lit cameras **214-215** will integrate the light during the dark time interval **1502** with the light from the lit time interval **1501**.

Because fluorescent lamps are generally not sold with specifications detailing their phosphor decay characteristics, it is necessary to determine the decay characteristics of fluorescent lamps experimentally. This can be readily done by adjusting the falling edge **1522** of sync signal **221** relative to the falling edge **1532** of sync signal **222**, and then observing the output of the dark cameras **204-205**. For example, in the embodiment shown in FIG. **15**, if edge **1522** falls too soon after edge **1532** during the fluorescent light decay **1542**, then non-phosphorescent objects will be captured in the dark cameras **204-205**. If the edge **1522** is then slowly delayed relative to edge **1532**, the non-phosphorescent objects in dark camera **204-205** will gradually get darker until the entire image captured is dark, except for the phosphorescent objects in the image. At that point, edge **1522** will be past the decay interval **1542** of the fluorescent lamps. The process described in this paragraph can be readily implemented in an application on a general-purpose computer that controls the output levels of sync signals **221-223**.

In another embodiment the decay of the phosphor in the fluorescent lamps is such that even after edge **1532** is delayed as long as possible after **1522** to allow for the dark cameras **204-205** to have a long enough shutter time to capture a bright enough image of phosphorescent patterns in the scene, there is still a small amount of light from the fluorescent lamp illuminating the scene such that non-phosphorescent objects in the scene are slightly visible. Generally, this does not present a problem for the pattern processing techniques described in the co-pending applications identified above. So long as the phosphorescent patterns in the scene are substantially brighter than the dimly-lit non-fluorescent objects in the scene, the pattern processing techniques will be able to adequately correlate and process the phosphorescent patterns and treat the dimly lit non-fluorescent objects as noise.

SYNCHRONIZING CAMERAS WITH LOWER FRAME RATES THAN THE LIGHT PANEL FLASHING RATE

In another embodiment the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. For example, the capture frame rate may be 30 frames per second (fps), but so as to keep the flashing of the light panels **208-209** about the threshold of human perception, the light panels **208-209** are flashed at 90 flashes per second. This situation is illustrated in FIG. **16**. The sync signals **221-3** are controlled the same as the are in FIG. **15** for lit time interval **1601** and dark time interval **1602** (light cycle **0**), but after that, only light panel **208-9** sync signal **222** continues to oscillate for light cycles **1** and **2**. Sync signals **221** and **223** remain in constant high state **1611** and **1626** during this interval. Then during light cycle **3**, sync signals **221** and **223** once again trigger with edges **1654** and **1662**, opening the shutters of lit cameras **214-215** during lit time interval **1604**, and then opening the shutters of dark cameras **204-205** during dark time interval **1605**.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, sync signal **223** causes the lit cameras **214-215** to open their shutters after sync signal **221** causes the dark cameras **204-205** to open their shutters. This is illustrated in FIG. **17**. An advantage of this timing arrangement over that of FIG. **16** is the fluorescent lamps transition from dark to lit (edge **1744**) more quickly than they decay from lit to dark (edge **1742**). This makes it possible to abut the dark frame interval **1702** more closely to the lit frame interval **1701**. Since captured lit textures are often used to be mapped onto 3D surfaces reconstructed from dark camera images, the closer the lit and dark captures occur in time, the closer the alignment will be if the captured object is in motion.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, the light panels **208-209** are flashed with varying light cycle intervals so as to allow for longer shutter times for either the dark cameras **204-205** or lit cameras **214-215**, or to allow for longer shutters times for both cameras. An example of this embodiment is illustrated in FIG. **18** where the light panels **208-209** are flashed at 3 times the frame rate of cameras **204-205** and **214-215**, but the open shutter interval **1821** of the dark cameras **204-205** is equal to almost half of the entire frame time **1803**. This is accomplished by having light panel **208-209** sync signal **222** turn off the light panels **208-209** for a long dark interval **1802** while dark cam sync signal **221** opens the dark shutter for the duration of long dark interval **1802**. Then sync signal **222** turns the light panels **208-209** on for a brief lit interval **1801**, to complete light cycle **0** and then rapidly flashes the light panels **208-209** through light cycles **1** and **2**. This results in the same number of flashes per second as the embodiment illustrated in FIG. **17**, despite the much longer dark interval **1802**. The reason this is a useful configuration is that the human visual system will still perceive rapidly flashing lights (e.g. at 90 flashes per second) as being lit continuously, even if there are some irregularities to the flashing cycle times. By varying the duration of the lit and dark intervals of the light panels **208-209**, the shutter times of either the dark cameras **204-205**, lit cameras **214-215** or both can be lengthened or shortened, while still maintaining the human perception that light panels **208-209** are continuously lit.

HIGH AGGREGATE FRAME RATES FROM CASCADED CAMERAS

FIG. **19** illustrates another embodiment where lit cameras **1941-1946** and dark cameras **1931-1936** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. FIG. **19** illustrates a similar motion capture system configuration as FIG. **2***a*, but given space limitations in the diagram only the light panels, the cameras, and the synchronization subsystem is shown. The remaining components of FIG. **2***a* that are not shown (i.e. the interfaces from the cameras to their camera controllers and the data processing subsystem, as well as the output of the data processing subsystem) are a part of the full configuration that is partially shown in FIG. **19**, and they are coupled to the components of FIG. **19** in the same manner as they are to the components of FIG. **2***a*. Also, FIG. **19** shows the Light Panels **208-209** in their “lit” state. Light Panels **208-209** can be switched off by sync signal **222** to their “dark” state, in which case performer **202** would no longer be lit and only the phosphorescent pattern applied to her face would be visible, as it is shown in FIG. **2***b*.

FIG. **19** shows 6 lit cameras **1941-1946** and 6 dark cameras **1931-1936**. In the presently preferred embodiment color cameras are used for the lit cameras **1941-1946** and grayscale cameras are used for the dark camera **1931-1936**, but either type could be used for either purpose. The shutters on the cameras **1941-1946** and **1931-1936** are driven by sync signals **1921-1926** from sync generator PCI card **224**. The sync generator card is installed in sync generator PC **220**, and operates as previously described. (Also, in another embodiment it may be replaced by using the parallel port outputs of sync generator PC **220** to drive sync signals **1921-1926**, and in this case, for example, bit **0** of the parallel port would drive sync signal **222**, and bits **1-6** of the parallel port would drive sync signals **1921-1926**, respectively.)

Unlike the previously described embodiments, where there is one sync signal **221** for the dark cameras and one sync signal **223** for the lit cameras, in the embodiment illustrated in FIG. **19**, there are 3 sync signals **1921-1923** for the dark cameras and 3 sync signals **1924-1926** for the dark cameras. The timing for these sync signals **1921-1926** is shown in FIG. **20**. When the sync signals **1921-1926** are in a high state they cause the shutters of the cameras attached to them to be closed, when the sync signals are in a low state, they cause the shutters of the cameras attached to them to be open.

In this embodiment, as shown in FIG. **20**, the light panels **208-209** are flashed at a uniform 90 flashes per second, as controlled by sync signal **222**. The light output of the light panels **208-209** is also shown, including the fluorescent lamp decay **2042**. Each camera **1931-1936** and **1941-1946** captures images at 30 frames per second (fps), exactly at a 1:3 ratio with the 90 flashes per second rate of the light panels. Each camera captures one image per each 3 flashes of the light panels, and their shutters are sequenced in a “cascading” order, as illustrated in FIG. **20**. A sequence of 3 frames is captured in the following manner:

Sync signal **222** transitions with edge **2032** from a high to low state **2031**. Low state **2031** turns off light panels **208-209**, which gradually decay to a dark state **2041** following decay curve **2042**. When the light panels are sufficiently dark for the purposes of providing enough contrast to separate the phosphorescent makeup, paint, or dye from the non-phosphorescent surfaces in the scene, sync signal **1921** transitions to low state **2021**. This causes dark cameras **1931-1932** to open their shutters and capture a dark frame. After the time interval **2002**, sync signal **222** transitions with edge **2034** to high state **2033** which causes the light panels **208-209** to transition with edge **2044** to lit state **2043**. Just prior to light panels **208-209** becoming lit, sync signal **1921** transitions to high state **2051** closing the shutter of dark cameras **1931-1932**. Just after the light panels **208-209** become lit, sync signal **1924** transition to low state **2024**, causing the shutters on the lit cameras **1941-1942** to open during time interval **2001** and capture a lit frame. Sync signal **222** transitions to a low state, which turns off the light panels **208-9**, and sync signal **1924** transitions to a high state at the end of time interval **2001**, which closes the shutters on lit cameras **1941-1942**.

The sequence of events described in the preceding paragraphs repeats 2 more times, but during these repetitions sync signals **1921** and **1924** remain high, keeping their cameras shutters closed. For the first repetition, sync signal **1922** opens the shutter of dark cameras **1933-1934** while light panels **208-209** are dark and sync signal **1925** opens the shutter of lit cameras **1943-1944** while light panels **208-209** are lit. For the second repetition, sync signal **1923** opens the shutter of dark cameras **1935-1936** while light panels **208-209** are dark and sync signal **1926** opens the shutter of lit cameras **1945-1946** while light panels **208-209** are lit.

Then, the sequence of events described in the prior 2 paragraphs continues to repeat while the motion capture session illustrated in FIG. **19** is in progress, and thus a “cascading” sequence of camera captures allows 3 sets of dark and 3 sets of lit cameras to capture motion at 90 fps (i.e. equal to the light panel flashing rate of 90 flashes per second), despite the fact each cameras is only capturing images at 30 fps. Because each camera only captures 1 of every 3 frames, the captured frames stored by the data processing system **210** are then interleaved so that the stored frame sequence at 90 fps has the frames in proper order in time. After that interleaving operation is complete, the data processing system will output reconstructed 3D surfaces **207** and textured 3D surfaces **217** at 90 fps.

Although the “cascading” timing sequence illustrated in FIG. **20** will allow cameras to operate at 30 fps while capturing images at an aggregate rate of 90 fps, it may be desirable to be able to switch the timing to sometimes operate all of the cameras **1921-1923** and **1924-1926** synchronously. An example of such a situation is for the determination of the relative position of the cameras relative to each other. Precise knowledge of the relative positions of the dark cameras **1921-1923** is used for accurate triangulation between the cameras, and precise knowledge of the position of the lit cameras **1924-1926** relative to the dark cameras **1921-1923** is used for establishing how to map the texture maps captured by the lit cameras **1924-1926** onto the geometry reconstructed from the images captured by the dark cameras **1921-1923**. One prior art method (e.g. that is used to calibrate cameras for the motion capture cameras from Motion Analysis Corporation) to determine the relative position of fixed cameras is to place a known object (e.g. spheres on the ends of a rods in a rigid array) within the field of view of the cameras, and then synchronously (i.e. with the shutters of all cameras opening and closing simultaneously) capture successive frames of the image of that known object by all the cameras as the object is in motion. By processing successive frames from all of the cameras, it is possible to calculate the relative position of the cameras to each other. But for this method to work, all of the cameras need to be synchronized so that they capture images simultaneously. If the camera shutters do not open simultaneously, then when each non-simultaneous shutter opens, its camera will capture the moving object at a different position in space than other cameras whose shutters open at different times. This will make it more difficult (or impossible) to precisely determine the relative position of all the cameras to each other.

FIG. **21** illustrates in another embodiment how the sync signals **1921-6** can be adjusted so that all of the cameras **1931-1936** and **1941-1946** open their shutters simultaneously. Sync signals **1921-1926** all transition to low states **2121-2126** during dark time interval **2102**. Although the light panels **208-209** would be flashed 90 flashes a second, the cameras would be capturing frames synchronously to each other at 30 fps. (Note that in this case, the lit cameras **1941-1946** which, in the presently preferred embodiment are color cameras, also would be capturing frames during the dark interval **2102** simultaneously with the dark cameras **1931-1936**.) Typically, this synchronized mode of operation would be done when a calibration object (e.g. an array of phosphorescent spheres) was placed within the field of view of some or all of the cameras, and potentially moved through successive frames, usually before or after a motion capture of a performer. In this way, the relative position of the cameras could determined while the cameras are running synchronously at 30 fps, as shown in FIG. **21**. Then, the camera timing would be switched to the "cascading" timing shown in FIG. **20** to capture a performance at 90 fps. When the 90 fps frames are reconstructed by data processing system **210**, then camera position information, determined previously (or subsequently) to the 90 fps capture with the synchronous mode time shown in FIG. **21**, will be used to both calculate the 3D surface **207** and map the captured lit frame textures onto the 3D surface to create textured 3D surface **217**

When a scene is shot conventionally using prior art methods and cameras are capturing only 2D images of that scene, the "cascading" technique to use multiple slower frame rate cameras to achieve a higher aggregate frame rate as illustrated in FIGS. **19** and **20** will not produce high-quality results. The reason for this is each camera in a "cascade" (e.g. cameras **1931**, **1933** and **1935**) will be viewing the scene from a different point of view. If the captured 30 fps frames of each camera are interleaved together to create a 90 fps sequence of successive frames in time, then when the 90 fps sequence is viewed, it will appear to jitter, as if the camera was rapidly jumping amongst multiple positions. But when slower frame rate cameras are "cascaded" to achieve a higher aggregate frame rate as illustrate in FIGS. **19** and **20** for the purpose capturing the 3D surfaces of objects in a scene, as described herein and in combination with the methods described in the co-pending applications, the resulting 90 fps interleaved 3D surfaces **207** and textured 3D surfaces **217** do not exhibit jitter at all, but rather look completely stable. The reason is the particular position of the cameras **1931-1936** and **1941-1946** does not matter in the reconstruction 3D surfaces, just so long as the at least a pair of dark cameras **1931-1936** during each dark frame interval **2002** has a non-oblique view (e.g. <30 degrees) of the surface area (with phosphorescent makeup, paint or dye) to be reconstructed. This provides a significant advantage over conventional prior art 2D motion image capture (i.e. commonly known as video capture), because typically the highest resolution sensors commercially available at a given time have a lower frame rate than commercially available lower resolution sensors. So, 2D motion image capture at high resolutions is limited to the frame rate of a single high resolution sensor. A 3D motion surface capture at high resolution, under the principles described herein, is able to achieve n times the frames rate of a single high resolution sensor, where n is the number of camera groups "cascaded" together, per the methods illustrated in FIGS. **19** and **20**.

COLOR MAPPING OF PHOSPHOR BRIGHTNESS

Ideally, the full dynamic range, but not more, of dark cameras **204-205** should be utilized to achieve the highest quality pattern capture. For example, if a pattern is captured that is too dark, noise patterns in the sensors in cameras **204-205** may become as prominent as captured patterns, resulting in incorrect 3D reconstruction. If a pattern is too bright, some areas of the pattern may exceed the dynamic range of the sensor, and all pixels in such areas will be recorded at the maximum brightness level (e.g. 255 in an 8-bit sensor), rather than at the variety or brightness levels that actually make up that area of the pattern. This also will result in incorrect 3D reconstruction. So, prior to capturing a pattern, per the techniques described herein, it is advantageous to try to make sure the brightness of the pattern throughout is not too dark, nor too bright (e.g. not reaching the maximum brightness level of the camera sensor).

When phosphorescent makeup is applied to a performer, or when phosphorescent makeup, paint or dye is applied to an object, it is difficult for the human eye to evaluate whether the phosphor application results in a pattern captured by the dark cameras **204-205** that is bright enough in all locations or too bright in some locations. FIG. **22** image **2201** shows a cylinder covered in a random pattern of phosphor. It is difficult, when viewing this image on a computer display (e.g. an LCD monitor) to determine precisely if there are parts of the pattern that are too bright (e.g. location **2220**) or too dark (e.g. location **2210**). There are many reasons for this. Computer monitors often do not have the same dynamic range as a sensor (e.g. a computer monitor may only display 128 unique gray levels, while the sensor captures 256 gray levels). The brightness and/or contrast may not be set correctly on the monitor. Also, the human eye may have trouble determining what constitutes a maximum brightness level because the brain may adapt to the brightness it sees, and consider whatever is the brightest area on the screen to be the maximum brightness. For all of these reasons, it is helpful to have an objective measure of brightness that humans can readily evaluate when applying phosphorescent makeup, paint or dye. Also, it is helpful to have an objective measure brightness as the lens aperture and/or gain is adjusted on dark cameras **204-205** and/or the brightness of the light panels **208-209** is adjusted.

Image **2202** shows such an objective measure. It shows the same cylinder as image **2201**, but instead of showing the brightness of each pixel of the image as a grayscale level (in this example, from 0 to 255), it shows it as a color. Each color represents a range of brightness. For example, in image **2202** blue represents brightness ranges 0-32, orange represents brightness ranges **192-223** and dark red represents brightness ranges **224-255**. Other colors represent other brightness ranges. Area **2211**, which is blue, is now clearly identifiable as an area that is very dark, and area **2221**, which is dark red, is now clearly identifiable as an area that is very bright. These determinations can be readily made by the human eye, even if the dynamic range of the display monitor is less than that of the sensor, or if the display monitor is incorrectly adjusted, or if the brain of the observer adapts to the brightness of the display. With this information the human observer can change the application of phosphorescent makeup, dye or paint. The human observer can also adjust the aperture and/or the gain setting on the cameras **204**-**205** and/or the brightness of the light panels **208**-**209**.

In one embodiment image **2202** is created by application software running on one camera controller computer **225** and is displayed on a color LCD monitor attached to the camera controller computer **225**. The camera controller computer **225** captures a frame from a dark camera **204** and places the pixel values of the captured frame in an array in its RAM. For example, if the dark cameras **204** is a 640×480 grayscale camera with 8 bits/pixel, then the array would be a 640×480 array of 8-bit bytes in RAM. Then, the application takes each pixel value in the array and uses it as an index into a lookup table of colors, with as many entries as the number of possible pixel values. With 8 bits/pixel, the lookup table has 256 entries. Each of the entries in the lookup table is pre-loaded (by the user or the developer of the application) with the desired Red, Green, Blue (RGB) color value to be displayed for the given brightness level. Each brightness level may be given a unique color, or a range of brightness levels can share a unique color. For example, for image **2202**, lookup table entries **0**-**31** are all loaded with the RGB value for blue, entries **192**-**223** are loaded with the RGB value for orange and entries **224**-**255** are loaded with the RGB value for dark red. Other entries are loaded with different RGB color values. The application uses each pixel value from the array (e.g. 640×480 of 8-bit grayscale values) of the captured frame as an index into this color lookup take, and forms a new array (e.g. 640×480 of 24-bit RGB values) of the looked-up colors. This new array of look-up colors is then displayed, producing a color image such as **1102**.

If a color camera (either lit camera **214** or dark camera **204**) is used to capture the image to generate an image such as **2202**, then one step is first performed after the image is captured and before it is processed as described in the preceding paragraph. The captured RGB output of the camera is stored in an array in camera controller computer **225** RAM (e.g. 640×480 with 24 bits/pixel). The application running on camera controller computer **225** then calculates the average brightness of each pixel by averaging the Red, Green and Blue values of each pixel (i.e. Average=(R+G+B)/3), and places those averages in a new array (e.g. 640×480 with 8 bits/pixel). This array of Average pixel brightnesses (the "Average array") will soon be processed as if it were the pixel output of a grayscale camera, as described in the prior paragraph, to produce a color image such as **2202**. But, first there is one more step: the application examines each pixel in the captured RGB array to see if any color channel of the pixel (i.e. R, G, or B) is at a maximum brightness value (e.g. 255). If any channel is, then the application sets the value in the Average array for that pixel to the maximum brightness value (e.g. 255). The reason for this is that it is possible for one color channel of a pixel to be driven beyond maximum brightness (but only output a maximum brightness value), while the other color channels are driven by relatively dim brightness. This may result in an average calculated brightness for that pixel that is a middle-range level (and would not be considered to be a problem for good-quality pattern capture). But, if any of the color channels has been overdriven in a given pixel, then that will result in an incorrect pattern capture. So, by setting the pixel value in the Average array to maximum brightness, this produces a color image **2202** where that pixel is shown to be at the highest brightness, which would alert a human observer of image **1102** of the potential of a problem for a high-quality pattern capture.

It should be noted that the underlying principles of the invention are not limited to the specific color ranges and color choices illustrated in FIG. **22**. Also, other methodologies can be used to determine the colors in **2202**, instead of using only a single color lookup table. For example, in one embodiment the pixel brightness (or average brightness) values of a captured image is used to specify the hue of the color displayed. In another embodiment, a fixed number of lower bits (e.g. 4) of the pixel brightness (or average brightness) values of a captured image are set to zeros, and then the resulting numbers are used to specify the hue for each pixel. This has the effect of assigning each single hue to a range of brightnesses.

Embodiments of the invention may include various steps as set forth above. The steps may be embodied in machine-executable instructions which cause a general-purpose or special-purpose processor to perform certain steps. Various elements which are not relevant to the underlying principles of the invention such as computer memory, hard drive, input devices, have been left out of the figures to avoid obscuring the pertinent aspects of the invention.

Alternatively, in one embodiment, the various functional modules illustrated herein and the associated steps may be performed by specific hardware components that contain hardwired logic for performing the steps, such as an application-specific integrated circuit ("ASIC") or by any combination of programmed computer components and custom hardware components.

Elements of the present invention may also be provided as a machine-readable medium for storing the machine-executable instructions. The machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of machine-readable media suitable for storing electronic instructions. For example, the present invention may be downloaded as a computer program which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Throughout the foregoing description, for the purposes of explanation, numerous specific details were set forth in order to provide a thorough understanding of the present system and method. It will be apparent, however, to one skilled in the art that the system and method may be practiced without some of these specific details. For example, although certain specific mixtures and types of phosphorescent material were described above, the underlying principles of the invention may be employed with various alternate mixtures and/or any type of material which exhibits phosphorescent properties. Accordingly, the scope and spirit of the present invention should be judged in terms of the claims which follow.

What is claimed is:

1. A method for performing motion capture comprising:

mixing phosphor with makeup to create a phosphor-makeup mixture;

applying the phosphor-makeup mixture to surface regions of a motion capture subject;

strobing a light source on and off, the light source charging phosphor within the phosphor-makeup mixture when on; and strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the phosphor-makeup mixture as the subject moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

2. The method as in claim **1** wherein the subject is a performer's face and/or body.

3. The method as in claim **1** wherein the subject is a fabric.

4. The method as in claim **1** wherein the phosphor-makeup mixture is applied in a random pattern.

5. The method as in claim **1** wherein the subject is a performer's face and the phosphor-makeup mixture is applied as a series of curves on the subject.

6. The method as in claim **1** further comprising:

tracking the motion of the phosphor within the phosphor-makeup mixture over time; and

generating motion data representing the movement of the subject's face and/or body using the tracked movement of the phosphor within the phosphor-makeup mixture.

7. The method as in claim **1** further comprising:

strobing the shutters of a second plurality of cameras synchronously with the strobing of the light source to capture sequences of lit images of the subject, as the subject moves or changes facial expressions during a performance, wherein the shutters of the second plurality of cameras are open to capture the lit images when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

8. The method as in claim **7** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

9. The method as in claim **1** wherein the phosphor within the phosphor-makeup mixture comprises ZnS:Cu.

10. The method as in claim **1** wherein the phosphor within the phosphor-makeup mixture comprises SrAl2O4:Eu^{2+}, Dy^{3+}.

11. The method as in claim **1** wherein the phosphor within the phosphor-makeup mixture comprises $SrAl_2O_4$:Eu^{2+}.

12. The method as in claim **1** wherein the light source comprises one or more fluorescent lamps.

13. The method as in claim **12** wherein the fluorescent lamps are illuminated by a set of circuits comprising:

a ballast circuit electrically coupled to a power source and to at least one of the one or more fluorescent lamps, the ballast circuit configured to provide power to the fluorescent lamp to turn the fluorescent lamp on; and

a synchronization control circuit electrically coupled to a synchronization signal generator and to the ballast circuit, the synchronization control circuit to receive a synchronization signal from the synchronization signal generator and to responsively cause the ballast circuit to turn the fluorescent lamp on and off.

14. A method for performing motion capture of a fabric comprising:

mixing phosphor with dye to create a phosphor-dye mixture;

applying the phosphor-dye mixture to surface regions of a fabric;

strobing a light source on and off, the light source charging phosphor within the phosphor-dye mixture when on; and

strobing the shutters of a first plurality of cameras synchronously with the strobing of the light source to capture sequences of images of the phosphor-dye mixture as the fabric is moved during a motion capture performance, wherein the shutters are open when the light source is off to capture the sequences of images of the phosphor-dye mixture and the shutters are closed when the light source is on.

15. The method as in claim **14** wherein the phosphor-dye mixture is applied in a random pattern.

16. The method as in claim **14** wherein the phosphor-dye mixture is applied in a random pattern.

17. The method as in claim **14** further comprising:

tracking the motion of the phosphor within the phosphor-dye mixture over time; and

generating motion data representing the movement of the phosphor-dye mixture.

18. The method as in claim **14** further comprising:

strobing the shutters of a second plurality of cameras synchronously with the strobing of the light source to capture sequences of lit images of the fabric, as the fabric is moved over time during a performance, wherein the shutters of the second plurality of cameras are open to capture the lit images of the fabric when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

19. The method as in claim **18** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

20. The method as in claim **14** wherein the phosphor within the phosphor-dye mixture comprises ZnS:Cu.

21. The method as in claim **14** wherein the phosphor within the phosphor-dye mixture comprises SrAl2O4:Eu^{2+}, Dy^{3+}.

22. The method as in claim **14** wherein the phosphor within the phosphor-dye mixture comprises $SrAl_2O_4$:Eu^{2+}.

23. The method as in claim **14** wherein the light source comprises one or more fluorescent lamps.

24. The method as in claim **23** wherein the fluorescent lamps are illuminated by a set of circuits comprising:

a ballast circuit electrically coupled to a power source and to at least one of the one or more fluorescent lamps, the ballast circuit configured to provide power to the fluorescent lamp to turn the fluorescent lamp on; and

a synchronization control circuit electrically coupled to a synchronization signal generator and to the ballast circuit, the synchronization control circuit to receive a synchronization signal from the synchronization signal generator and to responsively cause the ballast circuit to turn the fluorescent lamp on and off.

* * * * *

Exhibit 5

US007567293B2

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(54) **SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE BY STROBING A FLUORESCENT LAMP**

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H04N 5/225	(2006.01)
H04N 5/262	(2006.01)

(52) **U.S. Cl.** **348/371**; 348/208.14; 348/370; 348/207.99; 348/218.1; 348/239

(58) **Field of Classification Search** 348/208.14, 348/169–172, 370–371, 218.1, 77, 157; 396/180
See application file for complete search history.

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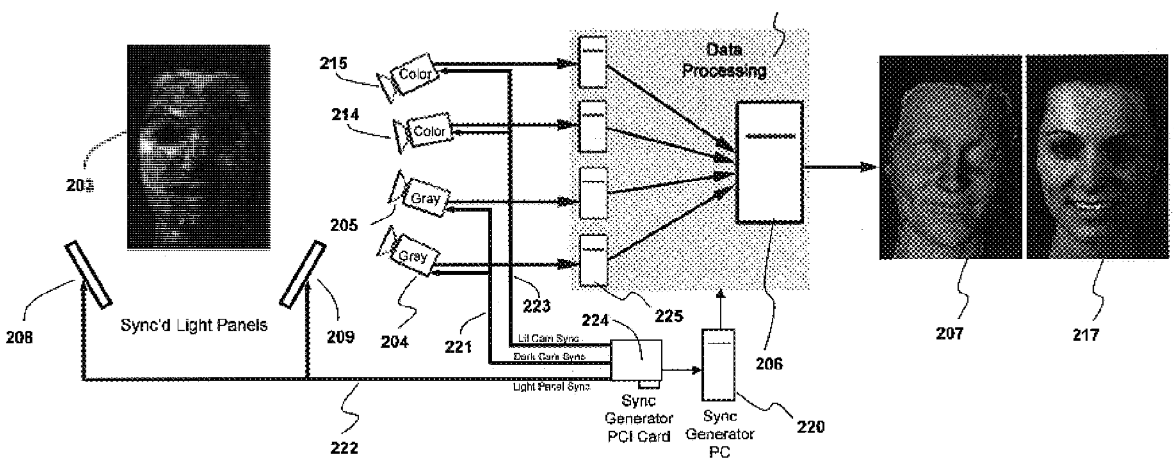
Primary Examiner—David L Ometz
Assistant Examiner—Richard M Bemben
(74) *Attorney, Agent, or Firm*—Blakely Sokoloff Taylor & Zafman LLP

(57) **ABSTRACT**

A system and method are described for performing motion capture on a subject using fluorescent lamps. For example, a system according to one embodiment of the invention comprises: a synchronization signal generator to generate one or more synchronization signals; one or more fluorescent lamps configured to strobe on and off responsive to a first one of the one or more synchronization signals, the fluorescent lamps charging phosphorescent makeup, paint or dye applied to a subject for a motion capture session; and a plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture images of the phosphorescent paint, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

30 Claims, 27 Drawing Sheets
(6 of 27 Drawing Sheet(s) Filed in Color)



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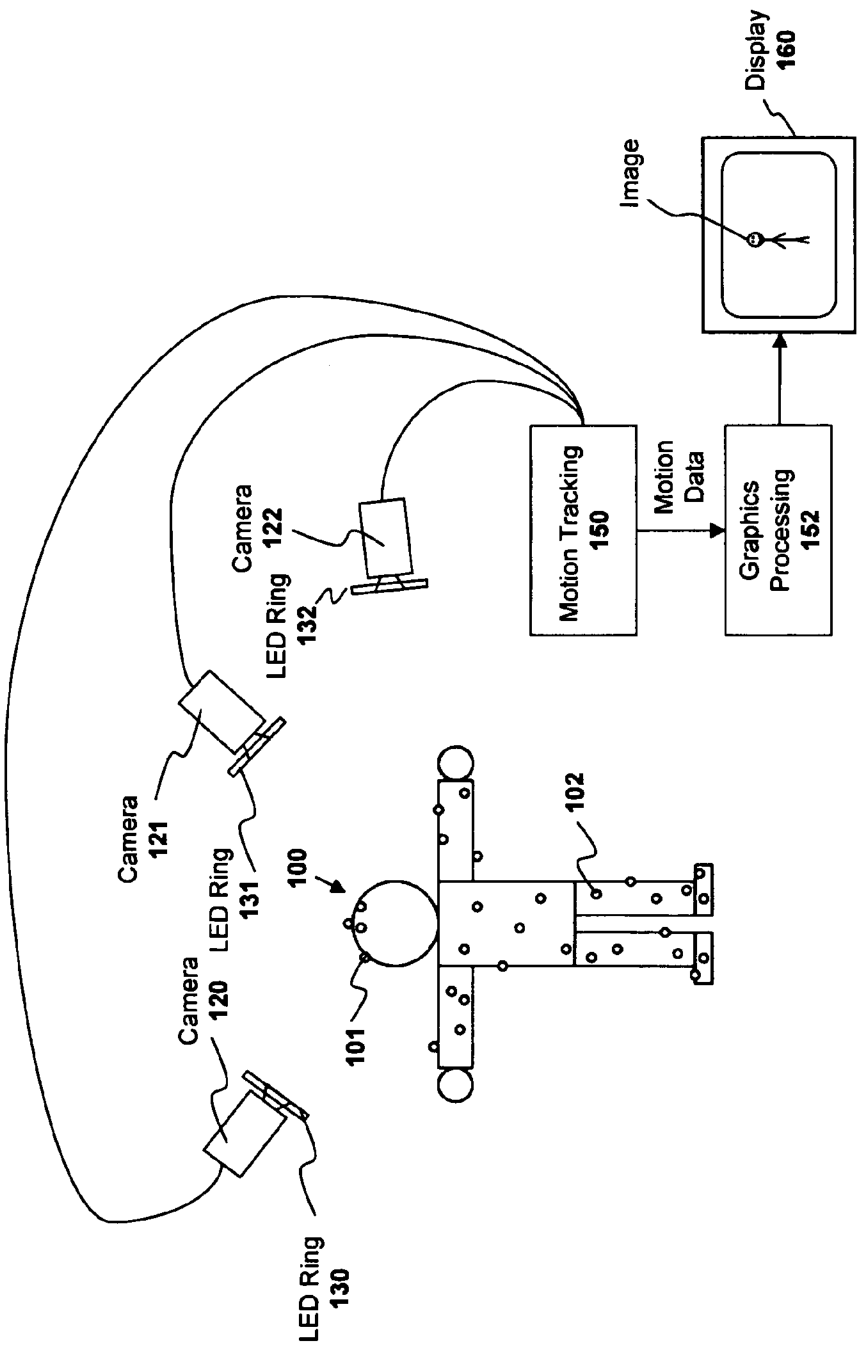

Fig. 1
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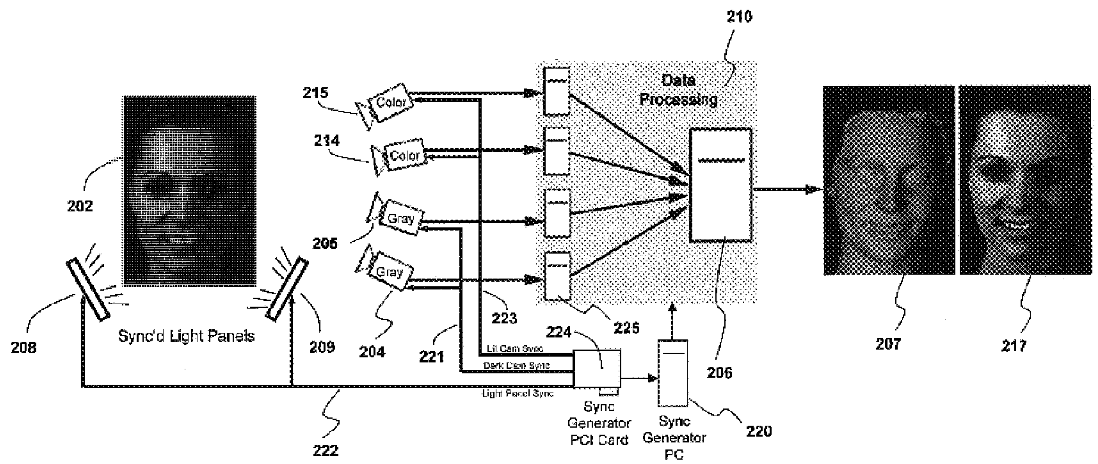
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Color
214
Color
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Gray
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Gray
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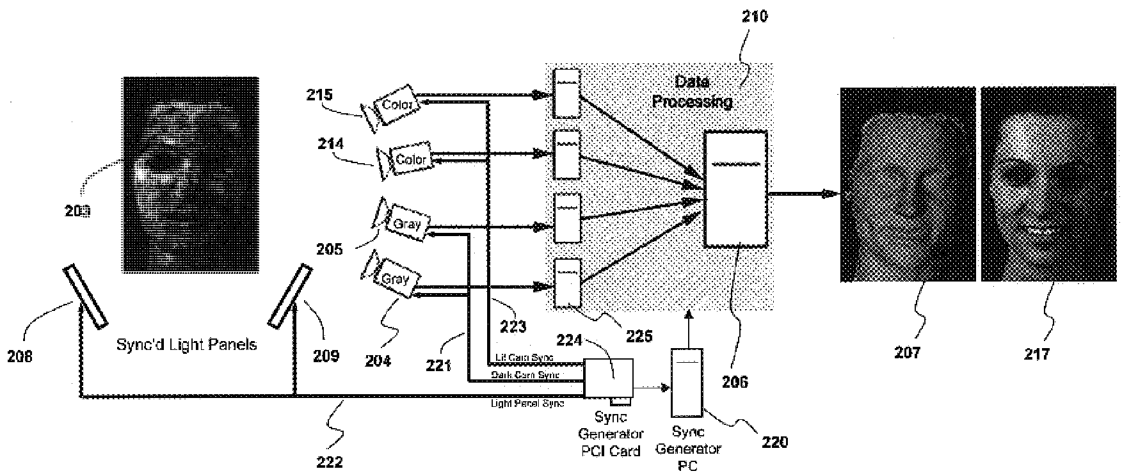
Sync'd Light Panels
209
204
221
223
224
225
Lit Cam Sync
Dark Cam Sync
Light Panel Sync
206
207
217
222
Sync Generator PCI Card
Sync Generator PC
220

Fig. 2a



210
Data Processing
215
Color
214
Color
Gray
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Gray
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Sync'd Light Panels
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221
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Lit Cam Sync
Dark Cam Sync
Light Panel Sync
Sync Generator PCI Card
Sync Generator PC
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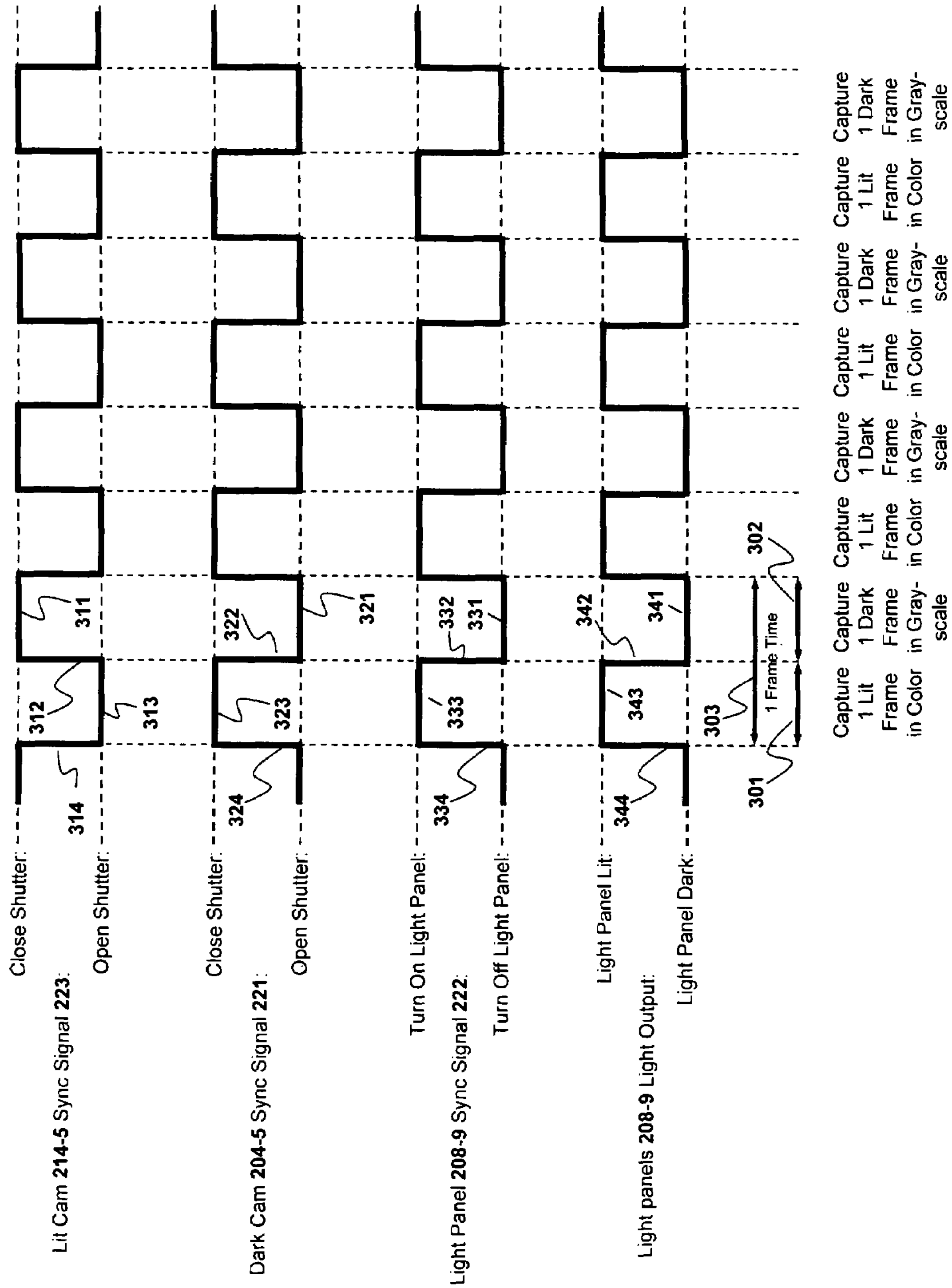
Fig. 2b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Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
311
312
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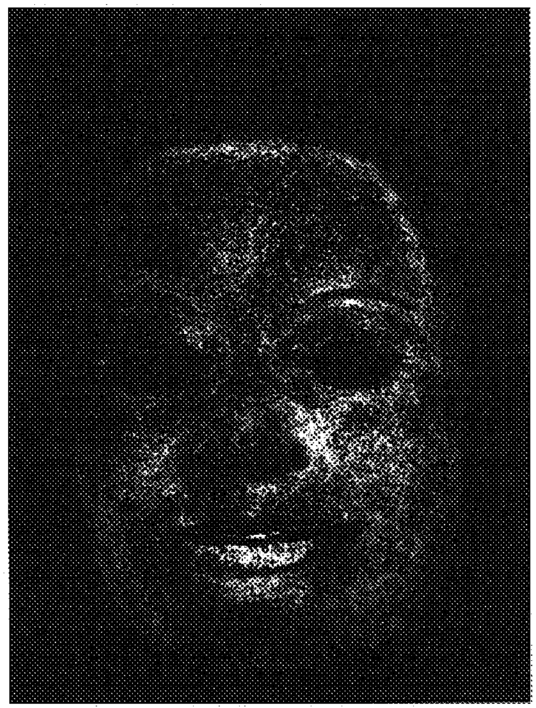
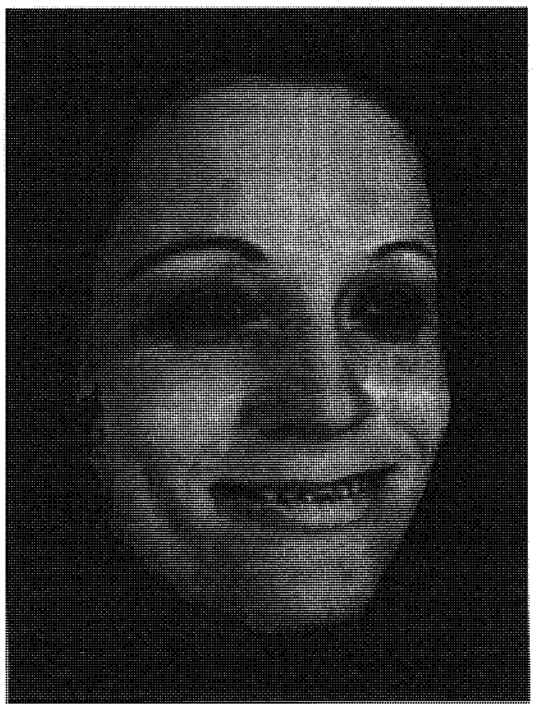
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 3

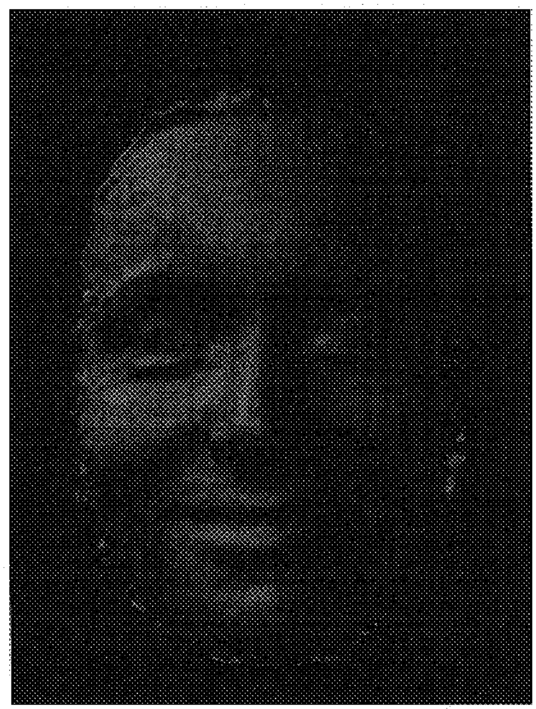
Lit Image **401**



Dark Image **402**



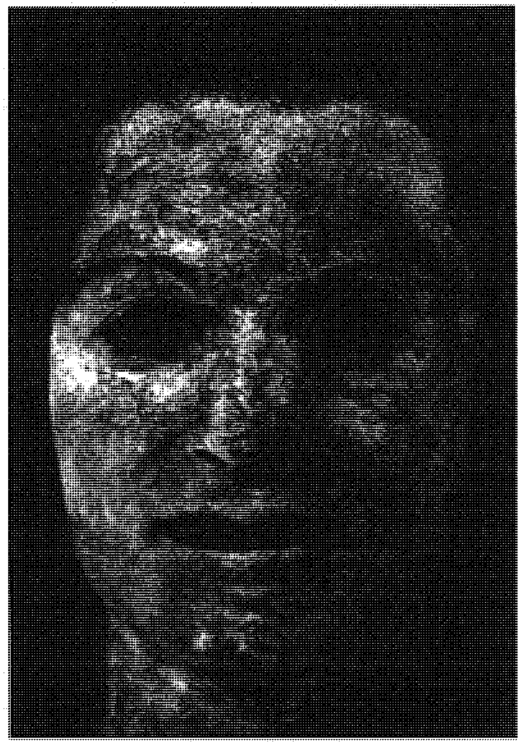
Textured 3D Surface **404**



3D Surface **403**

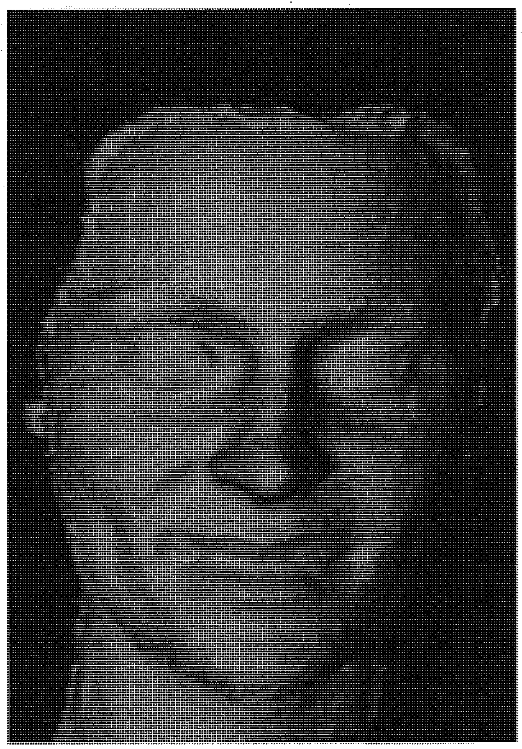
Fig. 4

Lit Image **501**



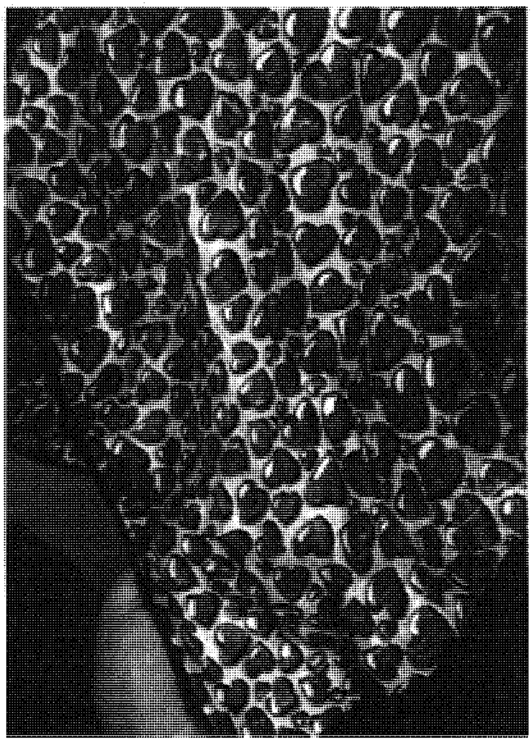
Dark Image **502**

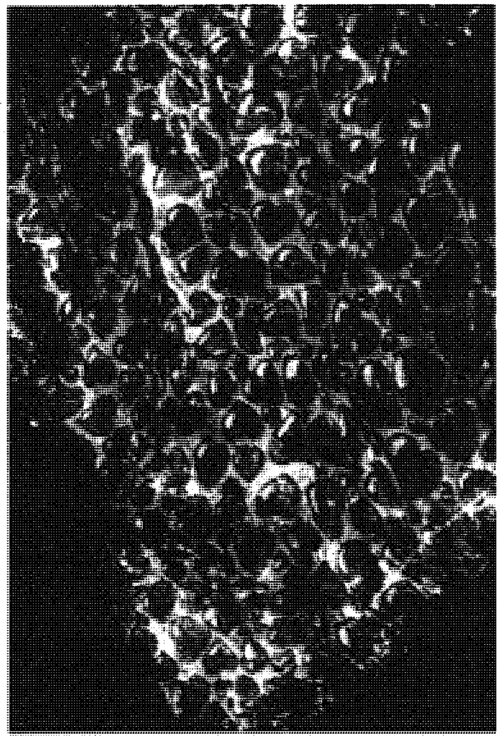
Textured 3D Surface **504**

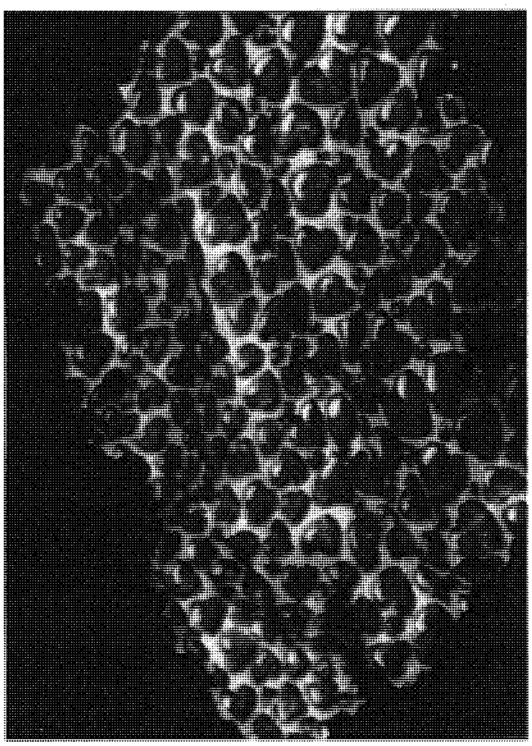


3D Surface **503**

Fig. 5


Lit Image 601


Dark Image 602


Textured 3D Surface 604


3D Surface 603

Fig. 6

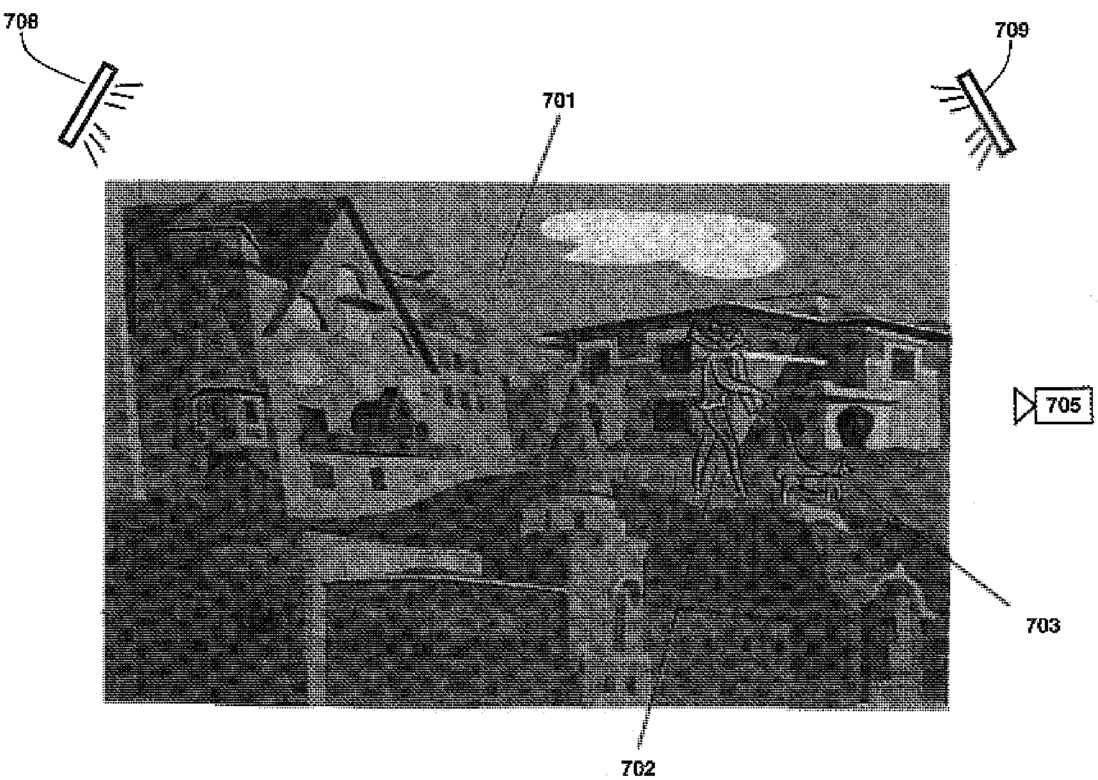


Fig. 7a
(prior art)

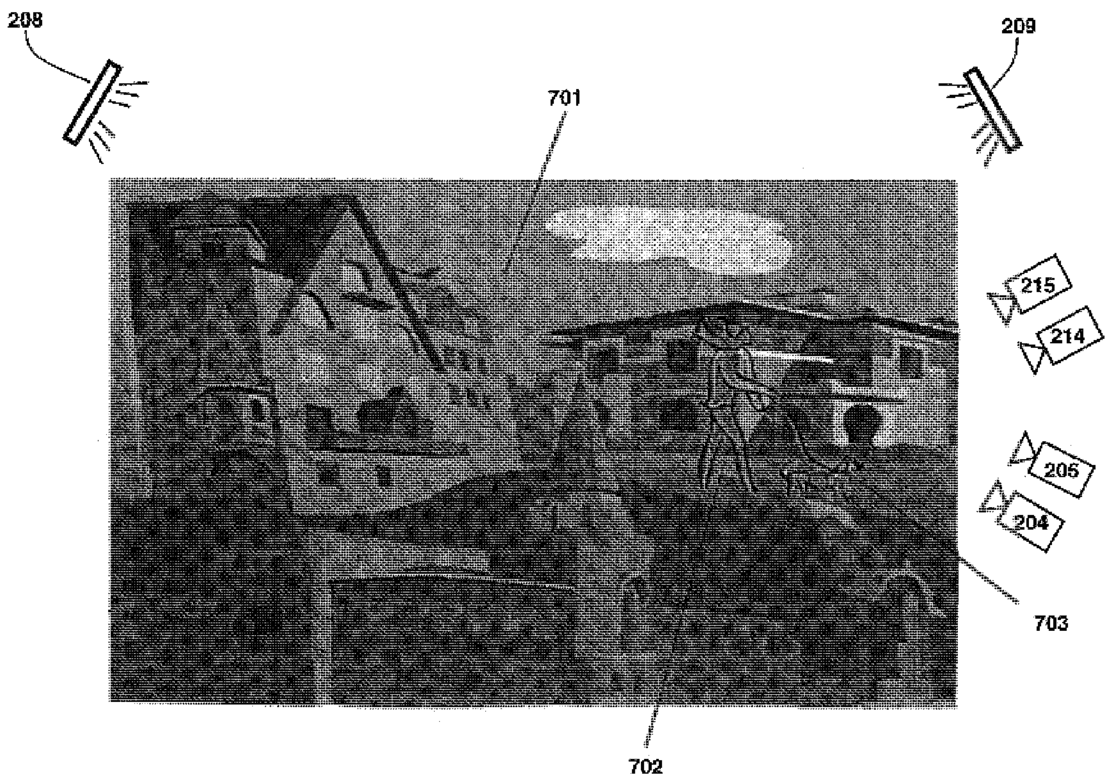


Fig. 7b

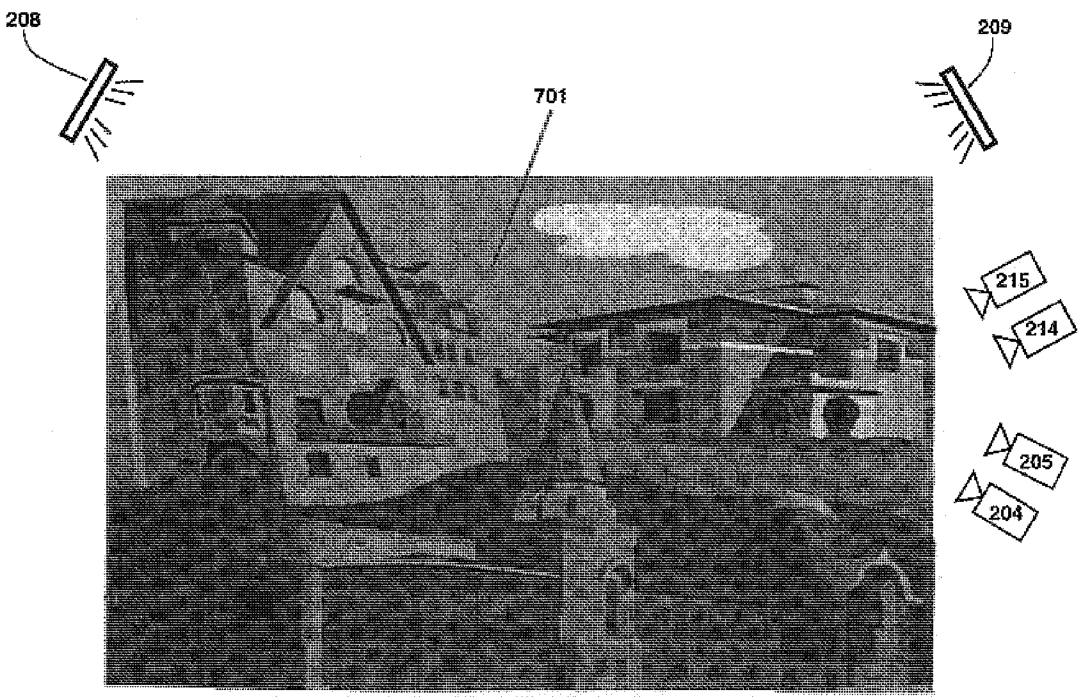


Fig. 7c

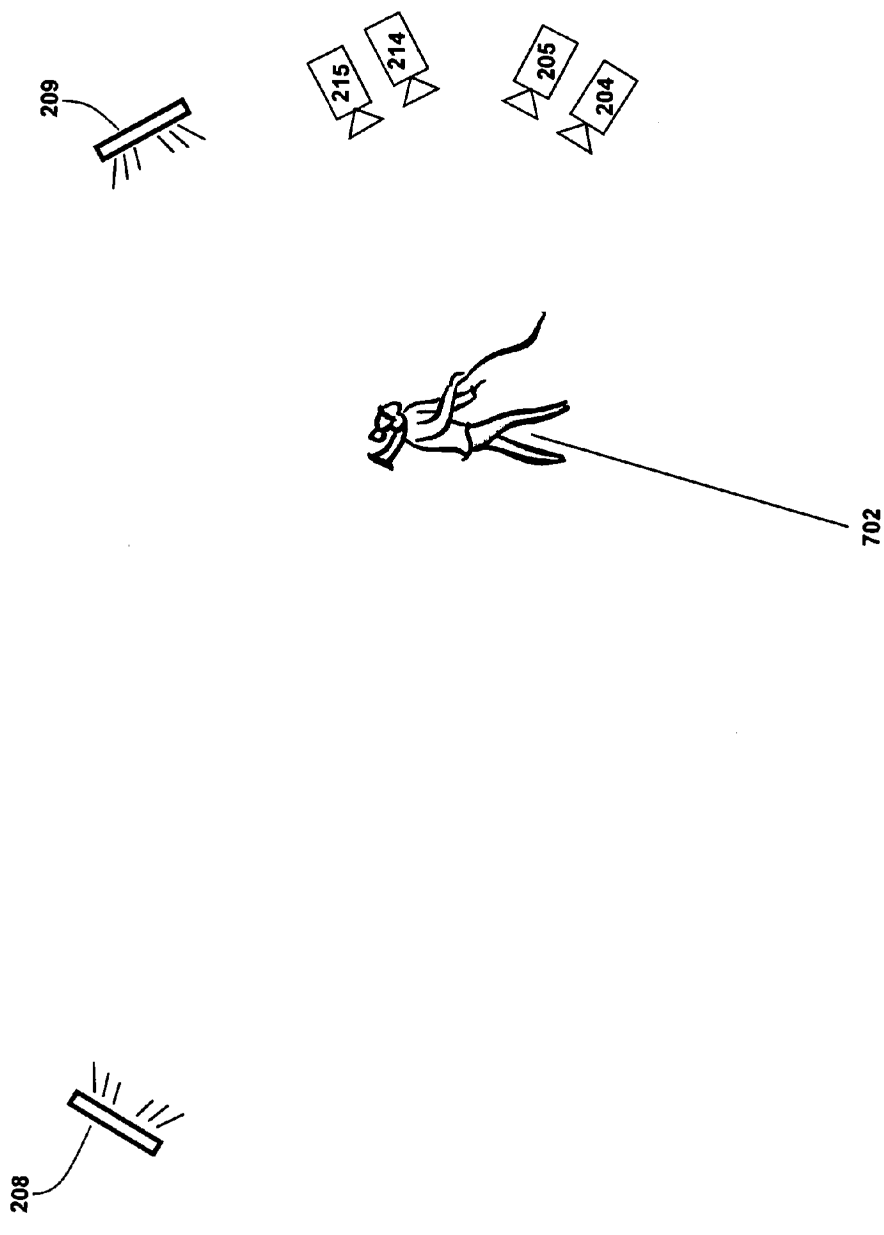


Fig. 7d

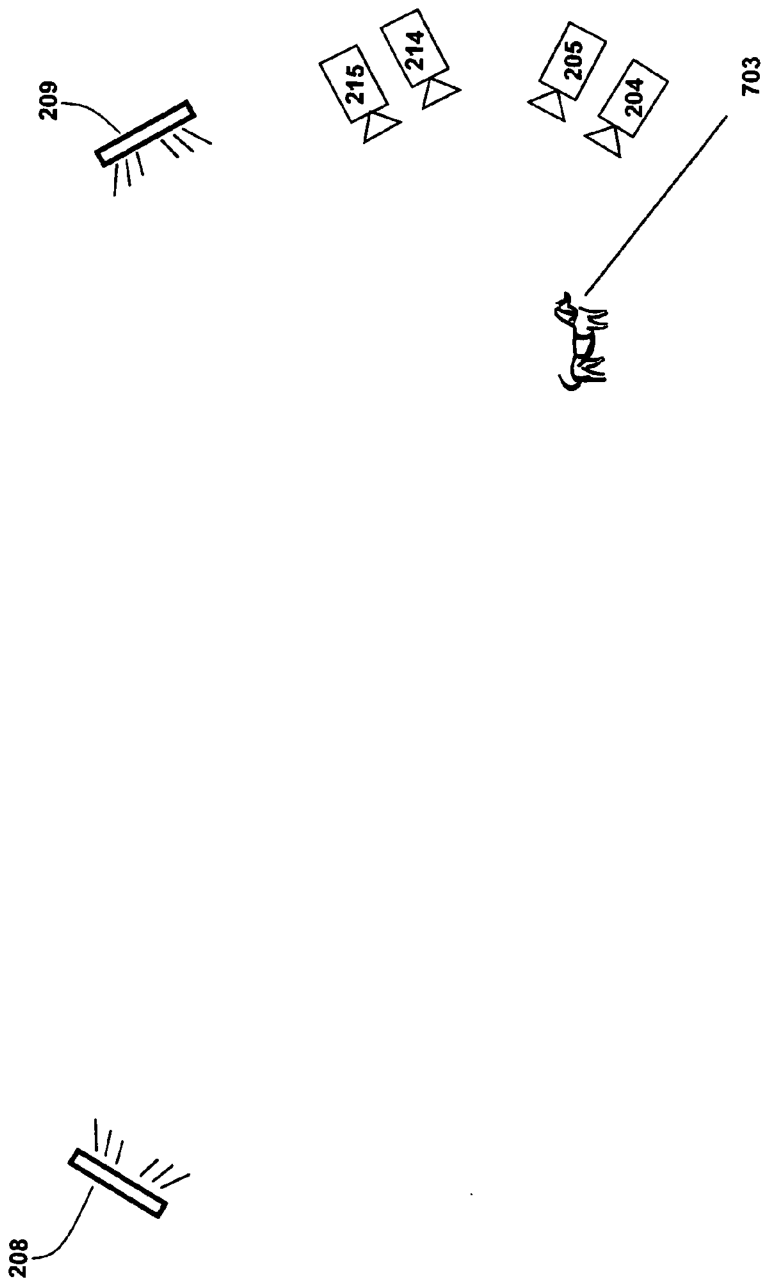
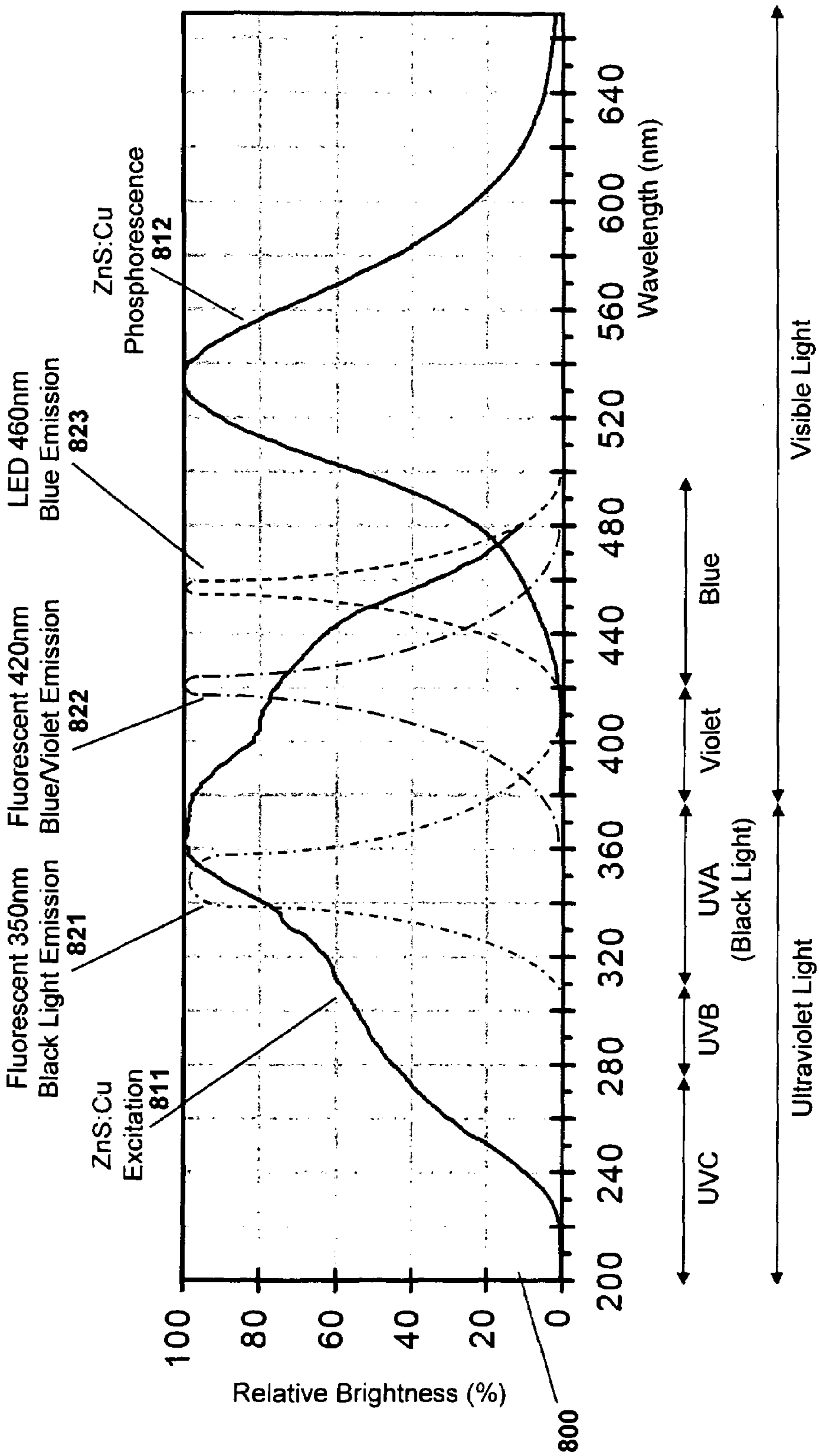


Fig. 7e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Phosphorescence
812
LED 460nm
Blue Emission
823
Fluorescent 420nm
Blue/Violet Emission
822
Fluorescent 350nm
Black Light Emission
821
ZnS:Cu
Excitation
811
100
80
60
40
20
0
Relative Brightness (%)
800
200
240
280
320
360
400
440
480
520
560
600
640
Wavelength (nm)
UVC
UVB
UVA
(Black Light)
Violet
Blue
Ultraviolet Light
Visible Light

Fig. 8

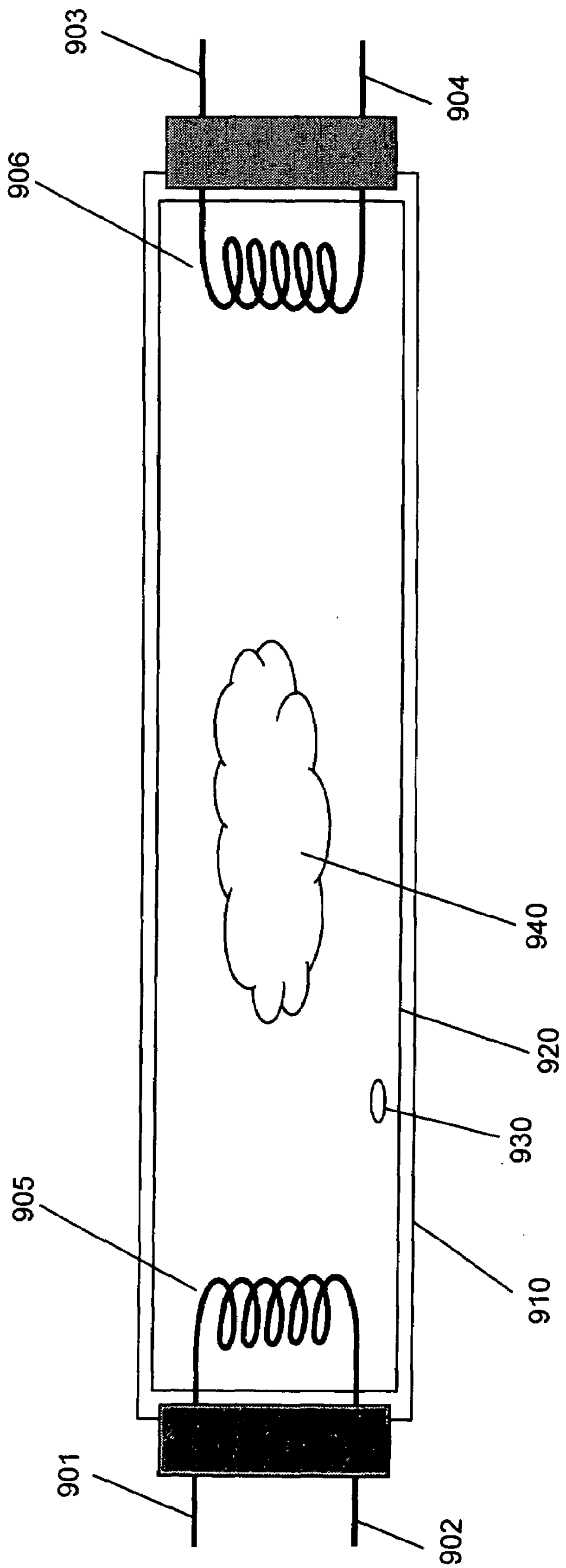


FIG. 9
(Prior Art)

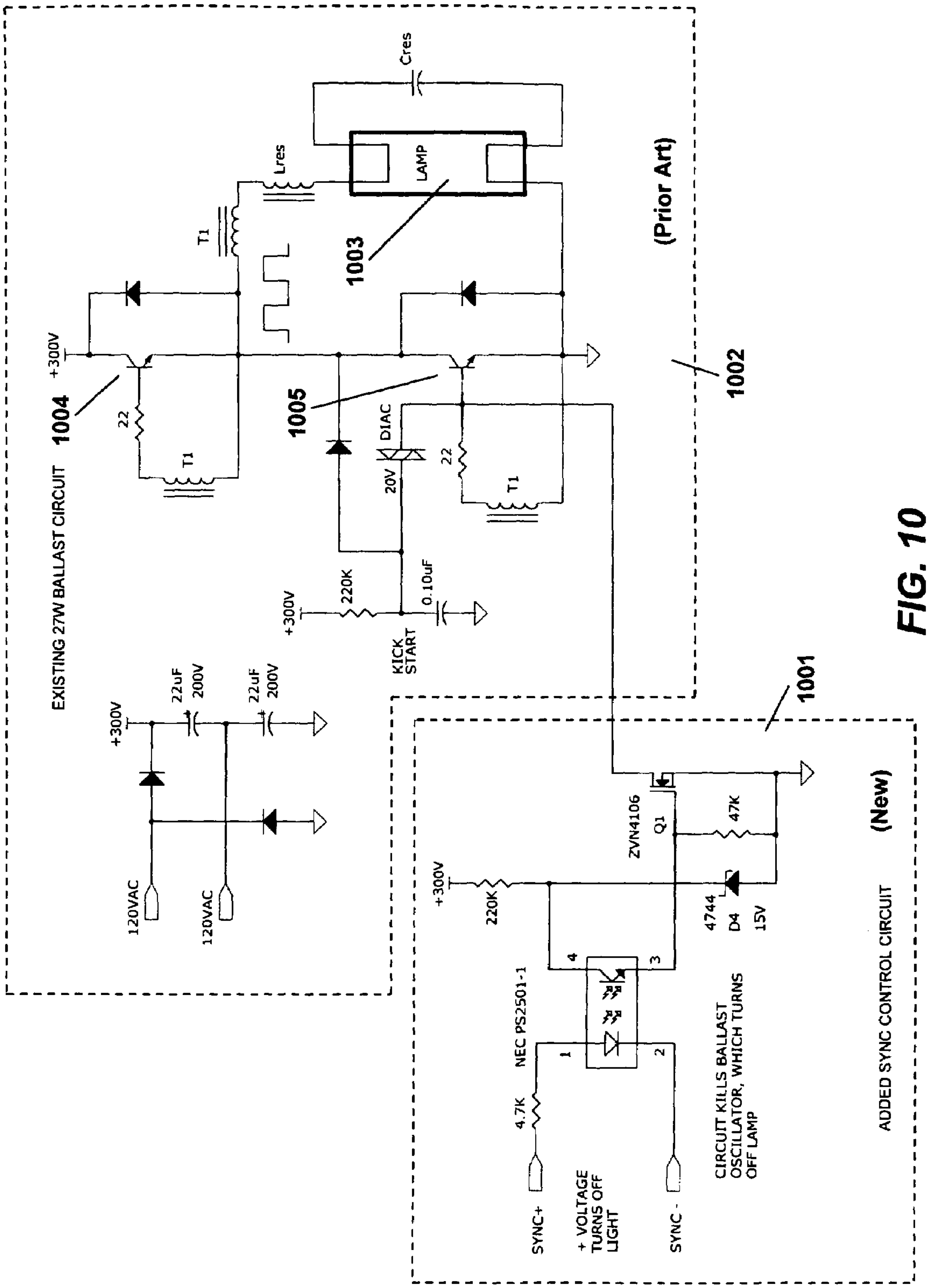

EXISTING 27W BALLAST CIRCUIT
1004
1005
1003
1002
1001
(Prior Art)
(New)
Cres
Lres
LAMP
T1
22
DIAC
20V
+300V
220K
0.10uF
KICK START
22uF 200V
120VAC
2VN4106
Q1
47K
4744
D4
15V
NEC PS2501-1
4.7K
SYNC+
SYNC -
+ VOLTAGE TURNS OFF LIGHT
CIRCUIT KILLS BALLAST OSCILLATOR, WHICH TURNS OFF LAMP
ADDED SYNC CONTROL CIRCUIT

FIG. 10

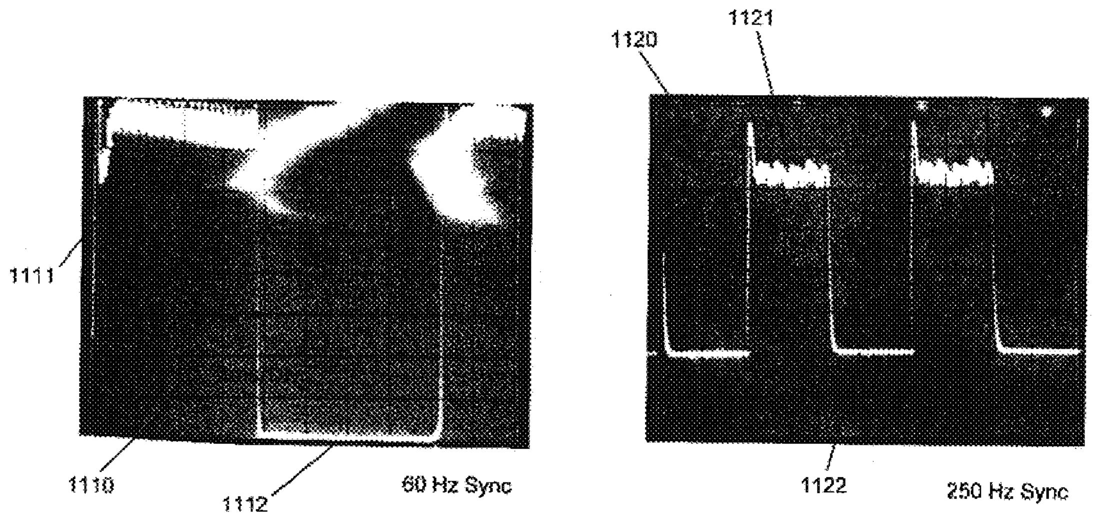


FIG. 11

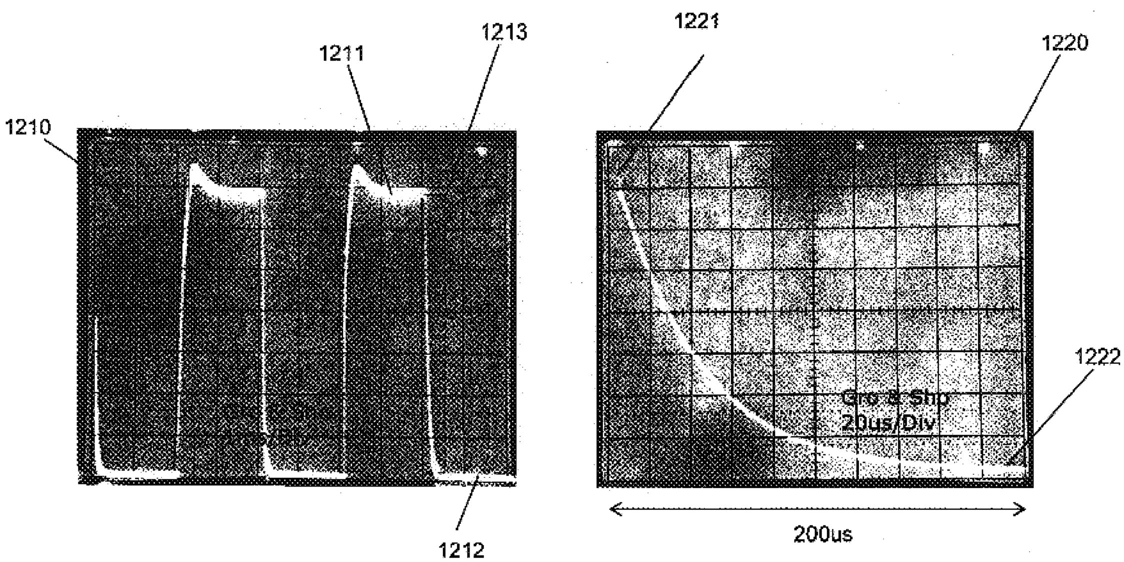
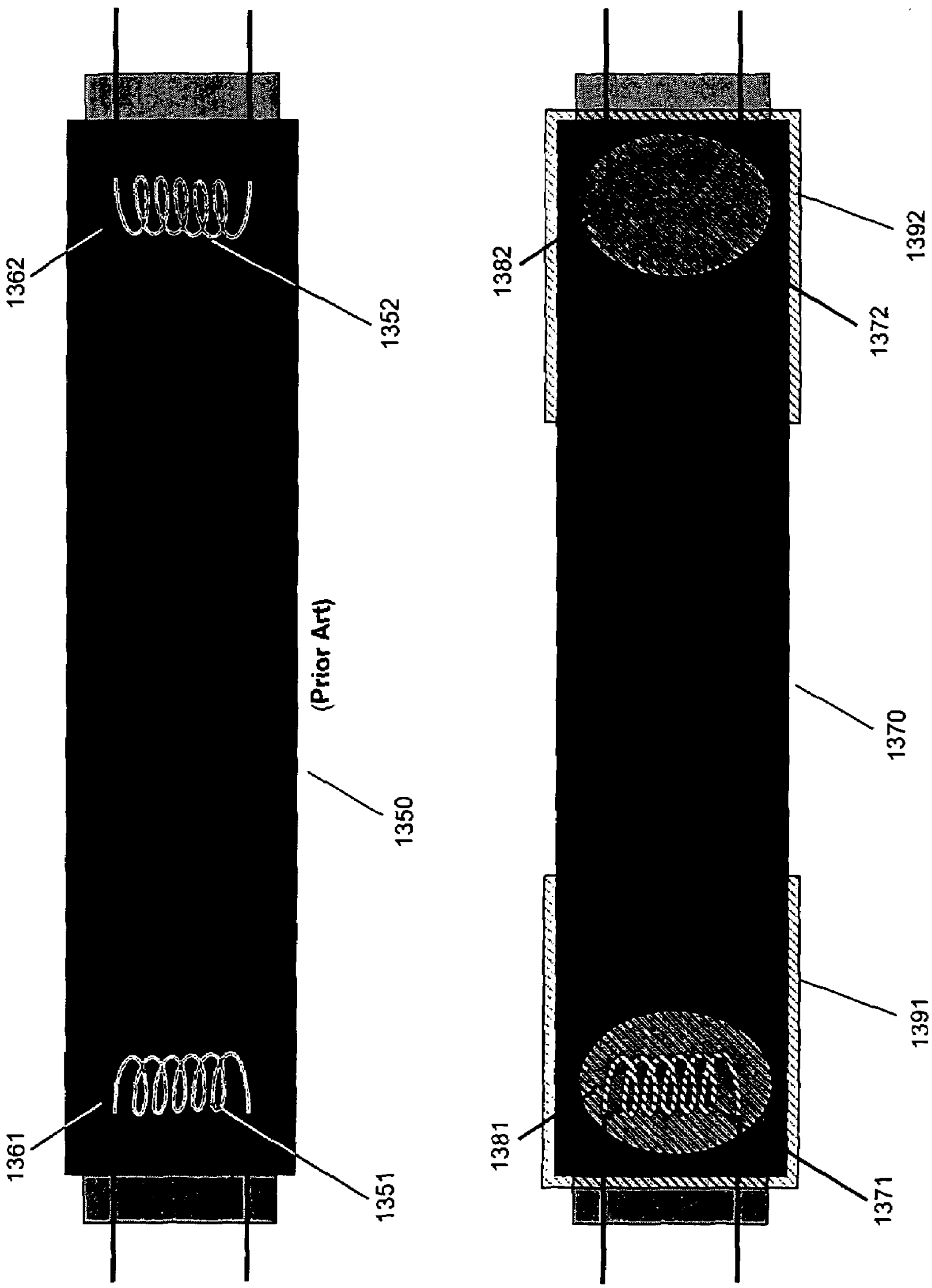


FIG. 12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(Prior Art)
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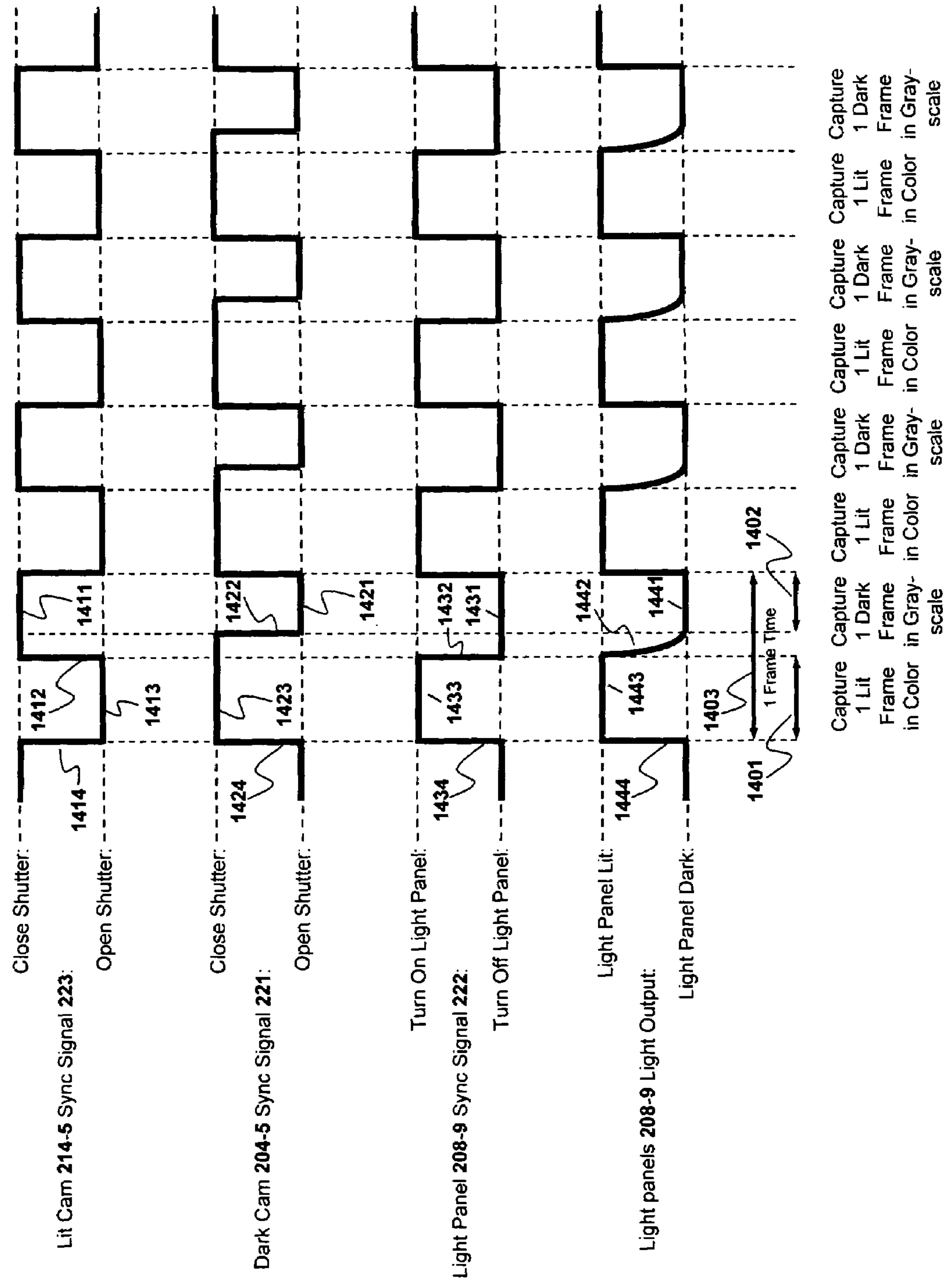
FIG. 13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Turn Off Light Panel:
Light panels 208-9 Light Output:
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Light Panel Dark:
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1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
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Capture 1 Dark Frame in Gray-scale
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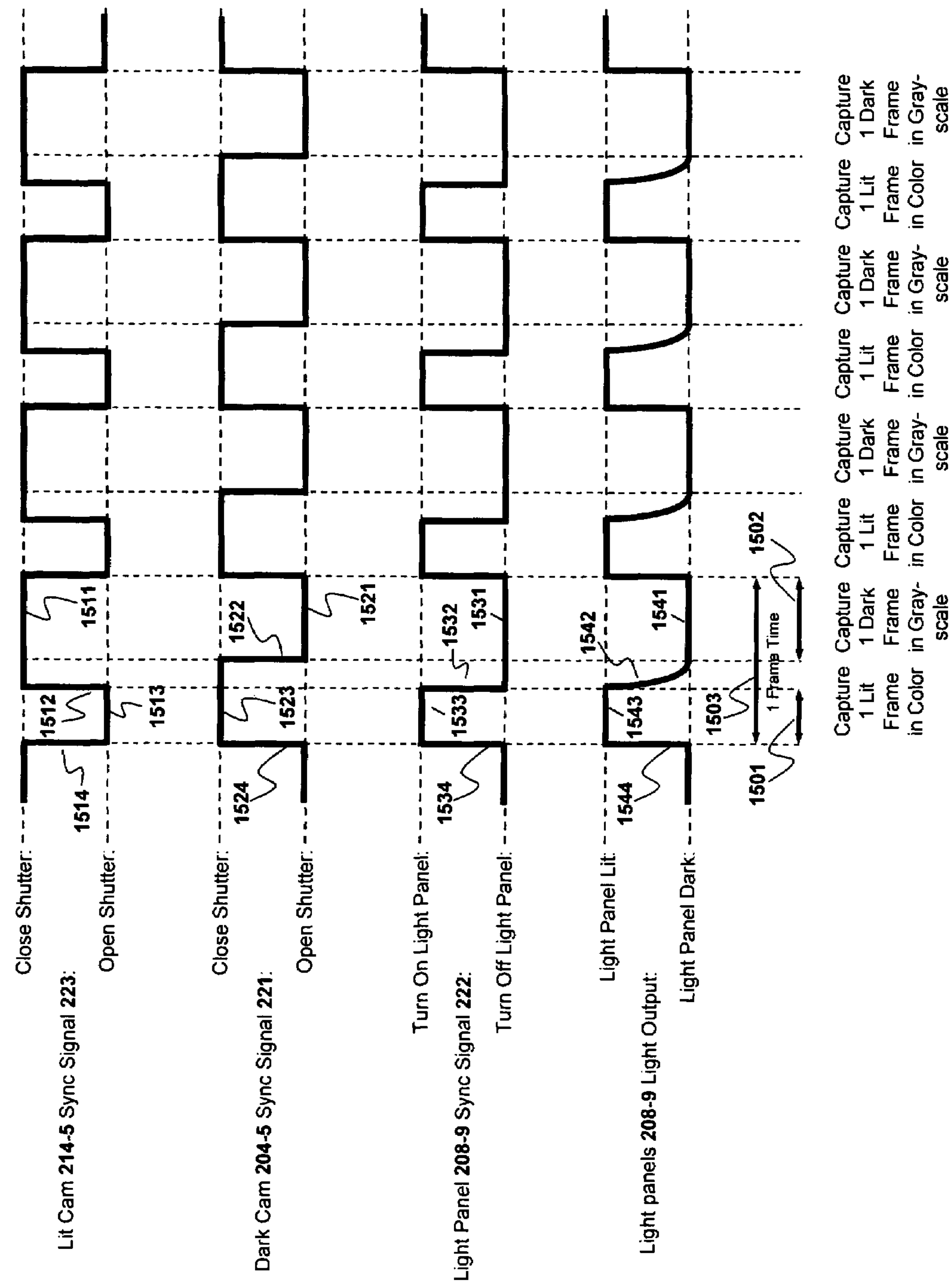
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 14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Light panels 208-9 Light Output:
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1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
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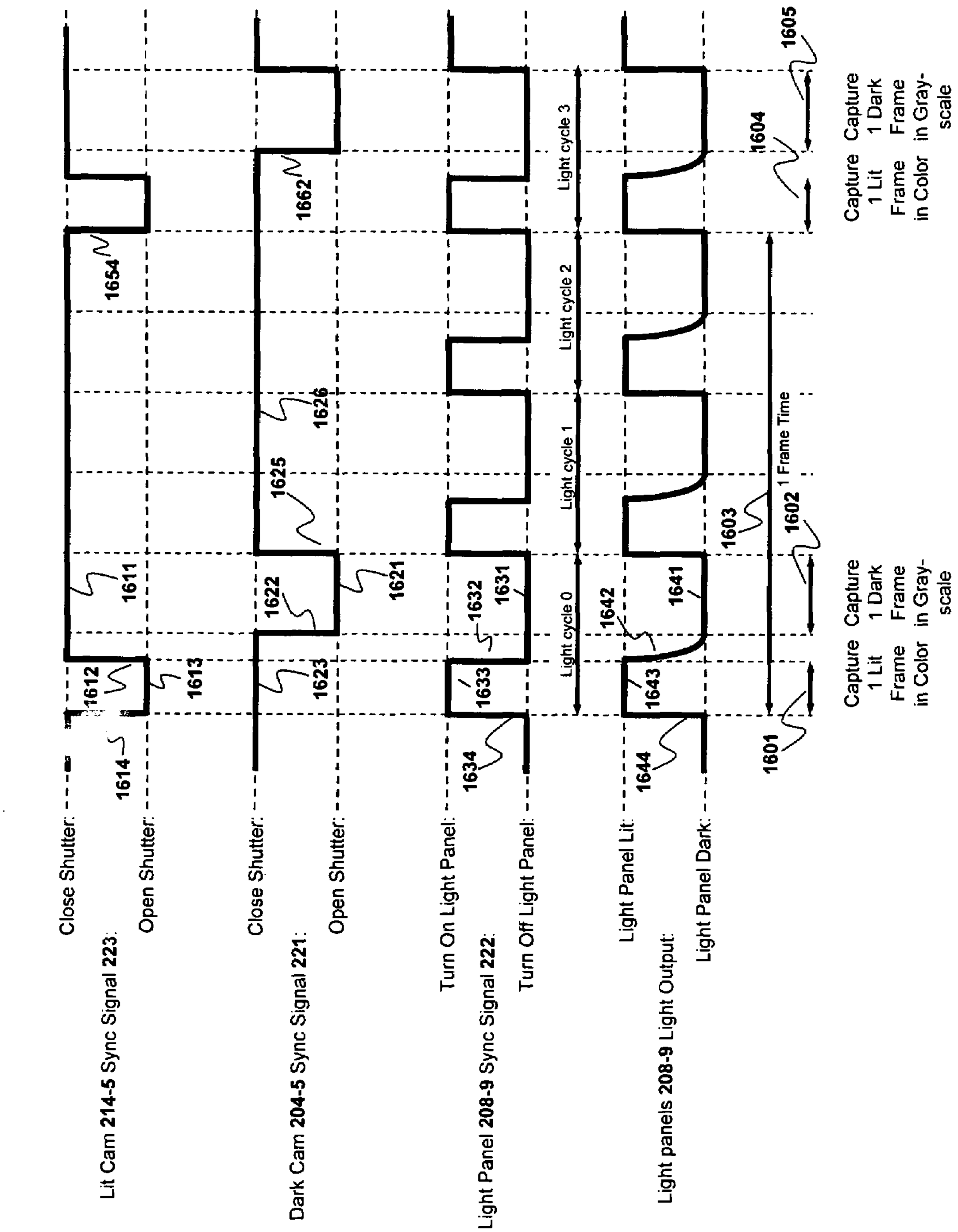
Capture 1 Dark Frame in Gray-scale

Fig. 15



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Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
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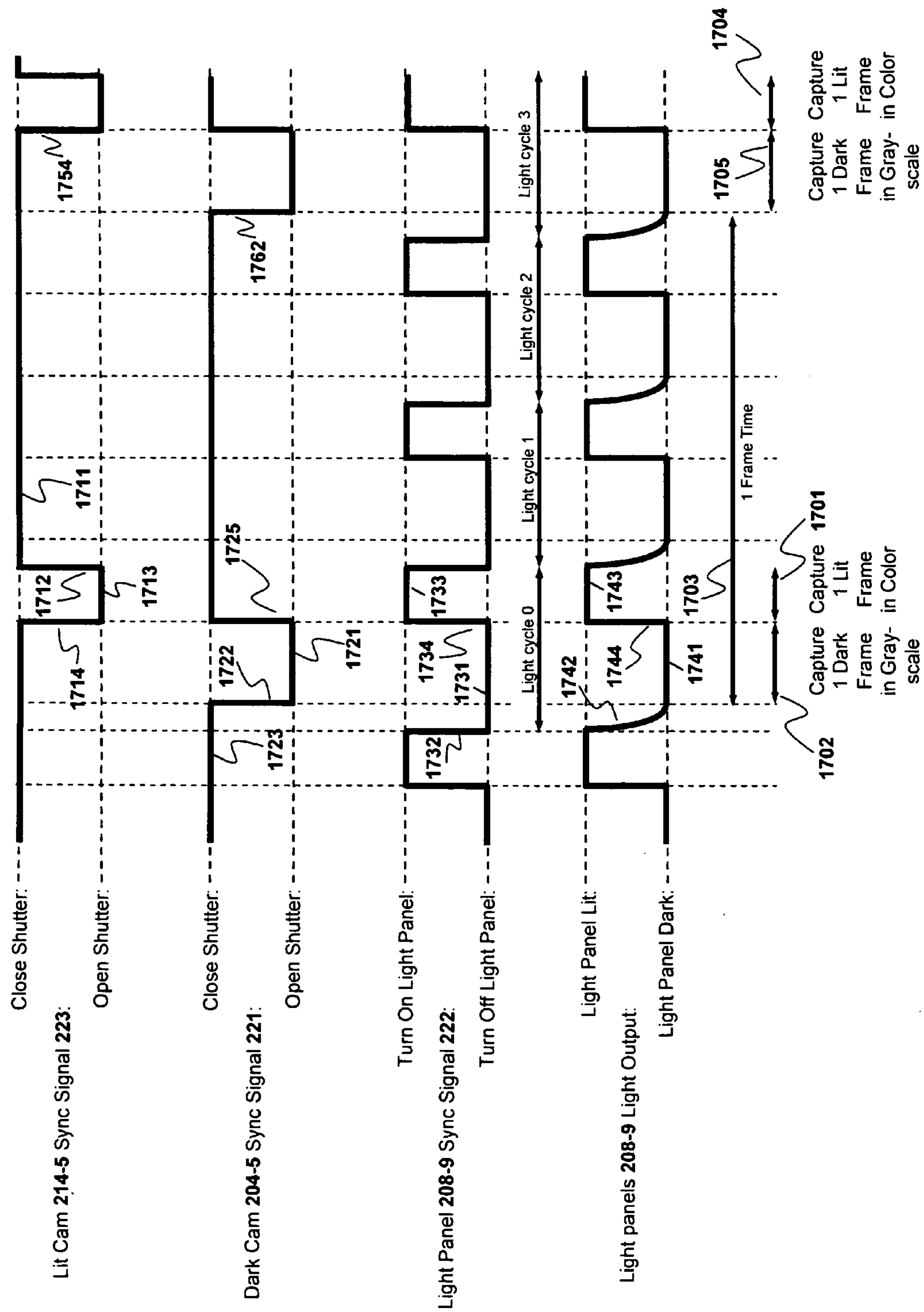
Fig. 16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Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
1701
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1762

Fig. 17

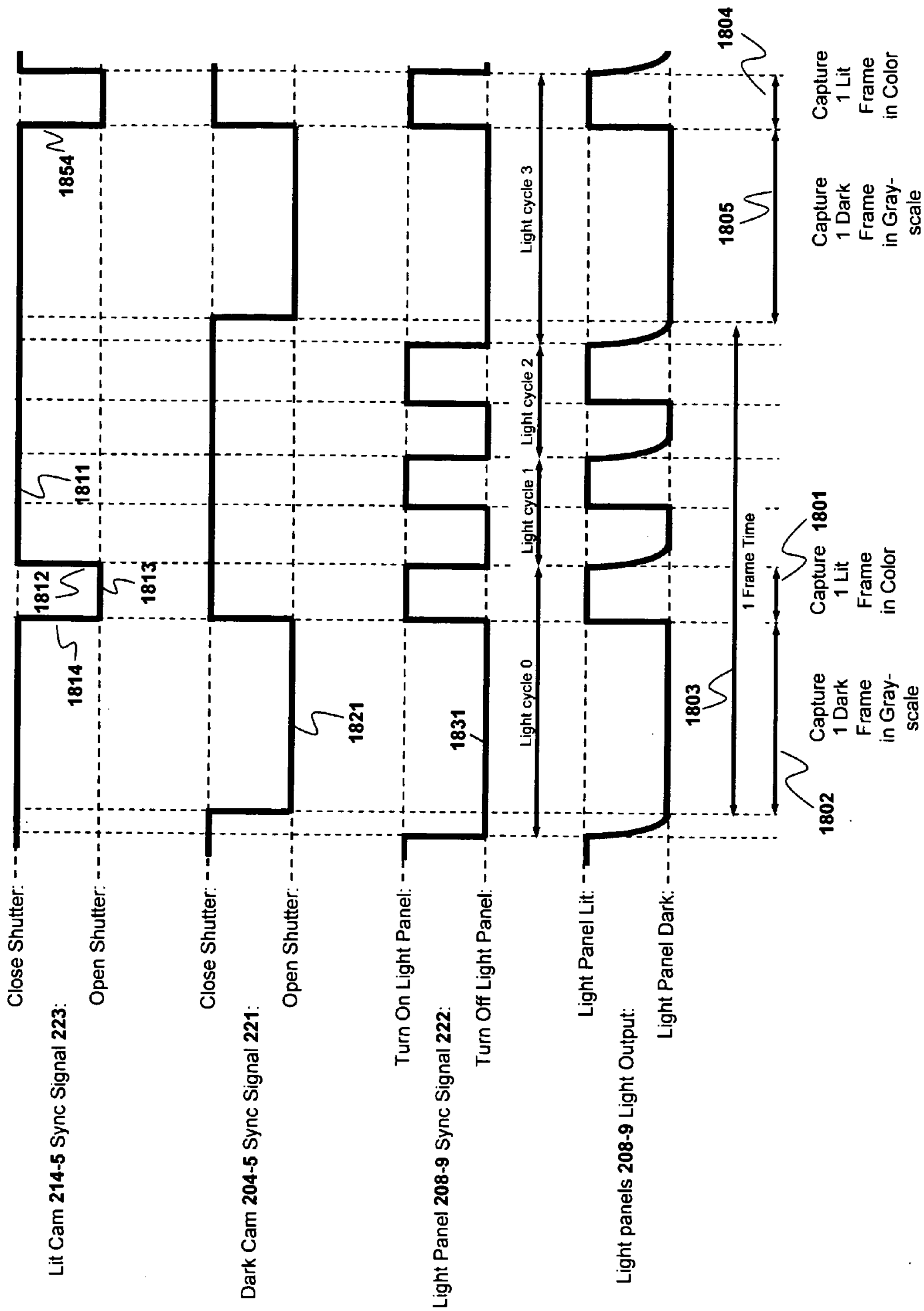
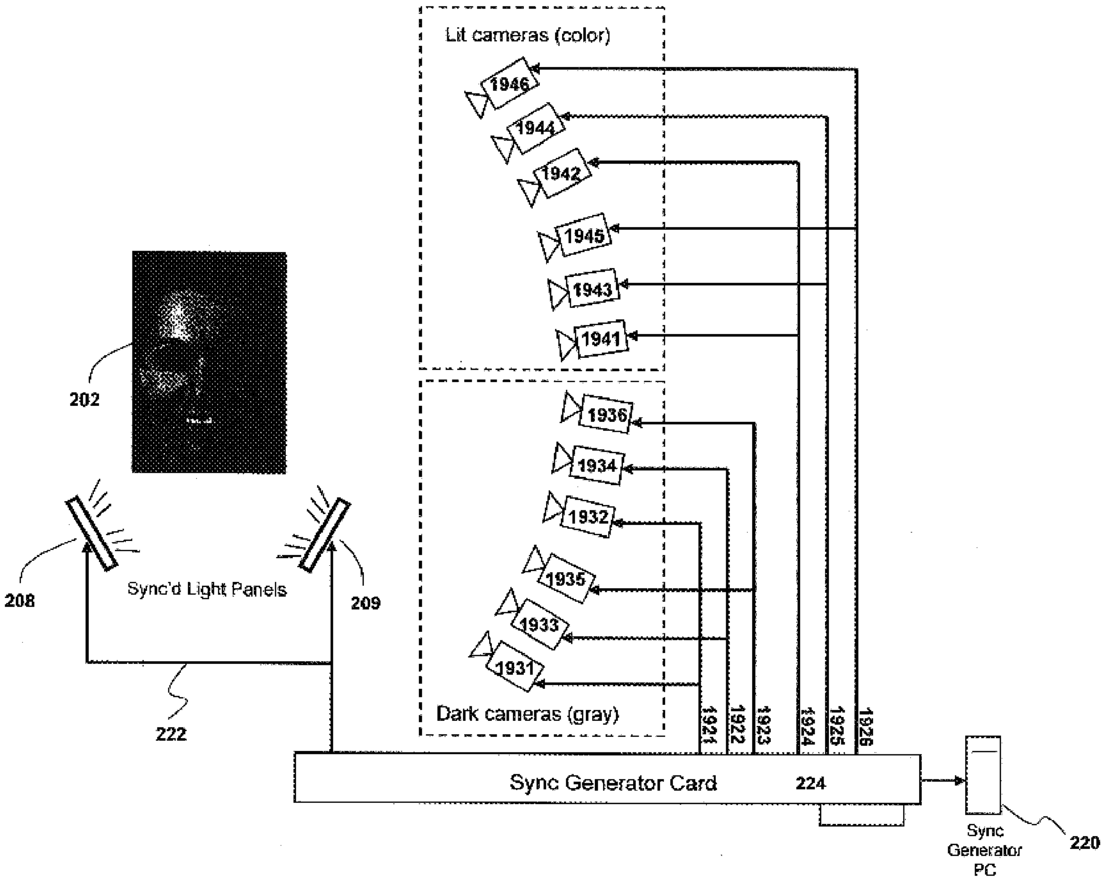
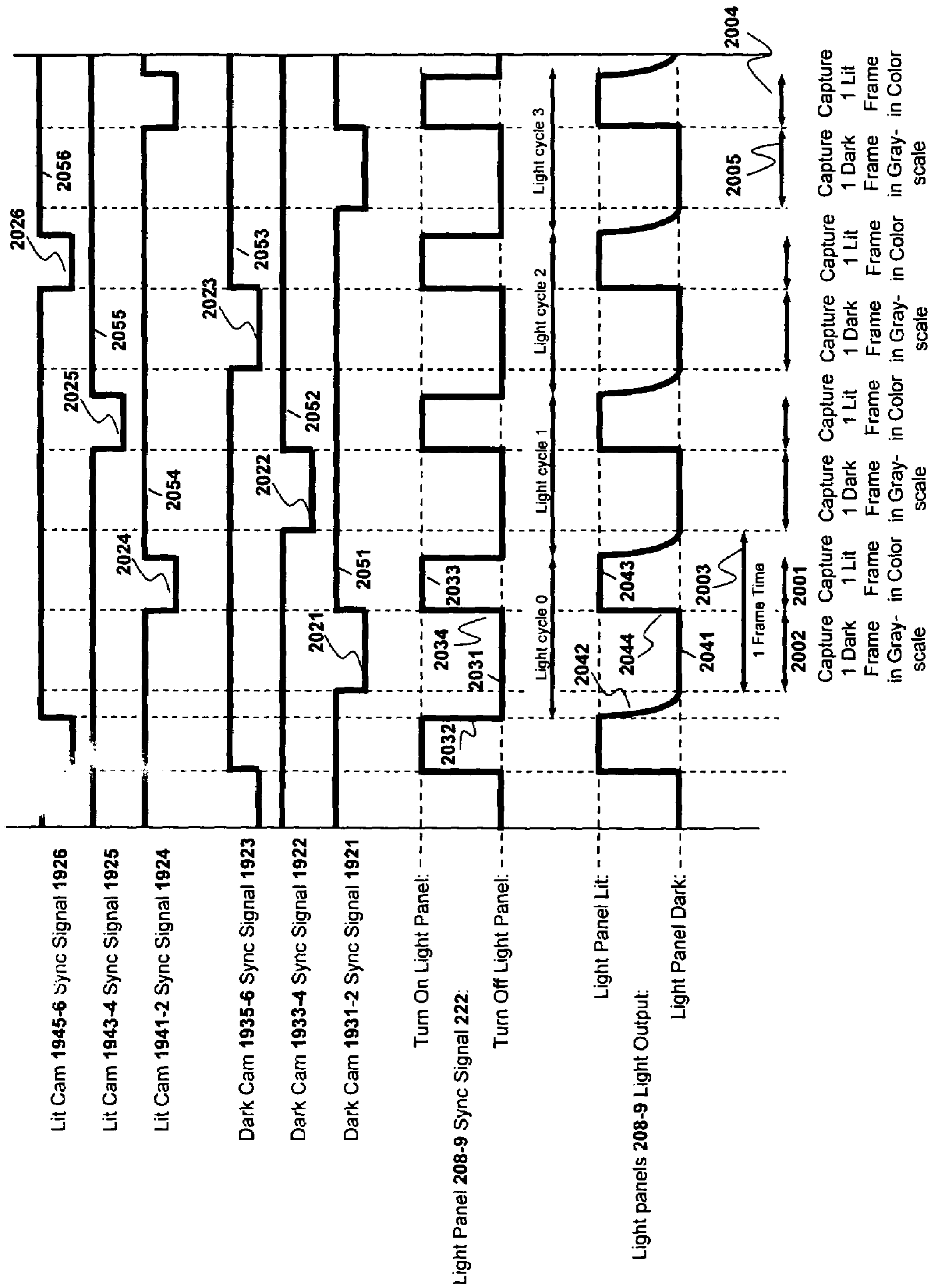

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
1854
1811
1812
1813
1814
1821
1831
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
1802
1803
1801
1804
1805
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color

Fig. 18



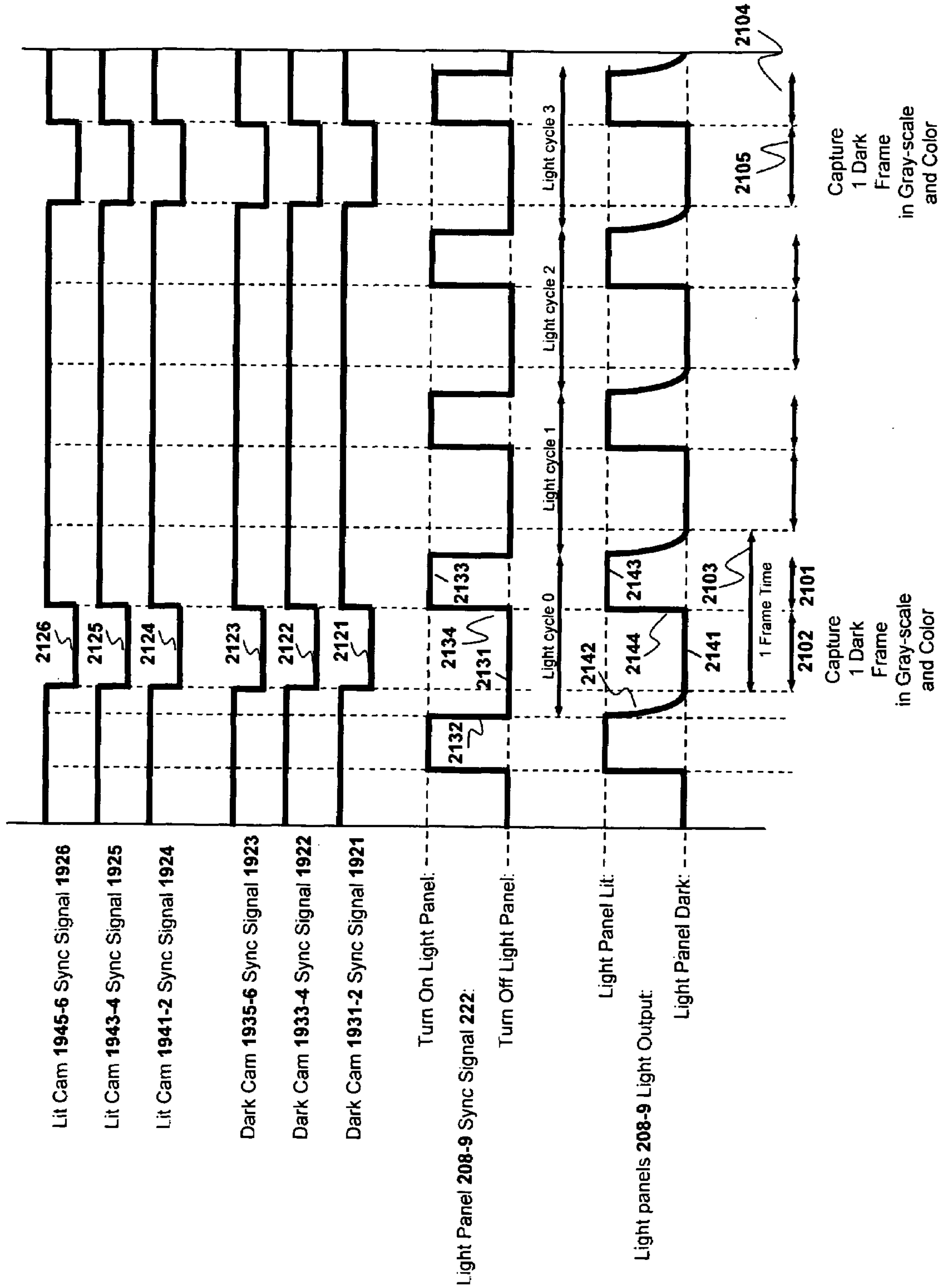
Lit cameras (color)
1946
1944
1942
1945
1943
1941
202
1936
1934
1932
1935
1933
1931
208
Sync'd Light Panels
209
222
Dark cameras (gray)
1921
1922
1923
1924
1925
1926
Sync Generator Card
224
Sync Generator PC
220

Fig. 19



Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
2001
2002
2003
2004
2005
2021
2022
2023
2024
2025
2026
2031
2032
2033
2034
2041
2042
2043
2044
2051
2052
2053
2054
2055
2056

Fig. 20



Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
2126
2125
2124
2123
2122
2121
2132
2134
2131
2133
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
2142
2144
2143
2141
2103
1 Frame Time
2102
2101
2104
2105
Capture 1 Dark Frame in Gray-scale and Color
Capture 1 Dark Frame in Gray-scale and Color

Fig. 21

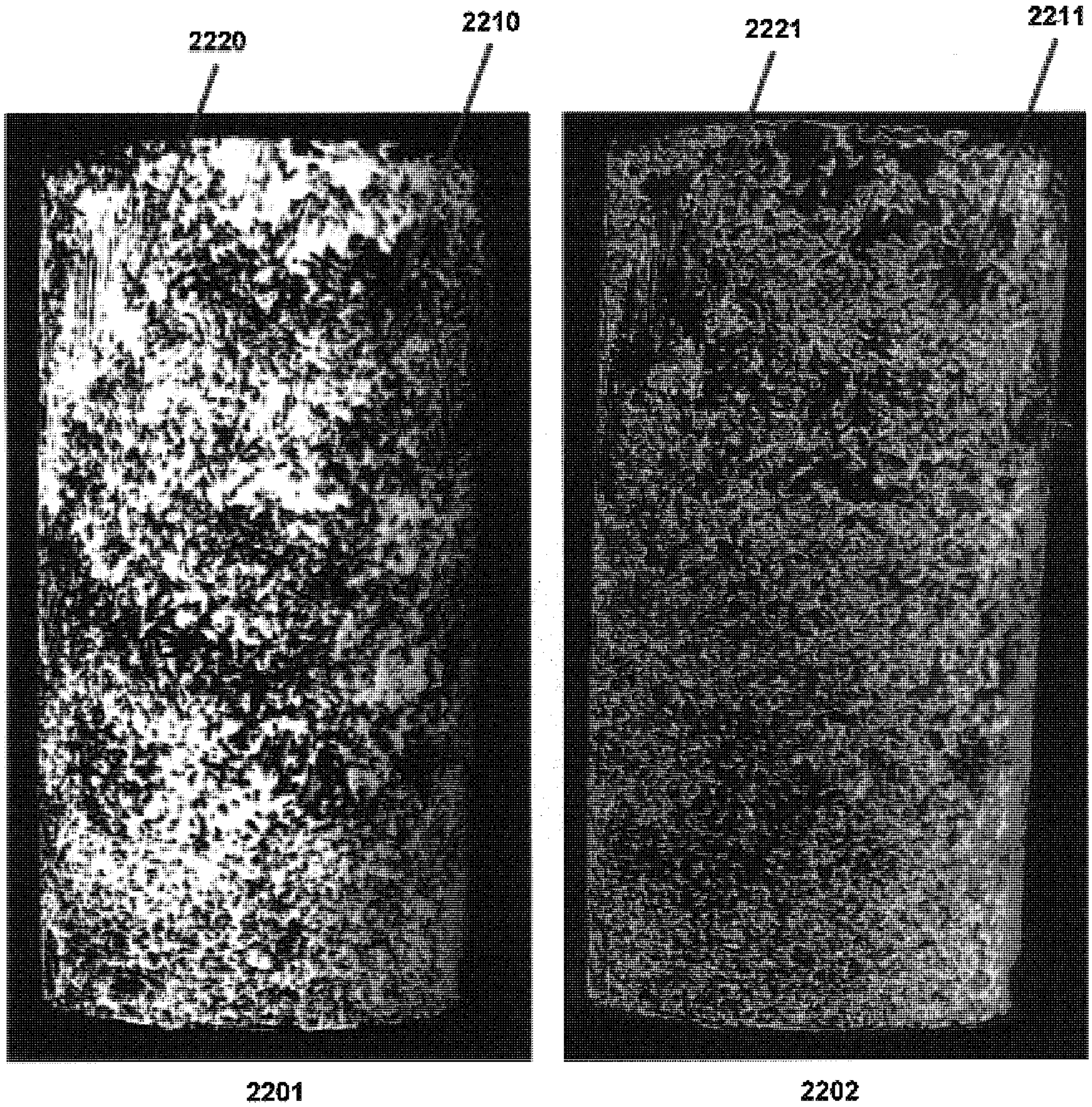


Fig. 22

SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE BY STROBING A FLUORESCENT LAMP

BACKGROUND OF THE INVENTION

1. Field of the Invention

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent publication with color drawing(s) will be provided by the U.S. Patent and Trademark Office upon request and payment of the necessary fee.

This invention relates generally to the field of motion capture. More particularly, the invention relates to an improved apparatus and method for performing motion capture using a phosphorescent mixture.

2. Description of the Related Art

"Motion capture" refers generally to the tracking and recording of human and animal motion. Motion capture systems are used for a variety of applications including, for example, video games and computer-generated movies. In a typical motion capture session, the motion of a "performer" is captured and translated to a computer-generated character.

As illustrated in FIG. **1** in a motion capture system, a plurality of motion tracking "markers" (e.g., markers **101**, **102**) are attached at various points on a performer's **100**'s body. The points are selected based on the known limitations of the human skeleton. Different types of motion capture markers are used for different motion capture systems. For example, in a "magnetic" motion capture system, the motion markers attached to the performer are active coils which generate measurable disruptions x, y, z and yaw, pitch, roll in a magnetic field.

By contrast, in an optical motion capture system, such as that illustrated in FIG. **1**, the markers **101**, **102** are passive spheres comprised of retro-reflective material, i.e., a material which reflects light back in the direction from which it came, ideally over a wide range of angles of incidence. A plurality of cameras **120**, **121**, **122**, each with a ring of LEDs **130**, **131**, **132** around its lens, are positioned to capture the LED light reflected back from the retro-reflective markers **101**, **102** and other markers on the performer. Ideally, the retro-reflected LED light is much brighter than any other light source in the room. Typically, a thresholding function is applied by the cameras **120**, **121**, **122** to reject all light below a specified level of brightness which, ideally, isolates the light reflected off of the reflective markers from any other light in the room and the cameras **120**, **121**, **122** only capture the light from the markers **101**, **102** and other markers on the performer.

A motion tracking unit **150** coupled to the cameras is programmed with the relative position of each of the markers **101**, **102** and/or the known limitations of the performer's body. Using this information and the visual data provided from the cameras **120-122**, the motion tracking unit **150** generates artificial motion data representing the movement of the performer during the motion capture session.

A graphics processing unit **152** renders an animated representation of the performer on a computer display **160** (or similar display device) using the motion data. For example, the graphics processing unit **152** may apply the captured motion of the performer to different animated characters and/or to include the animated characters in different computer-generated scenes. In one implementation, the motion tracking unit **150** and the graphics processing unit **152** are programmable cards coupled to the bus of a computer (e.g., such as the PCI and AGP buses found in many personal computers). One well known company which produces motion capture systems is Motion Analysis Corporation (see, e.g., www.motionanalysis.com).

SUMMARY

A system and method are described for performing motion capture on a subject using fluorescent lamps. For example, a system according to one embodiment of the invention comprises: a synchronization signal generator to generate one or more synchronization signals; one or more fluorescent lamps configured to strobe on and off responsive to a first one of the one or more synchronization signals, the fluorescent lamps charging phosphorescent makeup, paint or dye applied to a subject for a motion capture session; and a plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture images of the phosphorescent paint, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention can be obtained from the following detailed description in conjunction with the drawings, in which:

FIG. **1** illustrates a prior art motion tracking system for tracking the motion of a performer using retro-reflective markers and cameras.

FIG. **2***a* illustrates one embodiment of the invention during a time interval when the light panels are lit.

FIG. **2***b* illustrates one embodiment of the invention during a time interval when the light panels are dark.

FIG. **3** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **4** is images of heavily-applied phosphorescent makeup on a model during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **5** is images of phosphorescent makeup mixed with base makeup on a model both during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **6** is images of phosphorescent makeup applied to cloth during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **7***a* illustrates a prior art stop-motion animation stage.

FIG. **7***b* illustrates one embodiment of the invention where stop-motion characters and the set are captured together.

FIG. **7***c* illustrates one embodiment of the invention where the stop-motion set is captured separately from the characters.

FIG. **7***d* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **7***e* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **8** is a chart showing the excitation and emission spectra of ZnS:Cu phosphor as well as the emission spectra of certain fluorescent and LED light sources.

FIG. **9** is an illustration of a prior art fluorescent lamp.

FIG. **10** is a circuit diagram of a prior art fluorescent lamp ballast as well as one embodiment of a synchronization control circuit to modify the ballast for the purposes of the present invention.

FIG. **11** is oscilloscope traces showing the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **12** is oscilloscope traces showing the decay curve of the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **13** is a illustration of the afterglow of a fluorescent lamp filament and the use of gaffer's tape to cover the filament.

FIG. **14** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **15** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **16** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **17** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **18** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **19** illustrates one embodiment of the camera, light panel, and synchronization subsystems of the invention during a time interval when the light panels are lit.

FIG. **20** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **21** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **22** illustrates one embodiment of the invention where color is used to indicate phosphor brightness.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Described below is an improved apparatus and method for performing motion capture using shutter synchronization and/or phosphorescent makeup, paint or dye. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form to avoid obscuring the underlying principles of the invention.

The assignee of the present application previously developed a system for performing color-coded motion capture and a system for performing motion capture using a series of reflective curves painted on a performer's face. These systems are described in the co-pending applications entitled "APPARATUS AND METHOD FOR CAPTURING THE MOTION AND/OR EXPRESSION OF A PERFORMER," Ser. No. 10/942,609, and Ser. No. 10/942,413, Filed Sep. 15, 2004. These applications are assigned to the assignee of the present application and are incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture of random patterns applied to surfaces. This system is described in the co-pending applications entitled "APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING A RANDOM PATTERN ON CAPTURE SURFACES," Ser. No. 11/255,854, Filed Oct. 20, 2005. This application is assigned to the assignee of the present application and is incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture using shutter synchronization and phosphorescent paint. This system is described in the co-pending application entitled "APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING SHUTTER SYNCHRONIZATION," Ser. No. 11/077,628, Filed Mar. 10, 2005 (hereinafter "Shutter Synchronization" application). Briefly, in the Shutter Synchronization application, the efficiency of the motion capture system is improved by using phosphorescent paint or makeup and by precisely controlling synchronization between the motion capture cameras' shutters and the illumination of the painted curves. This application is assigned to the assignee of the present application and is incorporated herein by reference.

System Overview

As described in these co-pending applications, by analyzing curves or random patterns applied as makeup on a performer's face rather than discrete marked points or markers on a performer's face, the motion capture system is able to generate significantly more surface data than traditional marked point or marker-based tracking systems. The random patterns or curves are painted on the face of the performer using retro-reflective, non-toxic paint or theatrical makeup. In one embodiment of the invention, non-toxic phosphorescent makeup is used to create the random patterns or curves. By utilizing phosphorescent paint or makeup combined with synchronized lights and camera shutters, the motion capture system is able to better separate the patterns applied to the performer's face from the normally-illuminated image of the face or other artifacts of normal illumination such as highlights and shadows.

FIGS. **2***a* and **2***b* illustrate an exemplary motion capture system described in the co-pending applications in which a random pattern of phosphorescent makeup is applied to a performer's face and motion capture is system is operated in a light-sealed space. When the synchronized light panels **208-209** are on as illustrated FIG. **2***a*, the performers' face looks as it does in image **202** (i.e. the phosphorescent makeup is only slightly visible). When the synchronized light panels **208-209** (e.g. LED arrays) are off as illustrated in FIG. **2***b*, the performers' face looks as it does in image **203** (i.e. only the glow of the phosphorescent makeup is visible).

Grayscale dark cameras **204-205** are synchronized to the light panels **208-209** using the synchronization signal generator PCI Card **224** (an exemplary PCI card is a PCI-6601 manufactured by National Instruments of Austin, Tex.) coupled to the PCI bus of synchronization signal generator PC **220** that is coupled to the data processing system **210** and so that all of the systems are synchronized together. Light Panel Sync signal **222** provides a TTL-level signal to the light panels **208-209** such that when the signal **222** is high (i.e. ≧2.0V), the light panels **208-209** turn on, and when the signal **222** is low (i.e. ≦0.8V), the light panels turn off. Dark Cam Sync signal **221** provides a TTL-level signal to the grayscale dark cameras **204-205** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller PCs **205**. The synchronization timing (explained in detail below) is such that the camera **204-205** shutters open to capture a frame when the light panels **208-209** are off (the "dark" interval). As a result, grayscale dark cameras **204-205** capture images of only the output of the phosphorescent makeup. Similarly, Lit Cam Sync **223** provides TTL-level signal to color lit cameras **214-215** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller computers **225**. Color lit cameras **214-215** are synchronized (as explained in detail below) such that their shutters open to capture a frame when the light panels **208-209** are on (the "lit" interval). As a result, color lit cameras **214-215** capture images of the performers' face illuminated by the light panels.

As used herein, grayscale cameras **204-205** may be referenced as "dark cameras" or "dark cams" because their shutters normally only when the light panels **208-209** are dark. Similarly, color cameras **214-215** may be referenced as "lit cameras" or "lit cams" because normally their shutters are only open when the light panels **208-209** are lit. While grayscale and color cameras are used specifically for each lighting phase in one embodiment, either grayscale or color cameras can be used for either light phase in other embodiments.

In one embodiment, light panels **208-209** are flashed rapidly at 90 flashes per second (as driven by a 90 Hz square wave from Light Panel Sync signal **222**), with the cameras **204-205** and **214-205** synchronized to them as previously described. At 90 flashes per second, the light panels **208-209** are flashing at a rate faster than can be perceived by the vast majority of humans, and as a result, the performer (as well as any observers of the motion capture session) perceive the room as being steadily illuminated and are unaware of the flashing, and the performer is able to proceed with the performance without distraction from the flashing light panels **208-209**.

As described in detail in the co-pending applications, the images captured by cameras **204-205** and **214-215** are recorded by camera controllers **225** (coordinated by a centralized motion capture controller **206**) and the images and images sequences so recorded are processed by data processing system **210**. The images from the various grayscale dark cameras are processed so as to determine the geometry of the 3D surface of the face **207**. Further processing by data processing system **210** can be used to map the color lit images captured onto the geometry of the surface of the face **207**. Yet further processing by the data processing system **210** can be used to track surface points on the face from frame-to-frame.

In one embodiment, each of the camera controllers **225** and central motion capture controller **206** is implemented using a separate computer system. Alternatively, the camera controllers and motion capture controller may be implemented as software executed on a single computer system or as any combination of hardware and software. In one embodiment, the camera controller computers **225** are rack-mounted computers, each using a 945GT Speedster-A4R motherboard from MSI Computer Japan Co., Ltd. (C&K Bldg. 6F 1-17-6, Higashikanda, Chiyoda-ku, Tokyo 101-0031 Japan) with 2 Gbytes of random access memory (RAM) and a 2.16 GHz Intel Core Duo central processing unit from Intel Corporation, and a 300 GByte SATA hard disk from Western Digital, Lake Forest Calif. The cameras **204-205** and **214-215** interface to the camera controller computers **225** via IEEE 1394 cables.

In another embodiment the central motion capture controller **206** also serves as the synchronization signal generator PC **220**. In yet another embodiment the synchronization signal generator PCI card **224** is replaced by using the parallel port output of the synchronization signal generator. PC **220**. In such an embodiment, each of the TTL-level outputs of the parallel port are controlled by an application running on synchronization signal generator PC **220**, switching each TTL-level output to a high state or a low state in accordance with the desired signal timing. For example, bit **0** of the PC **220** parallel port is used to drive synchronization signal **221**, bit **1** is used to drive signal **222**, and bit **2** is used to drive signal **224**. However, the underlying principles of the invention are not limited to any particular mechanism for generating the synchronization signals.

The synchronization between the light sources and the cameras employed in one embodiment of the invention is illustrated in FIG. **3**. In this embodiment, the Light Panel and Dark Cam Sync signals **221** and **222** are in phase with each other, while the Lit Cam Sync Signal **223** is the inverse of signals **221**/**222**. In one embodiment, the synchronization signals cycle between 0 to 5 Volts. In response to the synchronization signal **221** and **223**, the shutters of the cameras **204-205** and **214-215**, respectively, are periodically opened and closed as shown in FIG. **3**. In response to sync signal **222**, the light panels are periodically turned off and on, respectively as shown in FIG. **3**. For example, on the falling edge **314** of sync signal **223** and on the rising edges **324** and **334** of sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are opened and the dark camera **204-215** shutters are closed and the light panels are illuminated as shown by rising edge **344**. The shutters remain in their respective states and the light panels remain illuminated for time interval **301**. Then, on the rising edge **312** of sync signal **223** and falling edges **322** and **332** of the sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are closed, the dark camera **204-215** shutters are opened and the light panels are turned off as shown by falling edge **342**. The shutters and light panels are left in this state for time interval **302**. The process then repeats for each successive frame time interval **303**.

As a result, during the first time interval **301**, a normally-lit image is captured by the color lit cameras **214-215**, and the phosphorescent makeup is illuminated (and charged) with light from the light panels **208-209**. During the second time interval **302**, the light is turned off and the grayscale dark cameras **204-205** capture an image of the glowing phosphorescent makeup on the performer. Because the light panels are off during the second time interval **302**, the contrast between the phosphorescent makeup and any surfaces in the room without phosphorescent makeup is extremely high (i.e., the rest of the room is pitch black or at least quite dark, and as a result there is no significant light reflecting off of surfaces in the room, other than reflected light from the phosphorescent emissions), thereby improving the ability of the system to differentiate the various patterns applied to the performer's face. In addition, because the light panels are on half of the time, the performer will be able to see around the room during the performance, and also the phosphorescent makeup is constantly recharged. The frequency of the synchronization signals is 1/(time interval **303**) and may be set at such a high rate that the performer will not even notice that the light panels are being turned on and off. For example, at a flashing rate of 90 Hz or above, virtually all humans are unable to perceive that a light is flashing and the light appears to be continuously illuminated. In psychophysical parlance, when a high frequency flashing light is perceived by humans to be continuously illuminated, it is said that "fusion" has been achieved. In one embodiment, the light panels are cycled at 120 Hz; in another embodiment, the light panels are cycled at 140 Hz, both frequencies far above the fusion threshold of any human.

However, the underlying principles of the invention are not limited to any particular frequency.

Surface Capture of Skin Using Phosphorescent Random Patterns

FIG. **4** shows images captured using the methods described above and the 3D surface and textured 3D surface reconstructed from them. Prior to capturing the images, a phosphorescent makeup was applied to a Caucasian model's face with an exfoliating sponge. Luminescent zinc sulfide with a copper activator (ZnS:Cu) is the phosphor responsible for the makeup's phosphorescent properties. This particular formulation of luminescent Zinc Sulfide is approved by the FDA color additives regulation 21 CFR Part 73 for makeup preparations. The particular brand is Fantasy F/XT Tube Makeup; Product #: FFX; Color Designation: GL; manufactured by Mehron Inc. of 100 Red Schoolhouse Rd. Chestnut Ridge, N.Y. 10977. The motion capture session that produced these images utilized 8 grayscale dark cameras (such as cameras **204**-**205**) surrounding the model's face from a plurality of angles and 1 color lit camera (such as cameras **214**-**215**) pointed at the model's face from an angle to provide the view seen in Lit Image **401**. The grayscale cameras were model A311f from Basler AG, An der Strusbek 60-62, 22926 Ahrensburg, Germany, and the color camera was a Basler model A311fc. The light panels **208**-**209** were flashed at a rate of 72 flashes per second.

Lit Image **401** shows an image of the performer captured by one of the color lit cameras **214**-**215** during lit interval **301**, when the light panels **208**-**209** are on and the color lit camera **214**-**215** shutters are open. Note that the phosphorescent makeup is quite visible on the performer's face, particularly the lips.

Dark Image **402** shows an image of the performer captured by one of the grayscale dark cameras **204**-**205** during dark interval **302**, when the light panels **208**-**209** are off and the grayscale dark camera **204**-**205** shutters are open. Note that only random pattern of phosphorescent makeup is visible on the surfaces where it is applied. All other surfaces in the image, including the hair, eyes, teeth, ears and neck of the performer are completely black.

3D Surface **403** shows a rendered image of the surface reconstructed from the Dark Images **402** from grayscale dark cameras **204**-**205** (in this example, 8 grayscale dark cameras were used, each producing a single Dark Image **402** from a different angle) pointed at the model's face from a plurality of angles. One reconstruction process which may be used to create this image is detailed in co-pending application APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING A RANDOM PATTERN ON CAPTURE SURFACES, Ser. No. 11/255,854, Filed Oct. 20, 2005. Note that 3D Surface **403** was only reconstructed from surfaces where there was phosphorescent makeup applied. Also, the particular embodiment of the technique that was used to produce the 3D Surface **403** fills in cavities in the 3D surface (e.g., the eyes and the mouth in this example) with a flat surface.

Textured 3D Surface **404** shows the Lit Image **401** used as a texture map and mapped onto 3D Surface **403** and rendered at an angle. Although Textured 3D Surface **404** is a computer-generated 3D image of the model's face, to the human eye it appears real enough that when it is rendered at an angle, such as it is in image **404**, it creates the illusion that the model is turning her head and actually looking at an angle. Note that no phosphorescent makeup was applied to the model's eyes and teeth, and the image of the eyes and teeth are mapped onto flat surfaces that fill those cavities in the 3D surface. Nonetheless, the rest of the 3D surface is reconstructed so accurately, the resulting Textured 3D Surface **404** approaches photorealism. When this process is applied to create successive frames of Textured 3D Surfaces **404**, when the frames are played back in real-time, the level of realism is such that, to the untrained eye, the successive frames look like actual video of the model, even though it is a computer-generated 3D image of the model viewed from side angle.

Since the Textured 3D Surfaces **404** produces computer-generated 3D images, such computer-generated images can manipulated with far more flexibility than actual video captured of the model. With actual video it is often impractical (or impossible) to show the objects in the video from any camera angles other than the angle from which the video was shot. With computer-generated 3D, the image can be rendered as if it is viewed from any camera angle. With actual video it is generally necessary to use a green screen or blue screen to separate an object from its background (e.g. so that a TV meteorologist can be composited in front of a weather map), and then that green- or blue-screened object can only be presented from the point of view of the camera shooting the object. With the technique just described, no green/blue screen is necessary. Phosphorescent makeup, paint, or dye is applied to the areas desired to be captured (e.g. the face, body and clothes of the meteorologist) and then the entire background will be separated from the object. Further, the object can be presented from any camera angle. For example, the meteorologist can be shown from a straight-on shot, or from an side angle shot, but still composited in front of the weather map.

Further, a 3D generated image can be manipulated in 3D. For example, using standard 3D mesh manipulation tools (such as those in Maya, sold by Autodesk, Inc.) the nose can be shortened or lengthened, either for cosmetic reasons if the performer feels her nose would look better in a different size, or as a creature effect, to make the performer look like a fantasy character like Gollum of "Lord of the Rings." More extensive 3D manipulations could add wrinkles to the performers face to make her appear to be older, or smooth out wrinkles to make her look younger. The face could also be manipulated to change the performer's expression, for example, from a smile to a frown. Although some 2D manipulations are possible with conventional 2D video capture, they are generally limited to manipulations from the point of view of the camera. If the model turns her head during the video sequence, the 2D manipulations applied when the head is facing the camera would have to be changed when the head is turned. 3D manipulations do not need to be changed, regardless of which way the head is turned. As a result, the techniques described above for creating successive frames of Textured 3D Surface **404** in a video sequence make it possible to capture objects that appear to look like actual video, but nonetheless have the flexibility of manipulation as computer-generated 3D objects, offering enormous advantages in production of video, motion pictures, and also video games (where characters may be manipulated by the player in 3D).

Note that in FIG. **4** the phosphorescent makeup is visible on the model's face in Lit Image **401** and appears like a yellow powder has been spread on her face. It is particularly prominent on her lower lip, where the lip color is almost entirely changed from red to yellow. These discolorations appear in Textured 3D Surface **404**, and they would be even more prominent on a dark-skinned model who is, for example, African in race. Many applications (e.g. creating a fantasy 3D character like Gollum) only require 3D Surface **403**, and Textured 3D Surface **404** would only serve as a reference to the director of the motion capture session or as a reference to

3D animators manipulating the 3D Surface **403**. But in some applications, maintaining the actual skin color of the model's skin is important and the discolorations from the phosphorescent makeup are not desirable.

Surface Capture Using Phosphorescent Makeup Mixed with Base

FIG. **5** shows a similar set of images as FIG. **4**, captured and created under the same conditions: with 8 grayscale dark cameras (such as **204-205**), 1 color camera (such as **214-215**), with the Lit Image **501** captured by the color lit camera during the time interval when the Light Array **208-9** is on, and the Dark Image **502** captured by one of the 8 grayscale dark cameras when the Light Array **208-9**. 3D Surface **503** is reconstructed from the 8 Dark Images **502** from the 8 grayscale dark cameras, and Textured 3D Surface **504** is a rendering of the Lit Image **501** texture-mapped onto 3D Surface **503** (and unlike image **404**, image **504** is rendered from a camera angle similar to the camera angle of the color lit camera that captured Lit Image **501**).

However, there is a notable differences between the images of FIG. **5** and FIG. **4**: The phosphorescent makeup that is noticeably visible in Lit Image **401** and Textured 3D Surface **404** is almost invisible in Lit Image **501** and Textured 3D Surface **504**. The reason for this is that, rather than applying the phosphorescent makeup to the model in its pure form, as was done in the motion capture session of FIG. **4**, in the embodiment illustrated in FIG. **5** the phosphorescent makeup was mixed with makeup base and was then applied to the model. The makeup base used was "Clean Makeup" in "Buff Beige" color manufactured by Cover Girl, and it was mixed with the same phosphorescent makeup used in the FIG. **4** shoot in a proportion of 80% phosphorescent makeup and 20% base makeup.

Note that mixing the phosphorescent makeup with makeup base does reduce the brightness of the phosphorescence during the Dark interval **302**. Despite this, the phosphorescent brightness is still sufficient to produce Dark Image **502**, and there is enough dynamic range in the dark images from the 8 grayscale dark cameras to reconstruct 3D Surface **503**. As previously noted, some applications do not require an accurate capture of the skin color of the model, and in that case it is advantageous to not mix the phosphorescent makeup with base, and then get the benefit of higher phosphorescent brightness during the Dark interval **302** (e.g. higher brightness allows for a smaller aperture setting on the camera lens, which allows for larger depth of field). But some applications do require an accurate capture of the skin color of the model. For such applications, it is advantageous to mix the phosphorescent makeup with base (in a color suited for the model's skin tone) makeup, and work within the constraints of lower phosphorescent brightness. Also, there are applications where some phosphor visibility is acceptable, but not the level of visibility seen in Lit Image **401**. For such applications, a middle ground can be found in terms of skin color accuracy and phosphorescent brightness by mixing a higher percentage of phosphorescent makeup relative to the base.

In another embodiment, luminescent zinc sulfide (ZnS:Cu) in its raw form is mixed with base makeup and applied to the model's face.

Surface Capture of Fabric with Phosphorescent Random Patterns

In another embodiment, the techniques described above are used to capture cloth. FIG. **6** shows a capture of a piece of cloth (part of a silk pajama top) with the same phosphorescent makeup used in FIG. **4** sponged onto it. The capture was done under the exact same conditions with 8 grayscale dark cameras (such as **204-205**) and 1 color lit camera (such as **214-215**). The phosphorescent makeup can be seen slightly discoloring the surface of Lit Frame **601**, during lit interval **301**, but it can be seen phosphorescing brightly in Dark Frame **602**, during dark interval **302**. From the 8 cameras of Dark Frame **602**, 3D Surface **603** is reconstructed using the same techniques used for reconstructing the 3D Surfaces **403** and **503**. And, then Lit Image **601** is texture-mapped onto 3D Surface **603** to produce Textured 3D Surface **604**.

FIG. **6** shows a single frame of captured cloth, one of hundreds of frames that were captured in a capture session while the cloth was moved, folded and unfolded. And in each frame, each area of the surface of the cloth was captured accurately, so long as at least 2 of the 8 grayscale cameras had a view of the area that was not overly oblique (e.g. the camera optical axis was within 30 degrees of the area's surface normal). In some frames, the cloth was contorted such that there were areas within deep folds in the cloth (obstructing the light from the light panels **208-209**), and in some frames the cloth was curved such that there were areas that reflected back the light from the light panels **208-209** so as to create a highlight (i.e. the silk fabric was shiny). Such lighting conditions would make it difficult, if not impossible, to accurately capture the surface of the cloth using reflected light during lit interval **301** because shadow areas might be too dark for an accurate capture (e.g. below the noise floor of the camera sensor) and some highlights might be too bright for an accurate capture (e.g. oversaturating the sensor so that it reads the entire area as solid white). But, during the dark interval **302**, such areas are readily captured accurately because the phosphorescent makeup emits light quite uniformly, whether deep in a fold or on an external curve of the cloth.

Because the phosphor charges from any light incident upon it, including diffused or reflected light that is not directly from the light panels **208-209**, even phosphor within folds gets charged (unless the folds are so tightly sealed no light can get into them, but in such cases it is unlikely that the cameras can see into the folds anyway). This illustrates a significant advantage of utilizing phosphorescent makeup (or paint or dye) for creating patterns on (or infused within) surfaces to be captured: the phosphor is emissive and is not subject to highlights and shadows, producing a highly uniform brightness level for the patterns seen by the grayscale dark cameras **204-205**, that neither has areas too dark nor areas too bright.

Another advantage of dyeing or painting a surface with phosphorescent dye or paint, respectively, rather than applying phosphorescent makeup to the surface is that with dye or paint the phosphorescent pattern on the surface can be made permanent throughout a motion capture session. Makeup, by its nature, is designed to be removable, and a performer will normally remove phosphorescent makeup at the end of a day's motion capture shoot, and if not, almost certainly before going to bed. Frequently, motion capture sessions extend across several days, and as a result, normally a fresh application of phosphorescent makeup is applied to the performer each day prior to the motion capture shoot. Typically, each fresh application of phosphorescent makeup will result in a different random pattern. One of the techniques disclosed in co-pending applications is the tracking of vertices ("vertex tracking") of the captured surfaces. Vertex tracking is accomplished by correlating random patterns from one captured frame to the next. In this way, a point on the captured surface can be followed from frame-to-frame. And, so long as the random patterns on the surface stay the same, a point on a captured surface even can be tracked from shot-to-shot. In the case of random patterns made using phosphorescent makeup, it is typically practical to leave the makeup largely undisturbed (although it is possible for some areas to get smudged, the bulk of the makeup usually stays unchanged until removed) during one day's-worth of motion capture shooting, but as previously mentioned it normally is removed at the end of the day. So, it is typically impractical to maintain the same phosphorescent random pattern (and with that, vertex tracking based on tracking a particular random pattern) from day-to-day. But when it comes to non-skin objects like fabric, phosphorescent dye or paint can be used to create a random pattern. Because dye and paint are essentially permanent, random patterns will not get smudged during the motion capture session, and the same random patterns will be unchanged from day-to-day. This allows vertex tracking of dyed or painted objects with random patterns to track the same random pattern through the duration of a multi-day motion capture session (or in fact, across multiple motion capture sessions spread over long gaps in time if desired).

Skin is also subject to shadows and highlights when viewed with reflected light. There are many concave areas (e.g., eye sockets) that often are shadowed. Also, skin may be shiny and cause highlights, and even if the skin is covered with makeup to reduce its shininess, performers may sweat during a physical performance, resulting in shininess from sweaty skin. Phosphorescent makeup emits uniformly both from shiny and matte skin areas, and both from convex areas of the body (e.g. the nose bridge) and concavities (e.g. eye sockets). Sweat has little impact on the emission brightness of phosphorescent makeup. Phosphorescent makeup also charges while folded up in areas of the body that fold up (e.g. eyelids) and when it unfolds (e.g. when the performer blinks) the phosphorescent pattern emits light uniformly.

Returning back to FIG. **6**, note that the phosphorescent makeup can be seen on the surface of the cloth in Lit Frame **601** and in Textured 3D Surface **604**. Also, while this is not apparent in the images, although it may be when the cloth is in motion, the phosphorescent makeup has a small impact on the pliability of the silk fabric. In another embodiment, instead of using phosphorescent makeup (which of course is formulated for skin application) phosphorescent dye is used to create phosphorescent patterns on cloth. Phosphorescent dyes are available from a number of manufacturers. For example, it is common to find t-shirts at novelty shops that have glow-in-the-dark patterns printed onto them with phosphorescent dyes. The dyes can also can be formulated manually by mixing phosphorescent powder (e.g. ZnS:Cu) with off-the-shelf clothing dyes, appropriate for the given type of fabric. For example, Dharma Trading Company with a store at 1604 Fourth Street, San Rafael, Calif. stocks a large number of dyes, each dye designed for certain fabrics types (e.g. Dharma Fiber Reactive Procion Dye is for all natural fibers, Sennelier Tinfix Design—French Silk Dye is for silk and wool), as well as the base chemicals to formulate such dyes. When phosphorescent powder is used as the pigment in such formulations, then a dye appropriate for a given fabric type is produced and the fabric can be dyed with phosphorescent pattern while minimizing the impact on the fabric's pliability.

Surface Capture of Stop-Motion Animation Characters with Phosphorescent Random Patterns

In another embodiment, phosphor is embedded in silicone or a moldable material such as modeling clay in characters, props and background sets used for stop-motion animation. Stop-motion animation is a technique used in animated motion pictures and in motion picture special effects. An exemplary prior art stop-motion animation stage is illustrated in FIG. **7***a*. Recent stop-motion animations are feature films *Wallace & Gromit in The Curse of the Were-Rabbit* (Academy Award-winning best animated feature film released in 2005) (hereafter referenced as WG) and *Corpse Bride* (Academy Award-nominated best animated feature film released in 2005) (hereafter referred to as CB). Various techniques are used in stop-motion animation. In WG the characters **702-703** are typically made of modeling clay, often wrapped around a metal armature to give the character structural stability. In CB the characters **702-703** are created from puppets with mechanical armatures which are then covered with molded silicone (e.g. for a face), or some other material (e.g. for clothing). The characters **702-703** in both films are placed in complex sets **701** (e.g. city streets, natural settings, or in buildings), the sets are lit with lights such as **708-709**, a camera such as **705** is placed in position, and then one frame is shot by the camera **705** (in modern stop-motion animation, typically, a digital camera). Then the various characters (e.g. the man with a leash **702** and the dog **703**) that are in motion in the scene are moved very slightly. In the case of WB, often the movement is achieved by deforming the clay (and potentially the armature underneath it) or by changing a detailed part of a character **702-703** (e.g. for each frame swapping in a different mouth shape on a character **702-703** as it speaks). In the case of CB, often motion is achieved by adjusting the character puppet **702-703** armature (e.g. a screwdriver inserted in a character puppet's **702-703** ear might turn a screw that actuates the armature causing the character's **702-703** mouth to open). Also, if the camera **705** is moving in the scene, then the camera **705** is placed on a mechanism that allows it to be moved, and it is moved slightly each frame time. After all the characters **702-703** and the camera **705** in a scene have been moved, another frame is captured by the camera **705**. This painstaking process continues frame-by-frame until the shot is completed.

There are many difficulties with the stop-motion animation process that both limit the expressive freedom of the animators, limit the degree of realism in motion, and add to the time and cost of production. One of these difficulties is animating many complex characters **702-703** within a complex set **701** on a stop-motion animation stage such as that shown in FIG. **7***a*. The animators often need to physically climb into the sets, taking meticulous care not to bump anything inadvertently, and then make adjustments to character **702-703** expressions, often with sub-millimeter precision. When characters **702-703** are very close to each other, it gets even more difficult. Also, sometimes characters **702-703** need to be placed in a pose where a character **702-703** can easily fall over (e.g. a character **702-703** is doing a hand stand or a character **702-703** is flying). In these cases the character **702-703** requires some support structure that may be seen by the camera **705**, and if so, needs to be erased from the shot in post-production.

In one embodiment illustrated by the stop-motion animation stage in FIG. **7***b*, phosphorescent phosphor (e.g. zinc sulfide) in powder form can be mixed (e.g. kneaded) into modeling clay resulting in the clay surface phosphorescing in darkness with a random pattern. Zinc sulfide powder also can be mixed into liquid silicone before the silicone is poured into a mold, and then when the silicone dries and solidifies, it has zinc sulfide distributed throughout. In another embodiment, zinc sulfide powder can be spread onto the inner surface of a mold and then liquid silicone can be poured into the mold to solidify (with the zinc sulfide embedded on the surface). In yet another embodiment, zinc sulfide is mixed in with paint that is applied to the surface of either modeling clay or silicone. In yet another embodiment, zinc sulfide is dyed into fabric worn by characters **702-703** or mixed into paint applied to props or sets **701**. In all of these embodiments the resulting effect is that the surfaces of the characters **702-703**, props and sets **701** in the scene phosphoresce in darkness with random surface patterns.

At low concentrations of zinc sulfide in the various embodiments described above, the zinc sulfide is not significantly visible under the desired scene illumination when light panels **208-208** are on. The exact percentage of zinc sulfide depends on the particular material it is mixed with or applied to, the color of the material, and the lighting circumstances of the character **702-703**, prop or set **701**. But, experimentally, the zinc sulfide concentration can be continually reduced until it is no longer visually noticeable in lighting situations where the character **702-703**, prop or set **701** is to be used. This may result in a very low concentration of zinc sulfide and very low phosphorescent emission. Although this normally would be a significant concern with live action frame capture of dim phosphorescent patterns, with stop-motion animation, the dark frame capture shutter time can be extremely long (e.g. 1 second or more) because by definition, the scene is not moving. With a long shutter time, even very dim phosphorescent emission can be captured accurately.

Once the characters **702-703**, props and the set **701** in the scene are thus prepared, they look almost exactly as they otherwise would look under the desired scene illumination when light panels **208-209** are on, but they phosphoresce in random patterns when the light panels **208-209** are turned off. At this point all of the characters **702-703**, props and the set **701** of the stop-motion animation can now be captured in 3D using a configuration like that illustrated in FIGS. **2***a* and **2***b* and described in the co-pending applications. (FIGS. **7***b*-**7***e* illustrate stop-motion animation stages with light panels **208-209**, dark cameras **204-205** and lit cameras **214-215** from FIGS. **2***a* and **2***b* surrounding the stop-motion animation characters **702-703** and set **701**. For clarity, the connections to devices **208-209**, **204-205** and **214-215** have been omitted from FIGS. **7***b*-**7***e*, but in they would be hooked up as illustrated in FIGS. **2***a* and **2***b*.) Dark cameras **204-205** and lit cameras **214-215** are placed around the scene illustrated in FIG. **7***b* so as to capture whatever surfaces will be needed to be seen in the final animation. And then, rather than rapidly switching sync signals **221-223** at a high capture frame rate (e.g. 90 fps), the sync signals are switched very slowly, and in fact may be switched by hand.

In one embodiment, the light panels **208-209** are left on while the animators adjust the positions of the characters **702-703**, props or any changes to the set **701**. Note that the light panels **208-209** could be any illumination source, including incandescent lamps, because there is no requirement in stop-motion animation for rapidly turning on and off the illumination source. Once the characters **702-703**, props and set **701** are in position for the next frame, lit cam sync signal **223** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the lit cameras **214-215** capture a frame for a specified duration based on the desired exposure time for the captured frames. In other embodiments, different cameras may have different exposure times based on individual exposure requirements.

Next, light panels **208-209** are turned off (either by sync signal **222** or by hand) and the lamps are allowed to decay until the scene is in complete darkness (e.g. incandescent lamps may take many seconds to decay). Then, dark cam sync signal **221** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the dark cameras **208-209** capture a frame of the random phosphorescent patterns for a specified duration based on the desired exposure time for the captured frames. Once again, different cameras have different exposure times based on individual exposure requirements. As previously mentioned, in the case of very dim phosphorescent emissions, the exposure time may be quite long (e.g., a second or more). The upper limit of exposure time is primarily limited by the noise accumulation of the camera sensors. The captured dark frames are processed by data processing system **210** to produce 3D surface **207** and then to map the images captured by the lit cameras **214-215** onto the 3D surface **207** to create textured 3D surface **217**. Then, the light panels, **208-9** are turned back on again, the characters **702-703**, props and set **701** are moved again, and the process described in this paragraph is repeated until the entire shot is completed.

The resulting output is the successive frames of textured 3D surfaces of all of the characters **702-703**, props and set **701** with areas of surfaces embedded or painted with phosphor that are in view of at least 2 dark cameras **204-205** at a non-oblique angle (e.g., <30 degrees from the optical axis of a camera). When these successive frames are played back at the desired frame rate (e.g., 24 fps), the animated scene will come to life, but unlike frames of a conventional stop-motion animation, the animation will be able to be viewed from any camera position, just by rendering the textured 3D surfaces from a chosen camera position. Also, if the camera position of the final animation is to be in motion during a frame sequence (e.g. if a camera is following a character **702-703**), it is not necessary to have a physical camera moving in the scene. Rather, for each successive frame, the textured 3D surfaces of the scene are simply rendered from the desired camera position for that frame, using a 3D modeling/animation application software such as Maya (from Autodesk, Inc.).

In another embodiment, illustrated in FIGS. **7***c*-**7***e*, some or all of the different characters **702-703**, props, and/or sets **701** within a single stop-motion animation scene are shot separately, each in a configuration such as FIGS. **2***a* and **2***b*. For example, if a scene had man with leash **702** and his dog **703** walking down a city street set **701**, the city street set **701**, the man with leash **702**, and the dog **703** would be shot individually, each with separate motion capture systems as illustrated in FIG. **7***c* (for city street set **701**, FIG. **7***d* (for man with leash **702**) and FIG. **7***e* (for dog **703**) a. The stop-motion animation of the 2 characters **702-703** and 1 set **701** would each then be separately captured as individual textured 3D surfaces **217**, in the manner described above. Then, with a 3D modeling and/or animation application software the 2 characters **702-703** and 1 set **701** would be rendered together into a 3D scene. In one embodiment, the light panel **208-209** lighting the characters **702-703** and the set **701** could be configured to be the same, so the man with leash **702** and the dog **703** appear to be illuminated in the same environment as the set **701**. In another embodiment, flat lighting (i.e. uniform lighting to minimize shadows and highlights) is used, and then lighting (including shadows and highlights) is simulated by the 3D modeling/animation application software. Through the 3D modeling/animation application software the animators will be able to see how the characters **702-703** look relative to each other and the set **701**, and will also be able to look at the characters **702-703** and set **701** from any camera angle they wish, without having to move any of the physical cameras **204-205** or **214-215** doing the capture.

This approach provides significant advantages to stop-motion animation. The following are some of the advantages of this approach: (a) individual characters **702-703** may be manipulated individually without worrying about the animator bumping into another character **702-703** or the characters

702-703 bumping into each other, (b) the camera position of the rendered frames may be chosen arbitrarily, including having the camera position move in successive frames, (c) the rendered camera position can be one where it would not be physically possible to locate a camera **705** in a conventional stop-motion configuration (e.g. directly between 2 characters **702-703** that are close together, where there is no room for a camera **705**), (d) the lighting, including highlights and shadows can be controlled arbitrarily, including creating lighting situations that are not physically possible to realize (e.g. making a character glow), (e) special effects can be applied to the characters **702-703** (e.g. a ghost character **702-703** can be made translucent when it is rendered into the scene), (f) a character **702-703** can remain in a physically stable position on the ground while in the scene it is not (e.g. a character **702-703** can be captured in an upright position, while it is rendered into the scene upside down in a hand stand, or rendered into the scene flying above the ground), (g) parts of the character **702-703** can be held up by supports that do not have phosphor on them, and as such will not be captured (and will not have to be removed from the shot later in post-production), (h) detail elements of a character **702-703**, like mouth positions when the character **702-703** is speaking, can be rendered in by the 3D modeling/animation application, so they do not have be attached and then removed from the character **702-703** during the animation, (i) characters **702-703** can be rendered into computer-generated 3D scenes (e.g. the man with leash **702** and dog **703** can be animated as clay animations, but the city street set **701** can be a computer-generated scene), (j) 3D motion blur can be applied to the objects as they move (or as the rendered camera position moves), resulting in a smoother perception of motion to the animation, and also making possible faster motion without the perception of jitter.

Additional Phosphorescent Phosphors

In another embodiment, different phosphors other than ZnS:Cu are used as pigments with dyes for fabrics or other non-skin objects. ZnS:Cu is the preferred phosphor to use for skin applications because it is FDA-approved as a cosmetic pigment. But a large variety of other phosphors exist that, while not approved for use on the skin, are in some cases approved for use within materials handled by humans. One such phosphor is $SrAl_2O_4:Eu^{2+}, Dy^{3+}$. Another is $SrAl_2O_4:Eu^{2+}$. Both phosphors have a much longer afterglow than ZnS:Cu for a given excitation.

Optimizing Phosphorescent Emission

Many phosphors that phosphoresce in visible light spectra are charged more efficiently by ultraviolet light than by visible light. This can be seen in chart **800** of FIG. **8** which show approximate excitation and emission curves of ZnS:Cu (which we shall refer to hereafter as "zinc sulfide") and various light sources. In the case of zinc sulfide, its excitation curve **811** spans from about 230 nm to 480 nm, with its peak at around 360 nm. Once excited by energy in this range, its phosphorescence curve **812** spans from about 420 nm to 650 nm, producing a greenish glow. The zinc sulfide phosphorescence brightness **812** is directly proportional to the excitation energy **811** absorbed by the zinc sulfide. As can be seen by excitation curve **811**, zinc sulfide is excited with varying degrees of efficiency depending on wavelength. For example, at a given brightness from an excitation source (i.e. in the case of the presently preferred embodiment, light energy from light panels **208-209**) zinc sulfide will absorb only 30% of the energy at 450 nm (blue light) that it will absorb at 360 nm (UVA light, commonly called "black light"). Since it is desirable to get the maximum phosphorescent emission **812** from the zinc sulfide (e.g. brighter phosphorescence will allow for smaller lens apertures and longer depth of field), clearly it is advantageous to excite the zinc sulfide with as much energy as possible. The light panels **208-209** can only produce up to a certain level of light output before the light becomes uncomfortable for the performers. So, to maximize the phosphorescent emission output of the zinc sulfide, ideally the light panels **208-209** should output light at wavelengths that are the most efficient for exciting zinc sulfide.

Other phosphors that may be used for non-skin phosphorescent use (e.g. for dyeing fabrics) also are excited best by ultraviolet light. For example, $SrAl_2O_4:Eu^{2+}, Dy^{3+}$ and $SrAl_2O_4:Eu^{2+}$ are both excited more efficiently with ultraviolet light than visible light, and in particular, are excited quite efficiently by UVA (black light).

As can be seen in FIG. **3**, a requirement for a light source used for the light panels **208-209** is that the light source can transition from completely dark to fully lit very quickly (e.g. on the order of a millisecond or less) and from fully lit to dark very quickly (e.g. also on the order of a millisecond or less). Most LEDs fulfill this requirement quite well, typically turning on an off on the order of microseconds. Unfortunately, though, current LEDs present a number of issues for use in general lighting. For one thing, LEDs currently available have a maximum light output of approximately 35 W. The BL-43F0-0305 from Lamina Ceramics, 120 Hancock Lane, Westampton, N.J. 08060 is one such RGB LED unit. For another, currently LEDs have special power supply requirements (in the case of the BL-43F0-0305, different voltage supplies are need for different color LEDs in the unit). In addition, current LEDs require very large and heavy heatsinks and produce a great deal of heat. Each of these issues results in making LEDs expensive and somewhat unwieldy for lighting an entire motion capture stage for a performance. For example, if 3500 Watts were needed to light a stage, 100 35 W LED units would be needed.

But, in addition to these disadvantages, the only very bright LEDs currently available are white or RGB LEDs. In the case of both types of LEDs, the wavelengths of light emitted by the LED does not overlap with wavelengths where the zinc sulfide is efficiently excited. For example, in FIG. **8** the emission curve **823** of the blue LEDs in the BL-43F0-0305 LED unit is centered around 460 nm. It only overlaps with the tail end of the zinc sulfide excitation curve **811** (and the Red and Green LEDs don't excite the zinc sulfide significantly at all). So, even if the blue LEDs are very bright (to the point where they are as bright as is comfortable to the performer), only a small percentage of that light energy will excite the zinc sulfide, resulting in a relatively dim phosphorescence. Violet and UVA ("black light") LEDs do exist, which would excite the zinc sulfide more efficiently, but they only currently are available at very low power levels, on the order of 0.1 Watts. To achieve 3500 Watts of illumination would require 35,000 such 0.1 Watt LEDs, which would be quite impractical and prohibitively expensive.

Fluorescent Lamps as a Flashing Illumination Source

Other lighting sources exist that output light at wavelengths that are more efficiently absorbed by zinc sulfide. For example, fluorescent lamps (e.g. 482-S9 from Kino-Flo, Inc. 2840 North Hollywood Way, Burbank, Calif. 91505) are available that emit UVA (black light) centered around 350 nm with an emission curve similar to **821**, and Blue/violet fluorescent lamps (e.g. 482-S10-S from Kino-Flo) exist that emit bluish/violet light centered around 420 nm with an emission curve similar to **822**. The emission curves **821** and **822** are much closer to the peak of the zinc sulfide excitation curve **811**, and as a result the light energy is far more efficiently absorbed, resulting in a much higher phosphorescent emission **812** for a given excitation brightness. Such fluorescent bulbs are quite inexpensive (typically $15/bulb for a 48" bulb), produce very little heat, and are very light weight. They are also available in high wattages. A typical 4-bulb fluorescent fixture produces 160 Watts or more. Also, theatrical fixtures are readily available to hold such bulbs in place as staging lights. (Note that UVB and UVC fluorescent bulbs are also available, but UVB and UVC exposure is known to present health hazards under certain conditions, and as such would not be appropriate to use with human or animal performers without suitable safety precautions.)

The primary issue with using fluorescent lamps is that they are not designed to switch on and off quickly. In fact, ballasts (the circuits that ignite and power fluorescent lamps) typically turn the lamps on very slowly, and it is common knowledge that fluorescent lamps may take a second or two until they are fully illuminated.

FIG. **9** shows a diagrammatic view of a prior art fluorescent lamp. The elements of the lamp are contained within a sealed glass bulb **910** which, in this example, is in the shape of a cylinder (commonly referred to as a "tube"). The bulb contains an inert gas **940**, typically argon, and a small amount of mercury **930**. The inner surface of the bulb is coated with a phosphor **920**. The lamp has 2 electrodes **905-906**, each of which is coupled to a ballast through connectors **901-904**. When a large voltage is applied across the electrodes **901-904**, some of the mercury in the tube changes from a liquid to a gas, creating mercury vapor, which, under the right electrical circumstances, emits ultraviolet light. The ultraviolet light excites the phosphor coating the inner surface of the bulb. The phosphor then fluoresces light at a higher wavelength than the excitation wavelength. A wide range of phosphors are available for fluorescent lamps with different wavelengths. For example, phosphors that are emissive at UVA wavelengths and all visible light wavelengths are readily available off-the-shelf from many suppliers.

Standard fluorescent ballasts are not designed to switch fluorescent lamps on and off quickly, but it is possible to modify an existing ballast so that it does. FIG. **10** is a circuit diagram of a prior art 27 Watt fluorescent lamp ballast **1002** modified with an added sync control circuit **1001** of the present invention.

For the moment, consider only the prior art ballast circuit **1002** of FIG. **10** without the modification **1001**. Prior art ballast **1002** operates in the following manner: A voltage doubler circuit converts 120VAC from the power line into 300 volts DC. The voltage is connected to a half bridge oscillator/driver circuit, which uses two NPN power transistors **1004-1005**. The half bridge driver, in conjunction with a multi-winding transformer, forms an oscillator. Two of the transformer windings provide high drive current to the two power transistors **1004-1005**. A third winding of the transformer is in line with a resonant circuit, to provide the needed feedback to maintain oscillation. The half bridge driver generates a square-shaped waveform, which swings from +300 volts during one half cycle, to zero volts for the next half cycle. The square wave signal is connected to an "LC" (i.e. inductor-capacitor) series resonant circuit. The frequency of the circuit is determined by the inductance Lres and the capacitance Cres. The fluorescent lamp **1003** is connected across the resonant capacitor. The voltage induced across the resonant capacitor from the driver circuit provides the needed high voltage AC to power the fluorescent lamp **1003**. To kick the circuit into oscillation, the base of the power transistor **1005** is connected to a simple relaxation oscillator circuit. Current drawn from the 300 v supply is routed through a resistor and charges up a 0.1 uF capacitor. When the voltage across the capacitor reaches about 20 volts, a DIAC (a bilateral trigger diode) quickly switches and supplies power transistor **1005** with a current spike. This spike kicks the circuit into oscillation.

Synchronization control circuit **1001** is added to modify the prior art ballast circuit **1002** described in the previous paragraph to allow rapid on-and-off control of the fluorescent lamp **1003** with a sync signal. In the illustrated embodiment in FIG. **10**, a sync signal, such as sync signal **222** from FIG. **2**, is electrically coupled to the SYNC+ input. SYNC− is coupled to ground. Opto-isolator NEC PS2501-1 isolates the SYNC+ and SYNC− inputs from the high voltages in the circuit. The opto-isolator integrated circuit consists of a light emitting diode (LED) and a phototransistor. The voltage differential between SYNC+ and SYNC− when the sync signal coupled to SYNC+ is at a high level (e.g. ≧2.0V) causes the LED in the opto-isolator to illuminate and turn on the phototransistor in the opto-isolator. When this phototransistor is turned on, voltage is routed to the gate of an n-channel MOSFET Q1 (Zetex Semiconductor ZVN4106F DMOS FET). MOSFET Q1 functions as a low resistance switch, shorting out the base-emitter voltage of power transistor **1005** to disrupt the oscillator, and turn off fluorescent lamp **1003**. To turn the fluorescent lamp back on, the sync signal (such as **222**) is brought to a low level (e.g. <0.8V), causing the LED in the opto-isolator to turn off, which turns off the opto-isolator phototransistor, which turns off MOSFET Q1 so it no longer shorts out the base-emitter voltage of power transistor **1005**. This allows the kick start circuit to initialize ballast oscillation, and the fluorescent lamp **1003** illuminates.

This process repeats as the sync signal coupled to SYNC+ oscillates between high and low level. The synch control circuit **1001** combined with prior art ballast **1002** will switch fluorescent lamp **1003** on and off reliably, well in excess of 120 flashes per second. It should be noted that the underlying principles of the invention are not limited to the specific set of circuits illustrated in FIG. **10**.

FIG. **11** shows the light output of fluorescent lamp **1003** when synch control circuit **1001** is coupled to prior art ballast **1002** and a sync signal **222** is coupled to circuit **1001** as described in the previous paragraph. Traces **1110** and **1120** are oscilloscope traces of the output of a photodiode placed on the center of the bulb of a fluorescent lamp using the prior art ballast circuit **1002** modified with the sync control circuit **1001** of the present invention. The vertical axis indicates the brightness of lamp **1003** and the horizontal axis is time. Trace **1110** (with 2 milliseconds/division) shows the light output of fluorescent lamp **1003** when sync signal **222** is producing a 60 Hz square wave. Trace **1120** (with the oscilloscope set to 1 millisecond/division and the vertical brightness scale reduced by 50%) shows the light output of lamp **1003** under the same test conditions except now sync signal **222** is producing a 250 Hz square wave. Note that the peak **1121** and minimum **1122** (when lamp **1003** is off and is almost completely dark) are still both relatively flat, even at a much higher switching frequency. Thus, the sync control circuit **1001** modification to prior art ballast **1002** produces dramatically different light output than the unmodified ballast **1002**, and makes it possible to achieve on and off switching of fluorescent lamps at high frequencies as required by the motion capture system illustrated in FIG. **2** with timing similar to that of FIG. **3**.

Although the modified circuit shown in FIG. **10** will switch a fluorescent lamp **1003** on and off rapidly enough for the requirements of a motion capture system such as that illustrated in FIG. **2**, there are certain properties of fluorescent lamps that may be modified for use in a practical motion capture system.

FIG. **12** illustrates one of these properties. Traces **1210** and **1220** are the oscilloscope traces of the light output of a General Electric Gro and Sho fluorescent lamp **1003** placed in circuit **1002** modified by circuit **1001**, using a photodiode placed on the center of the bulb. Trace **1210** shows the light output at 1 millisecond/division, and Trace **1220** shows the light output at 20 microseconds/division. The portion of the waveform shown in Trace **1220** is roughly the same as the dashed line area **1213** of Trace **1210**. Sync signal **222** is coupled to circuit **1002** as described previously and is producing a square wave at 250 Hz. Peak level **1211** shows the light output when lamp **1003** is on and minimum **1212** shows the light output when lamp **1003** is off. While Trace **1210** shows the peak level **1211** and minimum **1212** as fairly flat, upon closer inspection with Trace **1220**, it can be seen that when the lamp **1003** is turned off, it does not transition from fully on to completely off instantly. Rather, there is a decay curve of approximately 200 microseconds (0.2 milliseconds) in duration. This is apparently due to the decay curve of the phosphor coating the inside of the fluorescent bulb (i.e. when the lamp **1003** is turned off, the phosphor continues to fluoresce for a brief period of time). So, when sync signal **222** turns off the modified ballast **1001-1002**, unlike LED lights which typically switch off within a microsecond, fluorescent lamps take a short interval of time until they decay and become dark.

There exists a wide range of decay periods for different brands and types of fluorescent lamps, from as short as 200 microseconds, to as long as over a millisecond. To address this property of fluorescent lamps, one embodiment of the invention adjusts signals **221-223**. This embodiment will be discussed shortly.

Another property of fluorescent lamps that impacts their usability with a motion capture system such as that illustrated in FIG. **2** is that the electrodes within the bulb are effectively incandescent filaments that glow when they carry current through them, and like incandescent filaments, they continue to glow for a long time (often a second or more) after current is removed from them. So, even if they are switched on and off rapidly (e.g. at 90 Hz) by sync signal **222** using ballast **1002** modified by circuit **1001**, they continue to glow for the entire dark interval **302**. Although the light emitted from the fluorescent bulb from the glowing electrodes is very dim relative to the fully illuminated fluorescent bulb, it is still is a significant amount of light, and when many fluorescent bulbs are in use at once, together the electrodes add up to a significant amount of light contamination during the dark interval **302**, where it is advantageous for the room to be as dark as possible.

FIG. **13** illustrates one embodiment of the invention which addresses this problem. Prior art fluorescent lamp **1350** is shown in a state 10 milliseconds after the lamp as been shut off. The mercury vapor within the lamp is no longer emitting ultraviolet light and the phosphor lining the inner surface of the bulb is no longer emitting a significant amount of light. But the electrodes **1351-1352** are still glowing because they are still hot. This electrode glowing results in illuminated regions **1361-1362** near the ends of the bulb of fluorescent lamp **1350**.

Fluorescent lamp **1370** is a lamp in the same state as prior art lamp **1350**, 10 milliseconds after the bulb **1370** has been shut off, with its electrodes **1371-1372** still glowing and producing illuminated regions **1381-1382** near the ends of the bulb of fluorescent lamp **1370**, but unlike prior art lamp **1350**, wrapped around the ends of lamp **1370** is opaque tape **1391** and **1392** (shown as see-through with slanted lines for the sake of illustration). In the presently preferred embodiment black gaffers' tape is used, such as 4" P-665 from Permacel, A Nitto Denko Company, US Highway No. 1, P.O. Box 671, New Brunswick, N.J. 08903. The opaque tape **1391-1392** serves to block almost all of the light from glowing electrodes **1371-1372** while blocking only a small amount of the overall light output of the fluorescent lamp when the lamp is on during lit interval **301**. This allows the fluorescent lamp to become much darker during dark interval **302** when being flashed on and off at a high rate (e.g. 90 Hz). Other techniques can be used to block the light from the glowing electrodes, including other types of opaque tape, painting the ends of the bulb with an opaque paint, or using an opaque material (e.g. sheets of black metal) on the light fixtures holding the fluorescent lamps so as to block the light emission from the parts of the fluorescent lamps containing electrodes.

Returning now to the light decay property of fluorescent lamps illustrated in FIG. **12**, if fluorescent lamps are used for light panels **208-209**, the synchronization signal timing shown in FIG. **3** will not produce optimal results because when Light Panel sync signal **222** drops to a low level on edge **332**, the fluorescent light panels **208-209** will take time to become completely dark (i.e. edge **342** will gradually drop to dark level). If the Dark Cam Sync Signal triggers the grayscale cameras **204-205** to open their shutters at the same time as edge **322**, the grayscale camera will capture some of the scene lit by the afterglow of light panels **208-209** during its decay interval. Clearly, FIG. **3**'s timing signals and light output behavior is more suited for light panels **208-209** using a lighting source like LEDs that have a much faster decay than fluorescent lamps.

Synchronization Timing for Fluorescent Lamps

FIG. **14** shows timing signals which are better suited for use with fluorescent lamps and the resulting light panel **208-209** behavior (note that the duration of the decay curve **1442** is exaggerated in this and subsequent timing diagrams for illustrative purposes). The rising edge **1434** of sync signal **222** is roughly coincident with rising edge **1414** of lit cam sync signal **223** (which opens the lit camera **214-215** shutters) and with falling edge **1424** of dark cam sync signal **223** (which closes the dark camera **204-205** shutters). It also causes the fluorescent lamps in the light panels **208-209** to illuminate quickly. During lit time interval **1401**, the lit cameras **214-215** capture a color image illuminated by the fluorescent lamps, which are emitting relatively steady light as shown by light output level **1443**.

At the end of lit time interval **1401**, the falling edge **1432** of sync signal **222** turns off light panels **208-209** and is roughly coincident with the rising edge **1412** of lit cam sync signal **223**, which closes the shutters of the lit cameras **214-215**. Note, however, that the light output of the light panels **208-209** does not drop from lit to dark immediately, but rather slowly drops to dark as the fluorescent lamp phosphor decays as shown by edge **1442**. When the light level of the fluorescent lamps finally reaches dark level **1441**, dark cam sync signal **221** is dropped from high to low as shown by edge **1422**, and this opens the shutters of dark cameras **204-205**. This way the dark cameras **204-205** only capture the emissions from the phosphorescent makeup, paint or dye, and do not capture the reflection of light from any objects illuminated by the fluorescent lamps during the decay interval **1442**. So, in this embodiment the dark interval **1402** is shorter than the lit interval **1401**, and the dark camera **204-205** shutters are open for a shorter period of time than the lit camera **214-205** shutters.

Another embodiment is illustrated in FIG. **15** where the dark interval **1502** is longer than the lit interval **1501**. The advantage of this embodiment is it allows for a longer shutter time for the dark cameras **204-205**. In this embodiment, light panel sync signal **222** falling edge **1532** occurs earlier which causes the light panels **208-209** to turn off. Lit cam sync signal **223** rising edge **1512** occurs roughly coincident with falling edge **1532** and closes the shutters on the lit cameras **214-5**. The light output from the light panel **208-209** fluorescent lamps begins to decay as shown by edge **1542** and finally reaches dark level **1541**. At this point dark cam sync signal **221** is transitions to a low state on edge **1522**, and the dark cameras **204-205** open their shutters and capture the phosphorescent emissions.

Note that in the embodiments shown in both FIGS. **14** and **15** the lit camera **214-215** shutters were only open while the light output of the light panel **208-209** fluorescent lamps was at maximum. In another embodiment, the lit camera **214-215** shutters can be open during the entire time the fluorescent lamps are emitting any light, so as to maximize the amount of light captured. In this situation, however, the phosphorescent makeup, paint or dye in the scene will become more prominent relative to the non-phosphorescent areas in the scene because the phosphorescent areas will continue to emit light fairly steadily during the fluorescent lamp decay while the non-phosphorescent areas will steadily get darker. The lit cameras **214-215** will integrate this light during the entire time their shutters are open.

In yet another embodiment the lit cameras **214-215** leave their shutters open for some or all of the dark time interval **1502**. In this case, the phosphorescent areas in the scene will appear very prominently relative to the non-phosphorescent areas since the lit cameras **214-215** will integrate the light during the dark time interval **1502** with the light from the lit time interval **1501**.

Because fluorescent lamps are generally not sold with specifications detailing their phosphor decay characteristics, it is necessary to determine the decay characteristics of fluorescent lamps experimentally. This can be readily done by adjusting the falling edge **1522** of sync signal **221** relative to the falling edge **1532** of sync signal **222**, and then observing the output of the dark cameras **204-205**. For example, in the embodiment shown in FIG. **15**, if edge **1522** falls too soon after edge **1532** during the fluorescent light decay **1542**, then non-phosphorescent objects will be captured in the dark cameras **204-205**. If the edge **1522** is then slowly delayed relative to edge **1532**, the non-phosphorescent objects in dark camera **204-205** will gradually get darker until the entire image captured is dark, except for the phosphorescent objects in the image. At that point, edge **1522** will be past the decay interval **1542** of the fluorescent lamps. The process described in this paragraph can be readily implemented in an application on a general-purpose computer that controls the output levels of sync signals **221-223**.

In another embodiment the decay of the phosphor in the fluorescent lamps is such that even after edge **1532** is delayed as long as possible after **1522** to allow for the dark cameras **204-205** to have a long enough shutter time to capture a bright enough image of phosphorescent patterns in the scene, there is still a small amount of light from the fluorescent lamp illuminating the scene such that non-phosphorescent objects in the scene are slightly visible. Generally, this does not present a problem for the pattern processing techniques described in the co-pending applications identified above. So long as the phosphorescent patterns in the scene are substantially brighter than the dimly-lit non-fluorescent objects in the scene, the pattern processing techniques will be able to adequately correlate and process the phosphorescent patterns and treat the dimly lit non-fluorescent objects as noise.

Synchronizing Cameras with Lower Frame Rates than the Light Panel Flashing Rate

In another embodiment the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. For example, the capture frame rate may be 30 frames per second (fps), but so as to keep the flashing of the light panels **208-209** about the threshold of human perception, the light panels **208-209** are flashed at 90 flashes per second. This situation is illustrated in FIG. **16**. The sync signals **221-3** are controlled the same as the are in FIG. **15** for lit time interval **1601** and dark time interval **1602** (light cycle 0), but after that, only light panel **208-9** sync signal **222** continues to oscillate for light cycles 1 and 2. Sync signals **221** and **223** remain in constant high state **1611** and **1626** during this interval. Then during light cycle 3, sync signals **221** and **223** once again trigger with edges **1654** and **1662**, opening the shutters of lit cameras **214-215** during lit time interval **1604**, and then opening the shutters of dark cameras **204-205** during dark time interval **1605**.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, sync signal **223** causes the lit cameras **214-215** to open their shutters after sync signal **221** causes the dark cameras **204-205** to open their shutters. This is illustrated in FIG. **17**. An advantage of this timing arrangement over that of FIG. **16** is the fluorescent lamps transition from dark to lit (edge **1744**) more quickly than they decay from lit to dark (edge **1742**). This makes it possible to abut the dark frame interval **1702** more closely to the lit frame interval **1701**. Since captured lit textures are often used to be mapped onto 3D surfaces reconstructed from dark camera images, the closer the lit and dark captures occur in time, the closer the alignment will be if the captured object is in motion.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, the light panels **208-209** are flashed with varying light cycle intervals so as to allow for longer shutter times for either the dark cameras **204-205** or lit cameras **214-215**, or to allow for longer shutters times for both cameras. An example of this embodiment is illustrated in FIG. **18** where the light panels **208-209** are flashed at 3 times the frame rate of cameras **204-205** and **214-215**, but the open shutter interval **1821** of the dark cameras **204-205** is equal to almost half of the entire frame time **1803**. This is accomplished by having light panel **208-209** sync signal **222** turn off the light panels **208-209** for a long dark interval **1802** while dark cam sync signal **221** opens the dark shutter for the duration of long dark interval **1802**. Then sync signal **222** turns the light panels **208-209** on for a brief lit interval **1801**, to complete light cycle 0 and then rapidly flashes the light panels **208-209** through light cycles 1 and 2. This results in the same number of flashes per second as the embodiment illustrated in FIG. **17**, despite the much longer dark interval **1802**. The reason this is a useful configuration is that the human visual system will still perceive rapidly flashing lights (e.g. at 90 flashes per second) as being lit continuously, even if there are some irregularities to the flashing cycle times. By varying the duration of the lit and dark intervals of the light panels **208-209**, the shutter times of either the dark cameras **204-205**, lit cameras **214-215** or both can be lengthened or shortened, while still maintaining the human perception that light panels **208-209** are continuously lit.

High Aggregate Frame Rates from Cascaded Cameras

FIG. **19** illustrates another embodiment where lit cameras **1941-1946** and dark cameras **1931-1936** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. FIG. **19** illustrates a similar motion capture system configuration as FIG. **2***a*, but given space limitations in the diagram only the light panels, the cameras, and the synchronization subsystem is shown. The remaining components of FIG. **2***a* that are not shown (i.e. the interfaces from the cameras to their camera controllers and the data processing subsystem, as well as the output of the data processing subsystem) are a part of the full configuration that is partially shown in FIG. **19**, and they are coupled to the components of FIG. **19** in the same manner as they are to the components of FIG. **2***a*. Also, FIG. **19** shows the Light Panels **208-209** in their "lit" state. Light Panels **208-209** can be switched off by sync signal **222** to their "dark" state, in which case performer **202** would no longer be lit and only the phosphorescent pattern applied to her face would be visible, as it is shown in FIG. **2***b*.

FIG. **19** shows 6 lit cameras **1941-1946** and 6 dark cameras **1931-1936**. In the presently preferred embodiment color cameras are used for the lit cameras **1941-1946** and grayscale cameras are used for the dark camera **1931-1936**, but either type could be used for either purpose. The shutters on the cameras **1941-1946** and **1931-1936** are driven by sync signals **1921-1926** from sync generator PCI card **224**. The sync generator card is installed in sync generator PC **220**, and operates as previously described. (Also, in another embodiment it may be replaced by using the parallel port outputs of sync generator PC **220** to drive sync signals **1921-1926**, and in this case, for example, bit **0** of the parallel port would drive sync signal **222**, and bits **1-6** of the parallel port would drive sync signals **1921-1926**, respectively.)

Unlike the previously described embodiments, where there is one sync signal **221** for the dark cameras and one sync signal **223** for the lit cameras, in the embodiment illustrated in FIG. **19**, there are 3 sync signals **1921-1923** for the dark cameras and 3 sync signals **1924-1926** for the dark cameras. The timing for these sync signals **1921-1926** is shown in FIG. **20**. When the sync signals **1921-1926** are in a high state they cause the shutters of the cameras attached to them to be closed, when the sync signals are in a low state, they cause the shutters of the cameras attached to them to be open.

In this embodiment, as shown in FIG. **20**, the light panels **208-209** are flashed at a uniform 90 flashes per second, as controlled by sync signal **222**. The light output of the light panels **208-209** is also shown, including the fluorescent lamp decay **2042**. Each camera **1931-1936** and **1941-1946** captures images at 30 frames per second (fps), exactly at a 1:3 ratio with the 90 flashes per second rate of the light panels. Each camera captures one image per each 3 flashes of the light panels, and their shutters are sequenced in a "cascading" order, as illustrated in FIG. **20**. A sequence of 3 frames is captured in the following manner:

Sync signal **222** transitions with edge **2032** from a high to low state **2031**. Low state **2031** turns off light panels **208-209**, which gradually decay to a dark state **2041** following decay curve **2042**. When the light panels are sufficiently dark for the purposes of providing enough contrast to separate the phosphorescent makeup, paint, or dye from the non-phosphorescent surfaces in the scene, sync signal **1921** transitions to low state **2021**. This causes dark cameras **1931-1932** to open their shutters and capture a dark frame. After the time interval **2002**, sync signal **222** transitions with edge **2034** to high state **2033** which causes the light panels **208-209** to transition with edge **2044** to lit state **2043**. Just prior to light panels **208-209** becoming lit, sync signal **1921** transitions to high state **2051** closing the shutter of dark cameras **1931-1932**. Just after the light panels **208-209** become lit, sync signal **1924** transition to low state **2024**, causing the shutters on the lit cameras **1941-1942** to open during time interval **2001** and capture a lit frame. Sync signal **222** transitions to a low state, which turns off the light panels **208-9**, and sync signal **1924** transitions to a high state at the end of time interval **2001**, which closes the shutters on lit cameras **1941-1942**.

The sequence of events described in the preceding paragraphs repeats 2 more times, but during these repetitions sync signals **1921** and **1924** remain high, keeping their cameras shutters closed. For the first repetition, sync signal **1922** opens the shutter of dark cameras **1933-1934** while light panels **208-209** are dark and sync signal **1925** opens the shutter of lit cameras **1943-1944** while light panels **208-209** are lit. For the second repetition, sync signal **1923** opens the shutter of dark cameras **1935-1936** while light panels **208-209** are dark and sync signal **1926** opens the shutter of lit cameras **1945-1946** while light panels **208-209** are lit.

Then, the sequence of events described in the prior **2** paragraphs continues to repeat while the motion capture session illustrated in FIG. **19** is in progress, and thus a "cascading" sequence of camera captures allows 3 sets of dark and 3 sets of lit cameras to capture motion at 90 fps (i.e. equal to the light panel flashing rate of 90 flashes per second), despite the fact each cameras is only capturing images at 30 fps. Because each camera only captures 1 of every 3 frames, the captured frames stored by the data processing system **210** are then interleaved so that the stored frame sequence at 90 fps has the frames in proper order in time. After that interleaving operation is complete, the data processing system will output reconstructed 3D surfaces **207** and textured 3D surfaces **217** at 90 fps.

Although the "cascading" timing sequence illustrated in FIG. **20** will allow cameras to operate at 30 fps while capturing images at an aggregate rate of 90 fps, it may be desirable to be able to switch the timing to sometimes operate all of the cameras **1921-1923** and **1924-1926** synchronously. An example of such a situation is for the determination of the relative position of the cameras relative to each other. Precise knowledge of the relative positions of the dark cameras **1921-1923** is used for accurate triangulation between the cameras, and precise knowledge of the position of the lit cameras **1924-1926** relative to the dark cameras **1921-1923** is used for establishing how to map the texture maps captured by the lit cameras **1924-1926** onto the geometry reconstructed from the images captured by the dark cameras **1921-1923**. One prior art method (e.g. that is used to calibrate cameras for the motion capture cameras from Motion Analysis Corporation) to determine the relative position of fixed cameras is to place a known object (e.g. spheres on the ends of a rods in a rigid array) within the field of view of the cameras, and then synchronously (i.e. with the shutters of all cameras opening and closing simultaneously) capture successive frames of the image of that known object by all the cameras as the object is in motion. By processing successive frames from all of the cameras, it is possible to calculate the relative position of the cameras to each other. But for this method to work, all of the cameras need to be synchronized so that they capture images simultaneously. If the camera shutters do not open simultaneously, then when each non-simultaneous shutter opens, its camera will capture the moving object at a different position in space than other cameras whose shutters open at different times. This will make it more difficult (or impossible) to precisely determine the relative position of all the cameras to each other.

FIG. **21** illustrates in another embodiment how the sync signals **1921-6** can be adjusted so that all of the cameras **1931-1936** and **1941-1946** open their shutters simultaneously. Sync signals **1921-1926** all transition to low states **2121-2126** during dark time interval **2102**. Although the light panels **208-209** would be flashed 90 flashes a second, the cameras would be capturing frames synchronously to each other at 30 fps. (Note that in this case, the lit cameras **1941-1946** which, in the presently preferred embodiment are color cameras, also would be capturing frames during the dark interval **2102** simultaneously with the dark cameras **1931-1936**.) Typically, this synchronized mode of operation would be done when a calibration object (e.g. an array of phosphorescent spheres) was placed within the field of view of some or all of the cameras, and potentially moved through successive frames, usually before or after a motion capture of a performer. In this way, the relative position of the cameras could determined while the cameras are running synchronously at 30 fps, as shown in FIG. **21**. Then, the camera timing would be switched to the "cascading" timing shown in FIG. **20** to capture a performance at 90 fps. When the 90 fps frames are reconstructed by data processing system **210**, then camera position information, determined previously (or subsequently) to the 90 fps capture with the synchronous mode time shown in FIG. **21**, will be used to both calculate the 3D surface **207** and map the captured lit frame textures onto the 3D surface to create textured 3D surface **217**

When a scene is shot conventionally using prior art methods and cameras are capturing only 2D images of that scene, the "cascading" technique to use multiple slower frame rate cameras to achieve a higher aggregate frame rate as illustrated in FIGS. **19** and **20** will not produce high-quality results. The reason for this is each camera in a "cascade" (e.g. cameras **1931**, **1933** and **1935**) will be viewing the scene from a different point of view. If the captured 30 fps frames of each camera are interleaved together to create a 90 fps sequence of successive frames in time, then when the 90 fps sequence is viewed, it will appear to jitter, as if the camera was rapidly jumping amongst multiple positions. But when slower frame rate cameras are "cascaded" to achieve a higher aggregate frame rate as illustrate in FIGS. **19** and **20** for the purpose capturing the 3D surfaces of objects in a scene, as described herein and in combination with the methods described in the co-pending applications, the resulting 90 fps interleaved 3D surfaces **207** and textured 3D surfaces **217** do not exhibit jitter at all, but rather look completely stable. The reason is the particular position of the cameras **1931-1936** and **1941-1946** does not matter in the reconstruction 3D surfaces, just so long as the at least a pair of dark cameras **1931-1936** during each dark frame interval **2002** has a non-oblique view (e.g. <30 degrees) of the surface area (with phosphorescent makeup, paint or dye) to be reconstructed. This provides a significant advantage over conventional prior art 2D motion image capture (i.e. commonly known as video capture), because typically the highest resolution sensors commercially available at a given time have a lower frame rate than commercially available lower resolution sensors. So, 2D motion image capture at high resolutions is limited to the frame rate of a single high resolution sensor. A 3D motion surface capture at high resolution, under the principles described herein, is able to achieve n times the frames rate of a single high resolution sensor, where n is the number of camera groups "cascaded" together, per the methods illustrated in FIGS. **19** and **20**.

Color Mapping of Phosphor Brightness

Ideally, the full dynamic range, but not more, of dark cameras **204-205** should be utilized to achieve the highest quality pattern capture. For example, if a pattern is captured that is too dark, noise patterns in the sensors in cameras **204-205** may become as prominent as captured patterns, resulting in incorrect 3D reconstruction. If a pattern is too bright, some areas of the pattern may exceed the dynamic range of the sensor, and all pixels in such areas will be recorded at the maximum brightness level (e.g. 255 in an 8-bit sensor), rather than at the variety or brightness levels that actually make up that area of the pattern. This also will result in incorrect 3D reconstruction. So, prior to capturing a pattern, per the techniques described herein, it is advantageous to try to make sure the brightness of the pattern throughout is not too dark, nor too bright (e.g. not reaching the maximum brightness level of the camera sensor).

When phosphorescent makeup is applied to a performer, or when phosphorescent makeup, paint or dye is applied to an object, it is difficult for the human eye to evaluate whether the phosphor application results in a pattern captured by the dark cameras **204-205** that is bright enough in all locations or too bright in some locations. FIG. **22** image **2201** shows a cylinder covered in a random pattern of phosphor. It is difficult, when viewing this image on a computer display (e.g. an LCD monitor) to determine precisely if there are parts of the pattern that are too bright (e.g. location **2220**) or too dark (e.g. location **2210**). There are many reasons for this. Computer monitors often do not have the same dynamic range as a sensor (e.g. a computer monitor may only display **128** unique gray levels, while the sensor captures 256 gray levels). The brightness and/or contrast may not be set correctly on the monitor. Also, the human eye may have trouble determining what constitutes a maximum brightness level because the brain may adapt to the brightness it sees, and consider whatever is the brightest area on the screen to be the maximum brightness. For all of these reasons, it is helpful to have an objective measure of brightness that humans can readily evaluate when applying phosphorescent makeup, paint or dye. Also, it is helpful to have an objective measure brightness as the lens aperture and/or gain is adjusted on dark cameras **204-205** and/or the brightness of the light panels **208-209** is adjusted.

Image **2202** shows such an objective measure. It shows the same cylinder as image **2201**, but instead of showing the brightness of each pixel of the image as a grayscale level (in this example, from 0 to 255), it shows it as a color. Each color represents a range of brightness. For example, in image **2202** blue represents brightness ranges 0-32, orange represents brightness ranges 192-223 and dark red represents brightness ranges 224-255. Other colors represent other brightness ranges. Area **2211**, which is blue, is now clearly identifiable as an area that is very dark, and area **2221**, which is dark red, is now clearly identifiable as an area that is very bright. These determinations can be readily made by the human eye, even if the dynamic range of the display monitor is less than that of the sensor, or if the display monitor is incorrectly adjusted, or if the brain of the observer adapts to the brightness of the display. With this information the human observer can change the application of phosphorescent makeup, dye or paint. The human observer can also adjust the aperture and/or the gain setting on the cameras **204**-**205** and/or the brightness of the light panels **208**-**209**.

In one embodiment image **2202** is created by application software running on one camera controller computer **225** and is displayed on a color LCD monitor attached to the camera controller computer **225**. The camera controller computer **225** captures a frame from a dark camera **204** and places the pixel values of the captured frame in an array in its RAM. For example, if the dark cameras **204** is a 640×480 grayscale camera with 8 bits/pixel, then the array would be a 640×480 array of 8-bit bytes in RAM. Then, the application takes each pixel value in the array and uses it as an index into a lookup table of colors, with as many entries as the number of possible pixel values. With 8 bits/pixel, the lookup table has 256 entries. Each of the entries in the lookup table is pre-loaded (by the user or the developer of the application) with the desired Red, Green, Blue (RGB) color value to be displayed for the given brightness level. Each brightness level may be given a unique color, or a range of brightness levels can share a unique color. For example, for image **2202**, lookup table entries 0-31 are all loaded with the RGB value for blue, entries 192-223 are loaded with the RGB value for orange and entries 224-255 are loaded with the RGB value for dark red. Other entries are loaded with different RGB color values. The application uses each pixel value from the array (e.g. 640×480 of 8-bit grayscale values) of the captured frame as an index into this color lookup take, and forms a new array (e.g. 640×480 of 24-bit RGB values) of the looked-up colors. This new array of look-up colors is then displayed, producing a color image such as **1102**.

If a color camera (either lit camera **214** or dark camera **204**) is used to capture the image to generate an image such as **2202**, then one step is first performed after the image is captured and before it is processed as described in the preceding paragraph. The captured RGB output of the camera is stored in an array in camera controller computer **225** RAM (e.g. 640×480 with 24 bits/pixel). The application running on camera controller computer **225** then calculates the average brightness of each pixel by averaging the Red, Green and Blue values of each pixel (i.e. Average=(R+G+B)/3), and places those averages in a new array (e.g. 640×480 with 8 bits/pixel). This array of Average pixel brightnesses (the "Average array") will soon be processed as if it were the pixel output of a grayscale camera, as described in the prior paragraph, to produce a color image such as **2202**. But, first there is one more step: the application examines each pixel in the captured RGB array to see if any color channel of the pixel (i.e. R, G, or B) is at a maximum brightness value (e.g. 255). If any channel is, then the application sets the value in the Average array for that pixel to the maximum brightness value (e.g. 255). The reason for this is that it is possible for one color channel of a pixel to be driven beyond maximum brightness (but only output a maximum brightness value), while the other color channels are driven by relatively dim brightness. This may result in an average calculated brightness for that pixel that is a middle-range level (and would not be considered to be a problem for good-quality pattern capture). But, if any of the color channels has been overdriven in a given pixel, then that will result in an incorrect pattern capture. So, by setting the pixel value in the Average array to maximum brightness, this produces a color image **2202** where that pixel is shown to be at the highest brightness, which would alert a human observer of image **1102** of the potential of a problem for a high-quality pattern capture.

It should be noted that the underlying principles of the invention are not limited to the specific color ranges and color choices illustrated in FIG. **22**. Also, other methodologies can be used to determine the colors in **2202**, instead of using only a single color lookup table. For example, in one embodiment the pixel brightness (or average brightness) values of a captured image is used to specify the hue of the color displayed. In another embodiment, a fixed number of lower bits (e.g. 4) of the pixel brightness (or average brightness) values of a captured image are set to zeros, and then the resulting numbers are used to specify the hue for each pixel. This has the effect of assigning each single hue to a range of brightnesses.

Embodiments of the invention may include various steps as set forth above. The steps may be embodied in machine-executable instructions which cause a general-purpose or special-purpose processor to perform certain steps. Various elements which are not relevant to the underlying principles of the invention such as computer memory, hard drive, input devices, have been left out of the figures to avoid obscuring the pertinent aspects of the invention.

Alternatively, in one embodiment, the various functional modules illustrated herein and the associated steps may be performed by specific hardware components that contain hardwired logic for performing the steps, such as an application-specific integrated circuit ("ASIC") or by any combination of programmed computer components and custom hardware components.

Elements of the present invention may also be provided as a machine-readable medium for storing the machine-executable instructions. The machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of machine-readable media suitable for storing electronic instructions. For example, the present invention may be downloaded as a computer program which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Throughout the foregoing description, for the purposes of explanation, numerous specific details were set forth in order to provide a thorough understanding of the present system and method. It will be apparent, however, to one skilled in the art that the system and method may be practiced without some of these specific details. For example, although certain specific mixtures and types of phosphorescent material were described above, the underlying principles of the invention may be employed with various alternate mixtures and/or any type of material which exhibits phosphorescent properties. Accordingly, the scope and spirit of the present invention should be judged in terms of the claims which follow.

What is claimed is:

1. A system comprising:

a synchronization signal generator to generate one or more synchronization signals;

one or more fluorescent lamps configured to strobe on and off responsive to a first one of the one or more synchronization signals, the fluorescent lamps illuminating makeup, markers, paint or dye applied to a subject for a motion capture session; and

a first plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture sequences of images of the makeup, markers, paint or dye as the subject moves or changes facial expressions during a performance, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

2. The system as in claim **1** further comprising:

an image processing device generating motion data representing the movement of the subject using the tracked movement of the makeup, markers, paint or dye.

3. The system as in claim **1** wherein the subject is a performer and wherein makeup, markers, paint or dye is applied in a random pattern to the performer's face.

4. The system as in claim **1** wherein the markers are applied at specified areas of the performer's body.

5. The system as in claim **1** further comprising:

a second plurality of cameras having shutters strobed synchronously with the strobing of the fluorescent lamps to capture images of the performer, wherein the shutters of the second plurality of cameras are open when the fluorescent lamps are on and the shutters of the second plurality of cameras are closed when the fluorescent lamps are off.

6. The system as in claim **5** wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

7. The system as in claim **1** further comprising:

a ballast circuit electrically coupled to a power source and to at least one of the one or more fluorescent lamps, the ballast circuit configured to provide power to the fluorescent lamp to turn the fluorescent lamp on; and

a synchronization control circuit electrically coupled to the synchronization signal generator and to the ballast circuit, the synchronization control circuit to receive one of the synchronization signals from the synchronization signal generator and to responsively cause the ballast circuit to turn the fluorescent lamp on and off.

8. The system as in claim **1** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

9. The system as in claim **8** wherein the first period of time is longer than the second period of time.

10. The system as in claim **1** wherein the camera shutters are controlled by synchronization signals from a computer system.

11. The system as in claim **5** further comprising an image processing device separating the images captured by the first plurality of cameras from the images captured by the second plurality of cameras to generate two separate sets of image data.

12. The system as in claim **5** wherein the first plurality of cameras have a sensitivity which is different from the second plurality of cameras.

13. The system as in claim **5** wherein the second plurality of cameras are controlled to open their shutters for a relatively shorter period of time when the fluorescent lamps are on; and the first plurality of cameras are controlled to open their shutters for a relatively longer period of time when the fluorescent lamps are off.

14. The system as in claim **5** wherein the second plurality of cameras comprise color cameras and the first plurality of cameras comprise grayscale cameras.

15. The system as in claim **14** wherein the grayscale cameras have a relatively higher sensitivity than the color cameras.

16. The system as in claim **14** wherein two different synchronization signals are used to control the shutters of the color and grayscale cameras.

17. The system as in claim **16** wherein the different synchronization signals are 180 degrees out of phase.

18. The system as in claim **1** wherein strobing the shutters further comprises:

opening the shutters for a period of time when the fluorescent lamps are on to capture images of the performer's face and/or body.

19. The system as in claim **1** wherein after being opened to capture a first non-lit image with the fluorescent lamps off, the shutters of the first plurality of cameras are closed and then opened again when the fluorescent lamps are on to capture a lit image with the fluorescent lamps on, and then closed and then opened again with the fluorescent lamps off to capture a second non-lit image.

20. The system as in claim **18** wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, wherein the first period of time is not equal to the second period of time.

21. The system as in claim **19** further comprising:

an image processing device to separate the image frames captured while the fluorescent lamps are off from the image frames captured when the fluorescent lamps are on to generate two separate sets of image data.

22. The system as in claim **18** wherein sensitivity of the cameras is alternated between capturing the image frames when the fluorescent lamps are on and the image frames when the fluorescent lamps are off.

23. The system as in claim **20** wherein the shutters are opened for a relatively shorter period of time when the fluorescent lamps are on; and

wherein the shutters are opened for a relatively longer period of time when the fluorescent lamps are off.

24. The system as in claim **1** wherein the makeup, paint or dye comprises phosphorescent makeup, paint, dye or other material.

25. The system as in claim **24** where the fluorescent lamps are used to charge the phosphorescent makeup, paint, dye or other material.

26. The system as in claim **5** wherein the strobing of first plurality of cameras and the fluorescent lamps are timed to ensure that the shutters of the first plurality of cameras do not open until the light emanated from the fluorescent panels reaches a minimum threshold value.

27. The system as in claim **1** wherein the makeup or dye includes phosphor.

28. The system as in claim **27** wherein the phosphor comprises ZnS:Cu.

29. The system as in claim **27** wherein the phosphor comprises SrAl2O4:Eu^{2+}, Dy^{3+}.

30. The system as in claim **27** wherein the phosphor comprises $SrAl_2O_4$:Eu^{2+}.

* * * * *

Exhibit 6

US008207963B2

(12) **United States Patent**
Cotter et al.

(10) **Patent No.: US 8,207,963 B2**
(45) **Date of Patent: Jun. 26, 2012**

(54) **SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE AND IMAGE RECONSTRUCTION**

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(73) Assignee: **Onlive, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1146 days.

(21) Appl. No.: **11/888,377**

(22) Filed: **Jul. 31, 2007**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
G06T 15/00 (2011.01)
G06T 17/00 (2006.01)

(52) **U.S. Cl.** **345/419**; 345/420

(58) **Field of Classification Search** .... None
See application file for complete search history.

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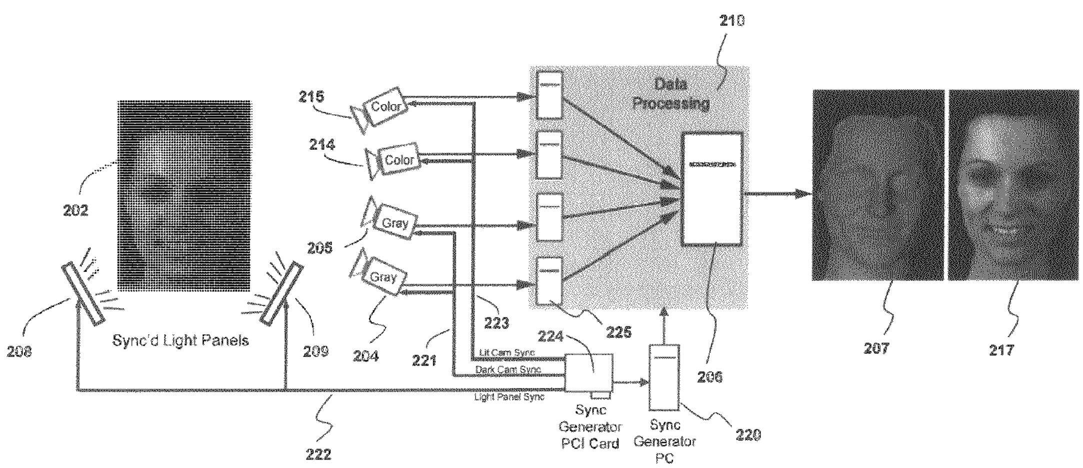
Primary Examiner — Daniel Hajnik
(74) *Attorney, Agent, or Firm* — Blakely Sokoloff Taylor & Zafman LLP

(57) **ABSTRACT**

A system and method are described for performing motion capture on a subject. For example, a computer-implemented method according to one embodiment of the invention comprise: creating a scalar field for the three-dimensional (3-D) capture volume of the subject; generating a surface mesh for the scalar field; retaining good vertices and removing bad vertices of the surface mesh; and storing the good vertices for use in subsequent reconstruction of the motion of the subject. Another computer-implemented method comprises: capturing a series of image frames of the subject over a period of time each frame each frame having a plurality of vertices defining a captured surface of the subject; establishing a reference frame having one or more of the plurality of vertices; performing frame-to-frame tracking to identify vertices within the N'th frame based on the (N−1)'th frame or an earlier frame; and performing reference-to-frame tracking to identify vertices within the N'th frame based on the reference frame to counter potential drift between the frames. Yet another computer-implemented method comprises: capturing motion capture data including a plurality of images of the N vertices during a motion capture session; retrospectively identifying X of the N vertices to track across the plurality of images where X<N; and tracking the X vertices across the plurality of images.

26 Claims, 33 Drawing Sheets
(6 of 33 Drawing Sheet(s) Filed in Color)



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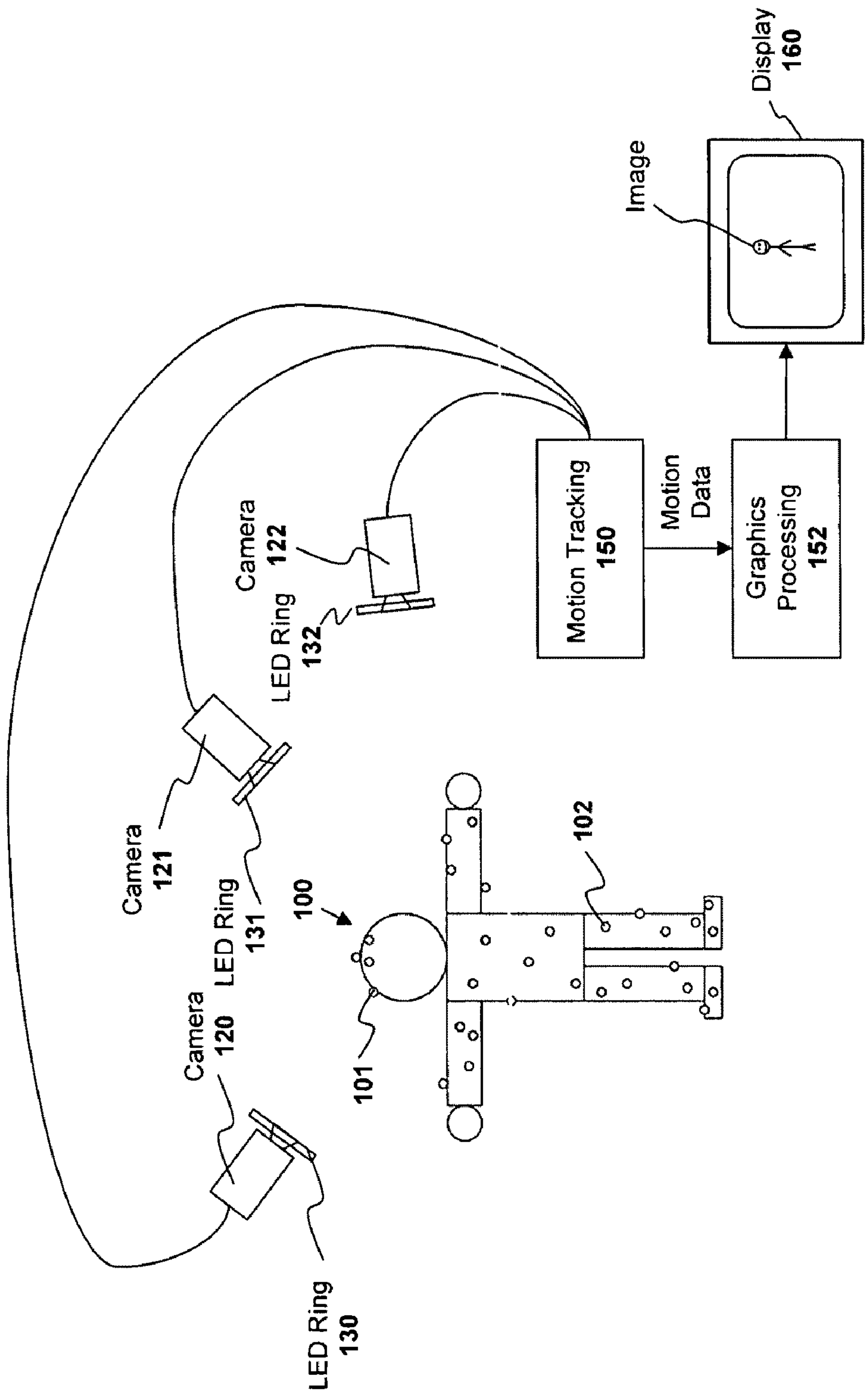
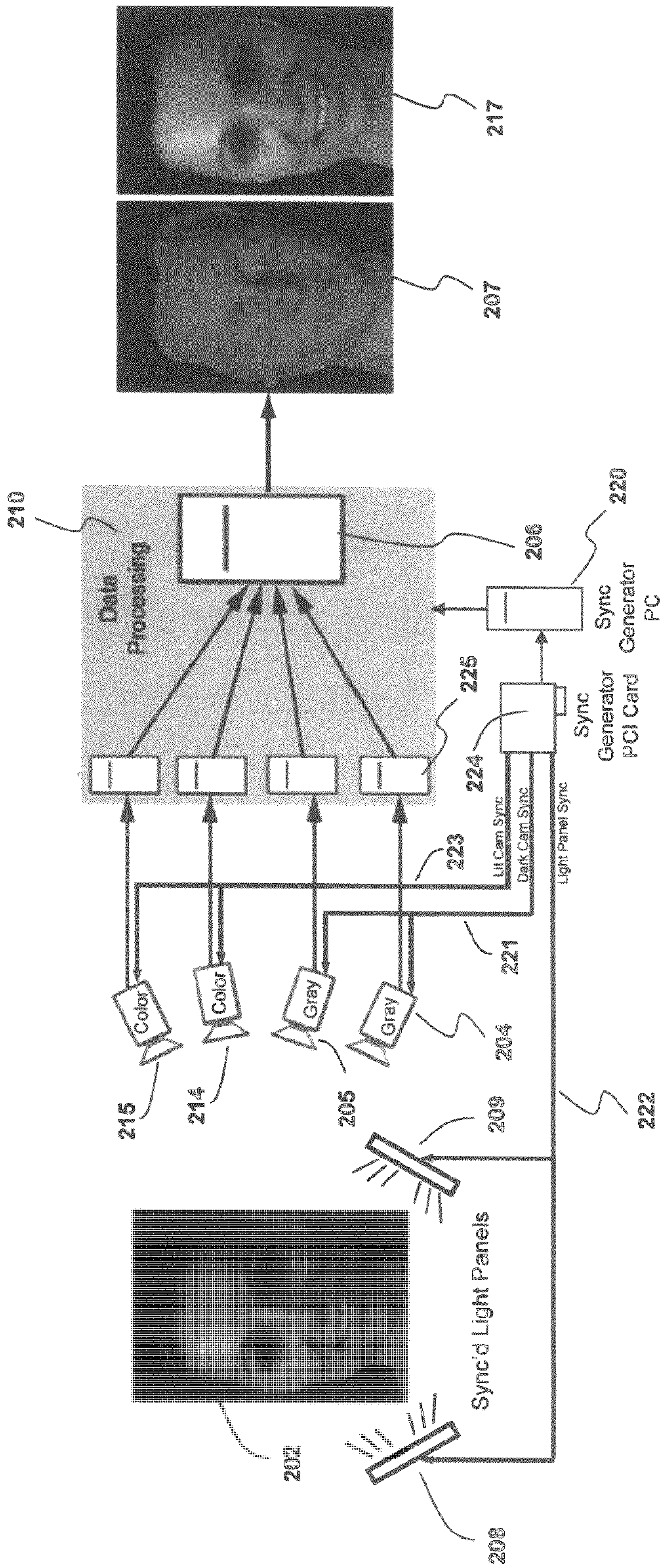
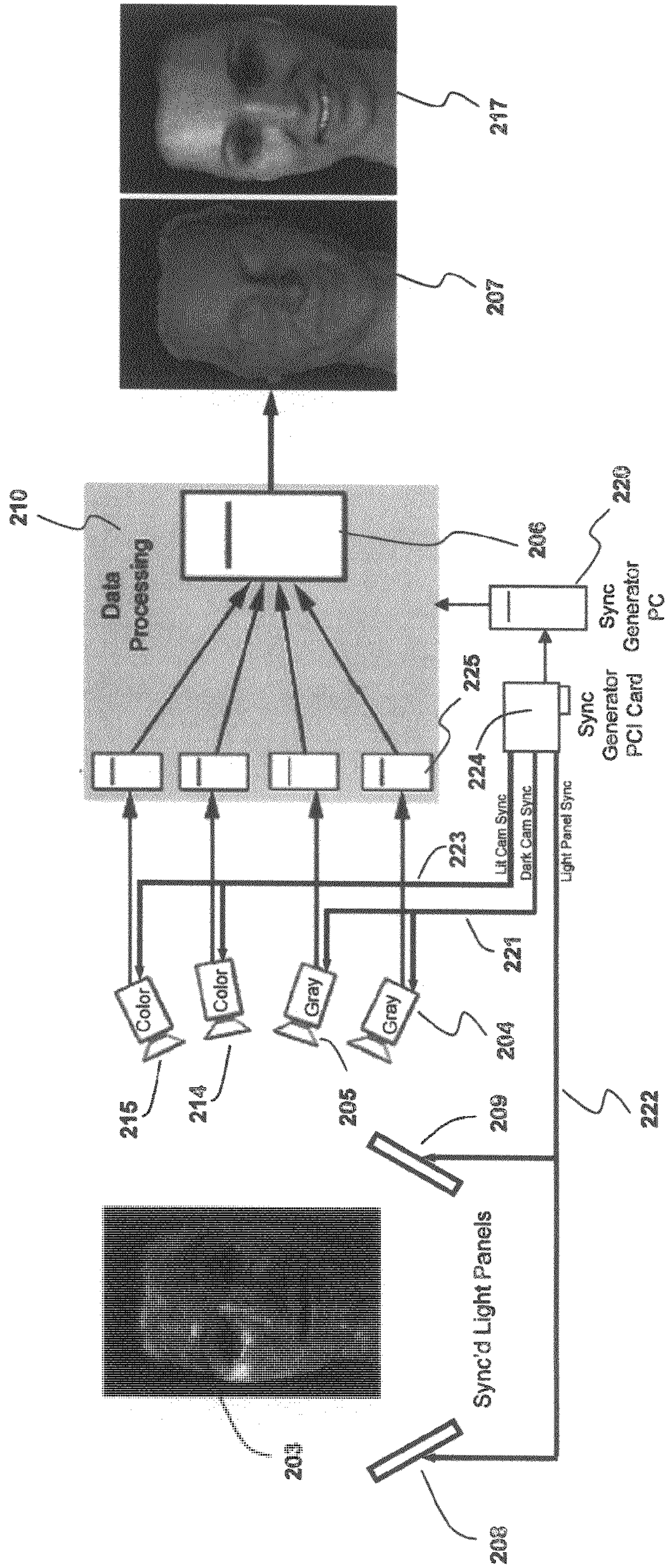


Fig. 1
(prior art)



217
207
210
Data Processing
206
220
Sync Generator PC
225
Sync Generator PCI Card
224
223
Lit Cam Sync
Dark Cam Sync
Light Panel Sync
221
Color
Color
Gray
Gray
204
215
214
205
209
222
Sync'd Light Panels
202
208

Fig. 2a


217
207
210
Data Processing
206
220
Sync Generator PC
225
224
Sync Generator PCI Card
223
Lit Cam Sync
Dark Cam Sync
Light Panel Sync
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Color
Color
Gray
Gray
215
214
205
204
209
222
Sync'd Light Panels
203
208

Fig. 2b

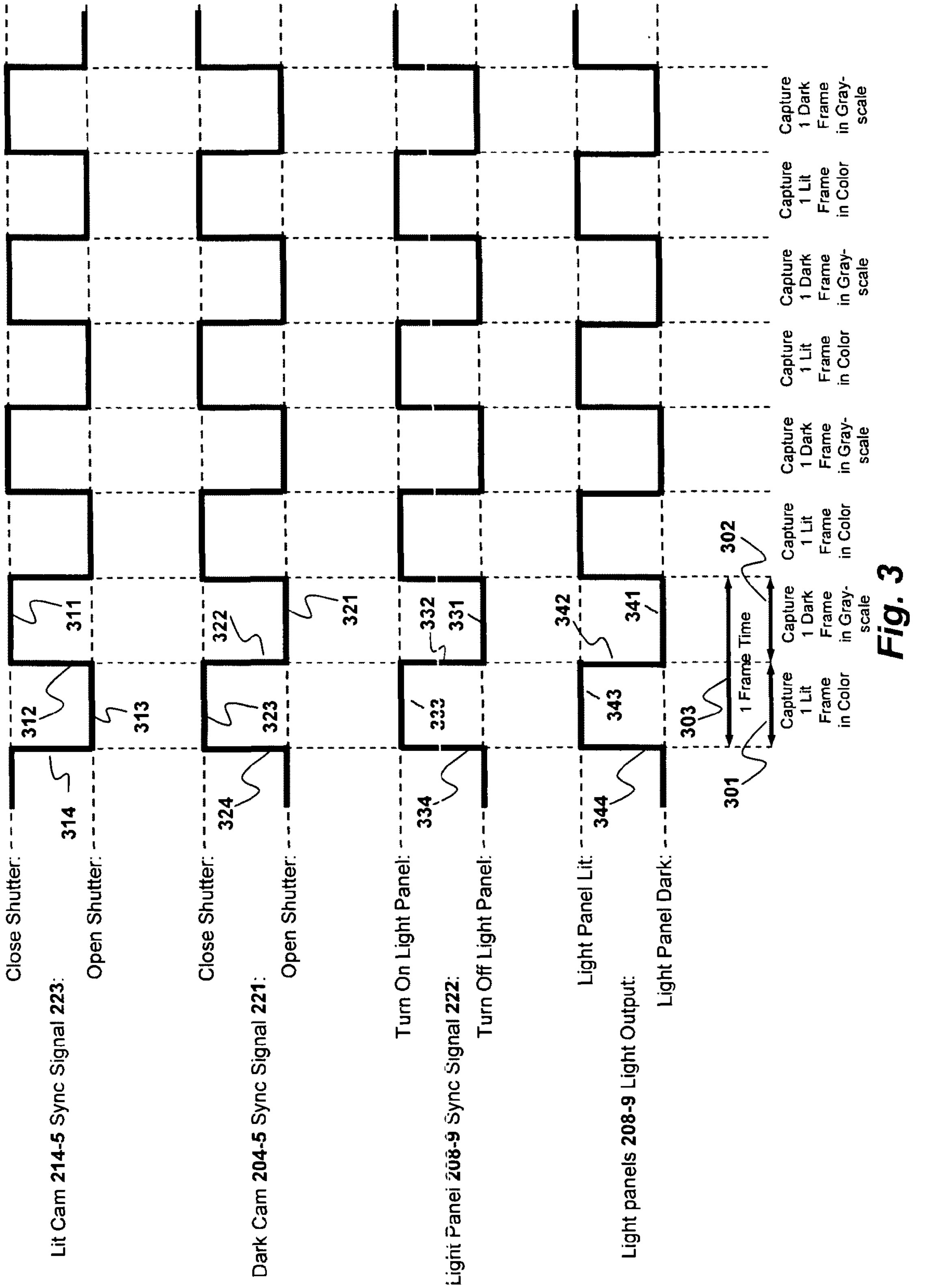
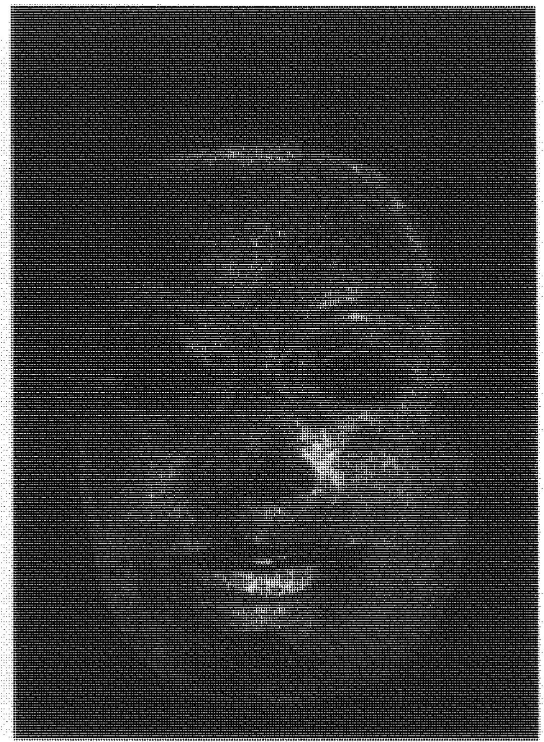

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
311
312
313
314
321
322
323
324
331
332
333
334
341
342
343
344
301
302
303
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

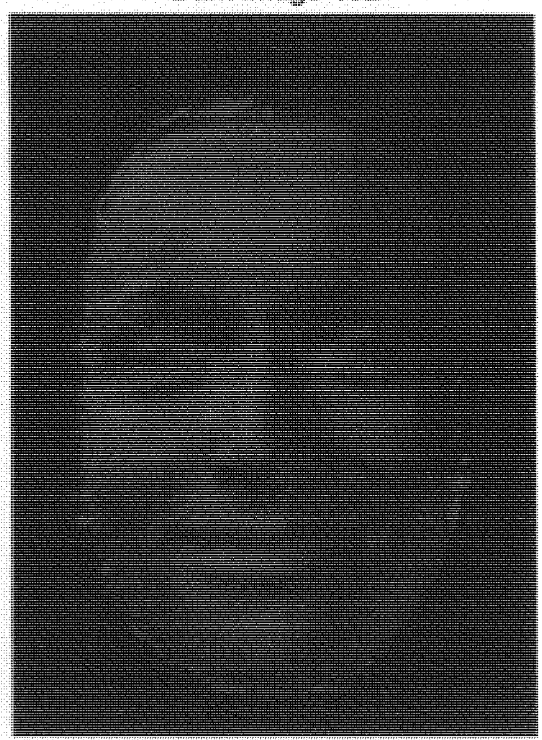
Fig. 3

Lit Image 401



Dark Image 402

Textured 3D Surface 404



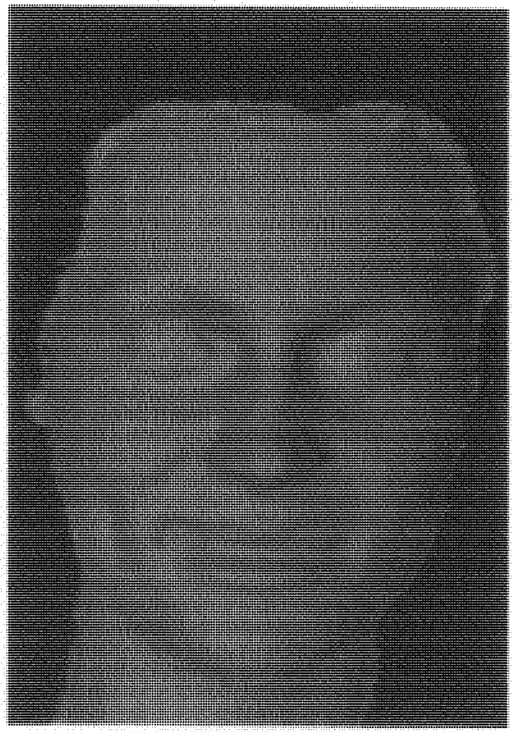
3D Surface 403

Fig. 4

Lit Image 501

Dark Image 502

Textured 3D Surface 504



3D Surface 503

Fig. 5

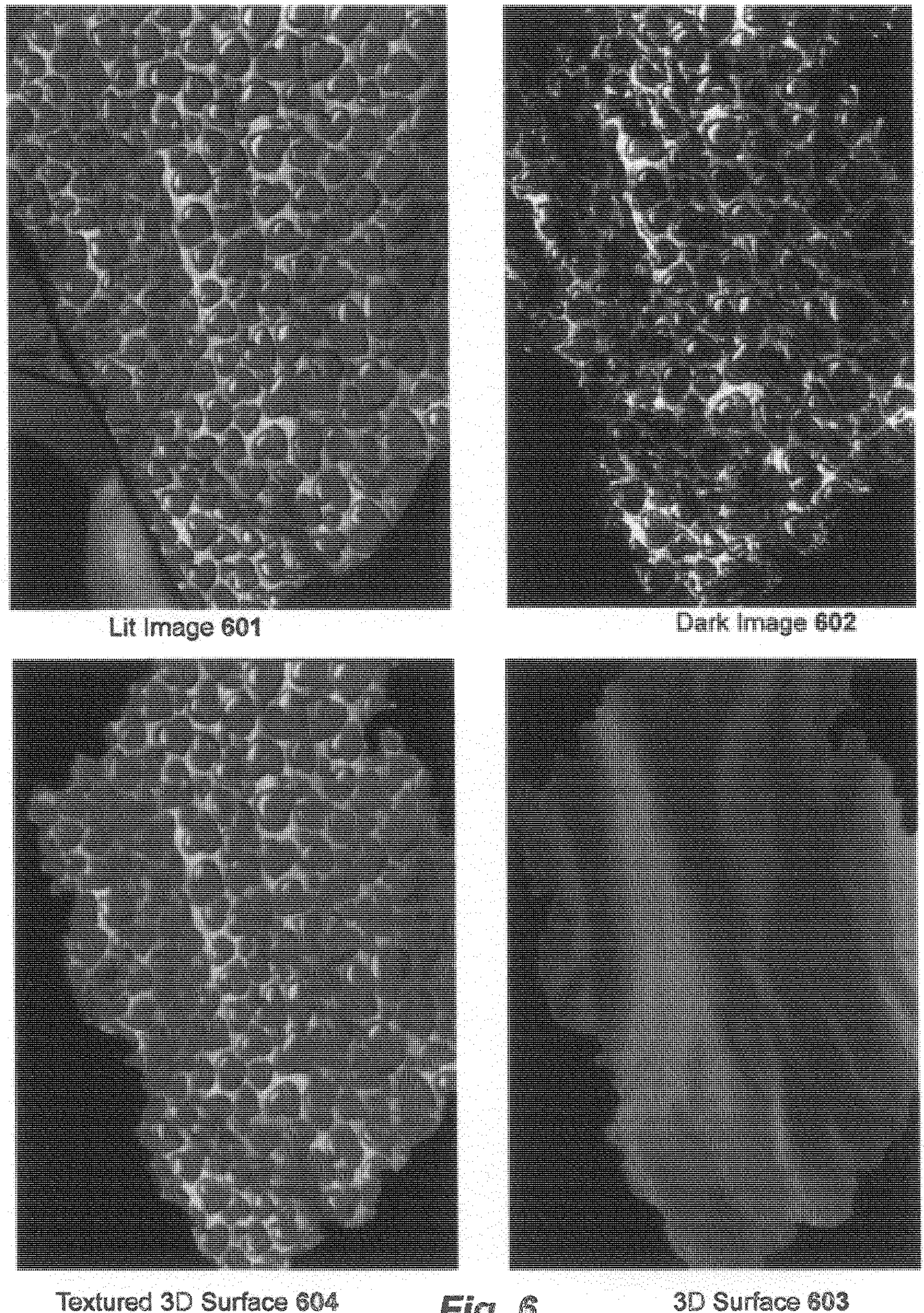

Lit Image 601
Dark Image 602
Textured 3D Surface 604
3D Surface 603

Fig. 6

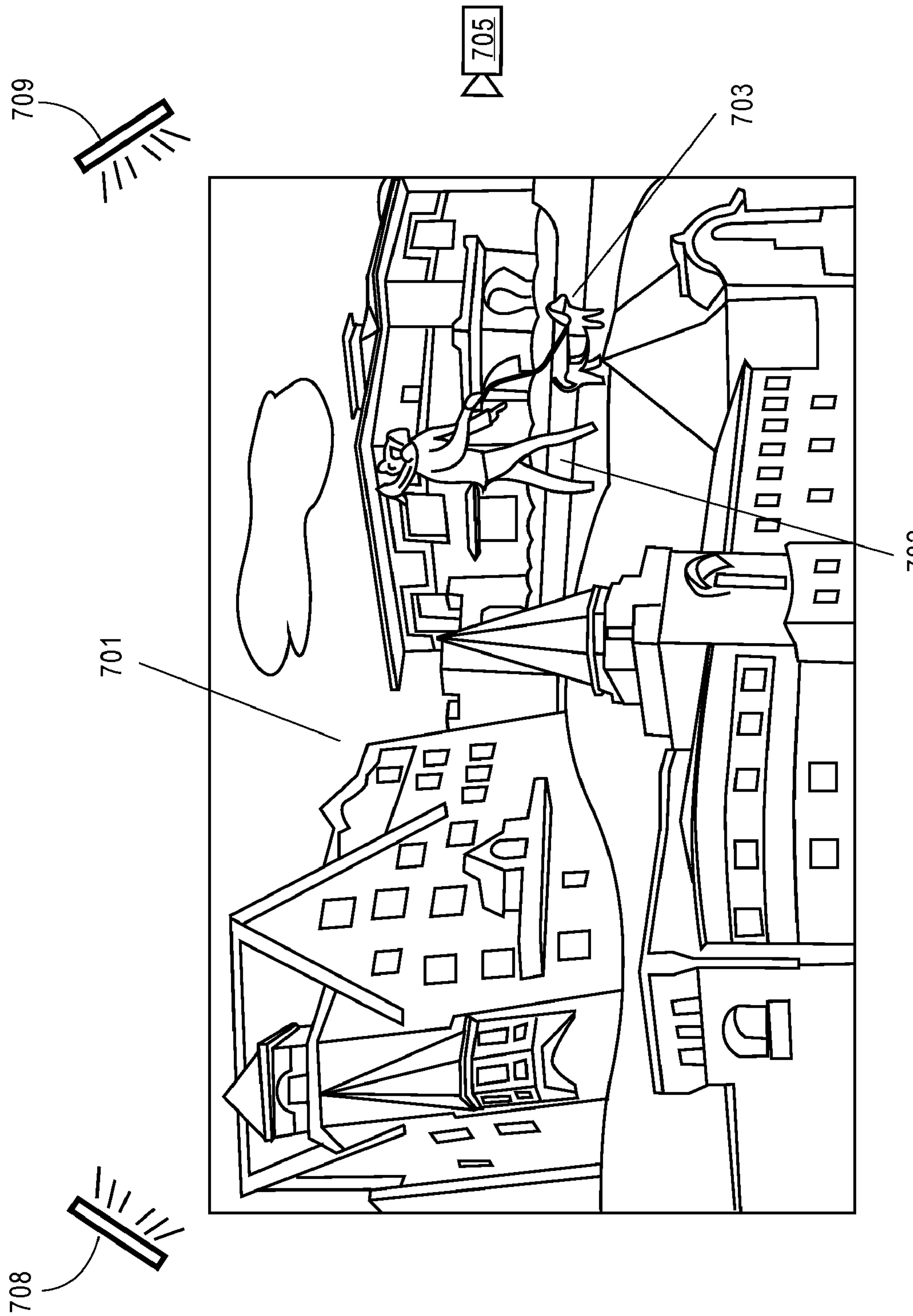


FIG. 7A
(PRIOR ART)

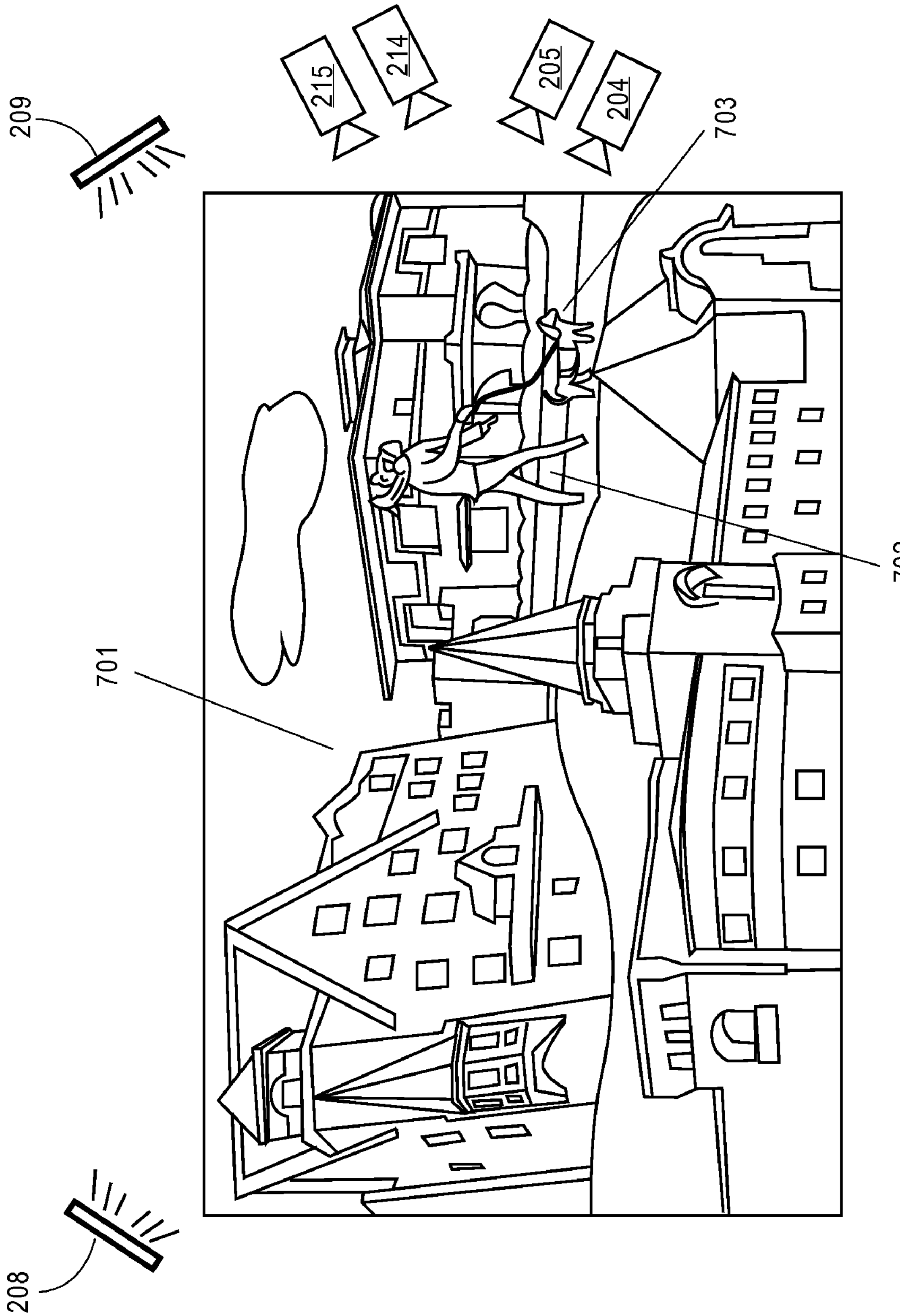


FIG. 7B

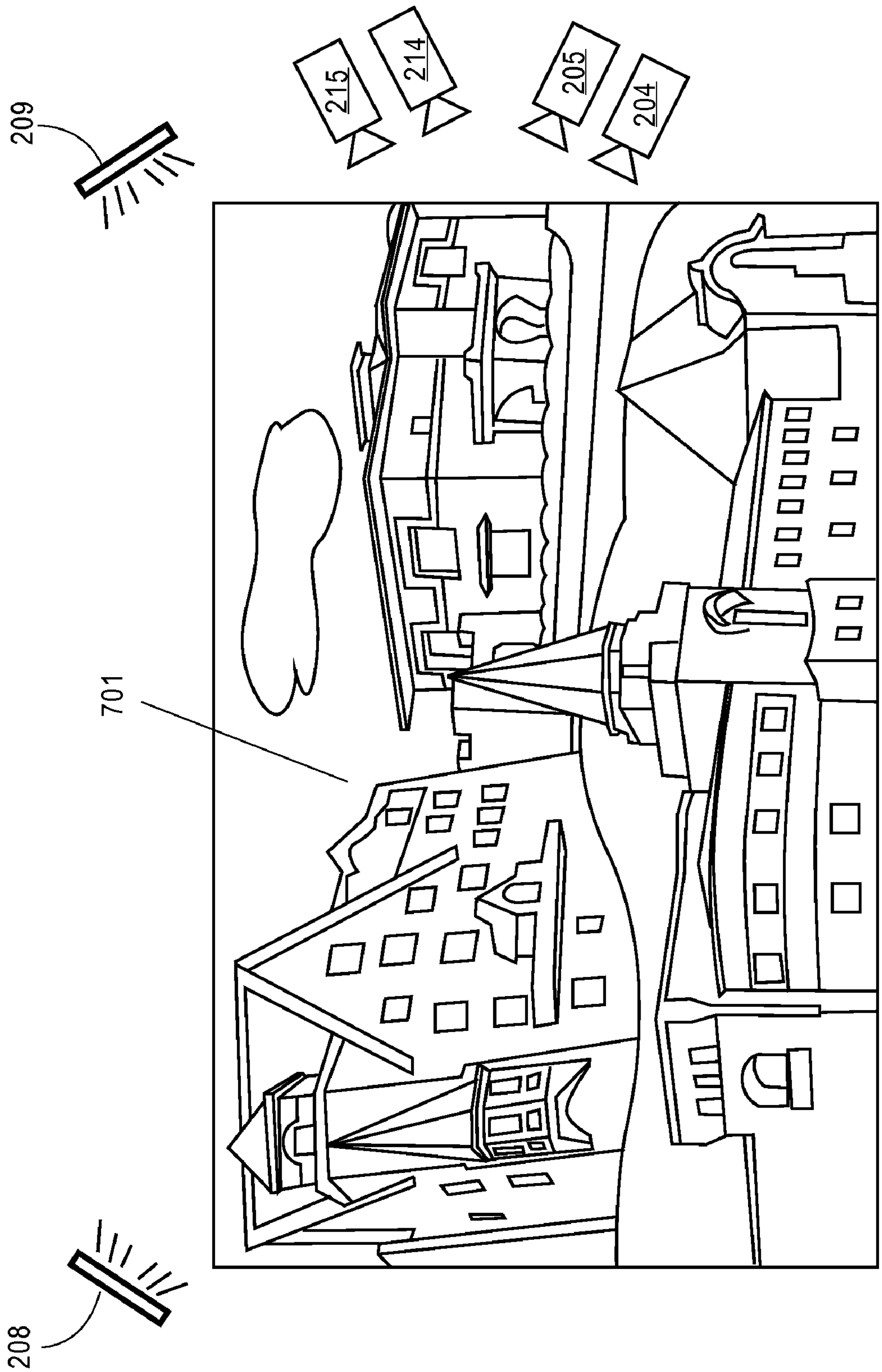


FIG. 7C

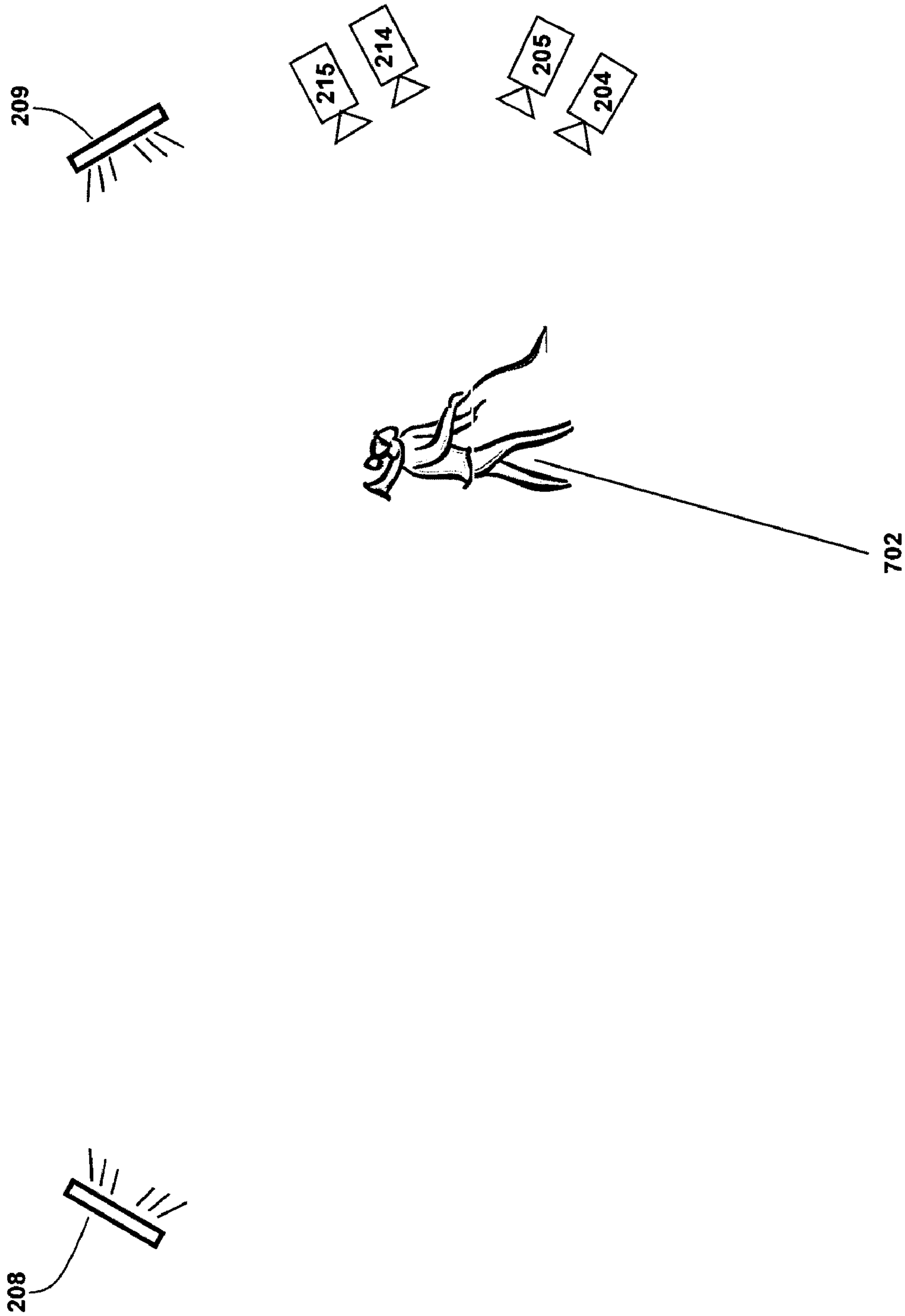


Fig. 7d

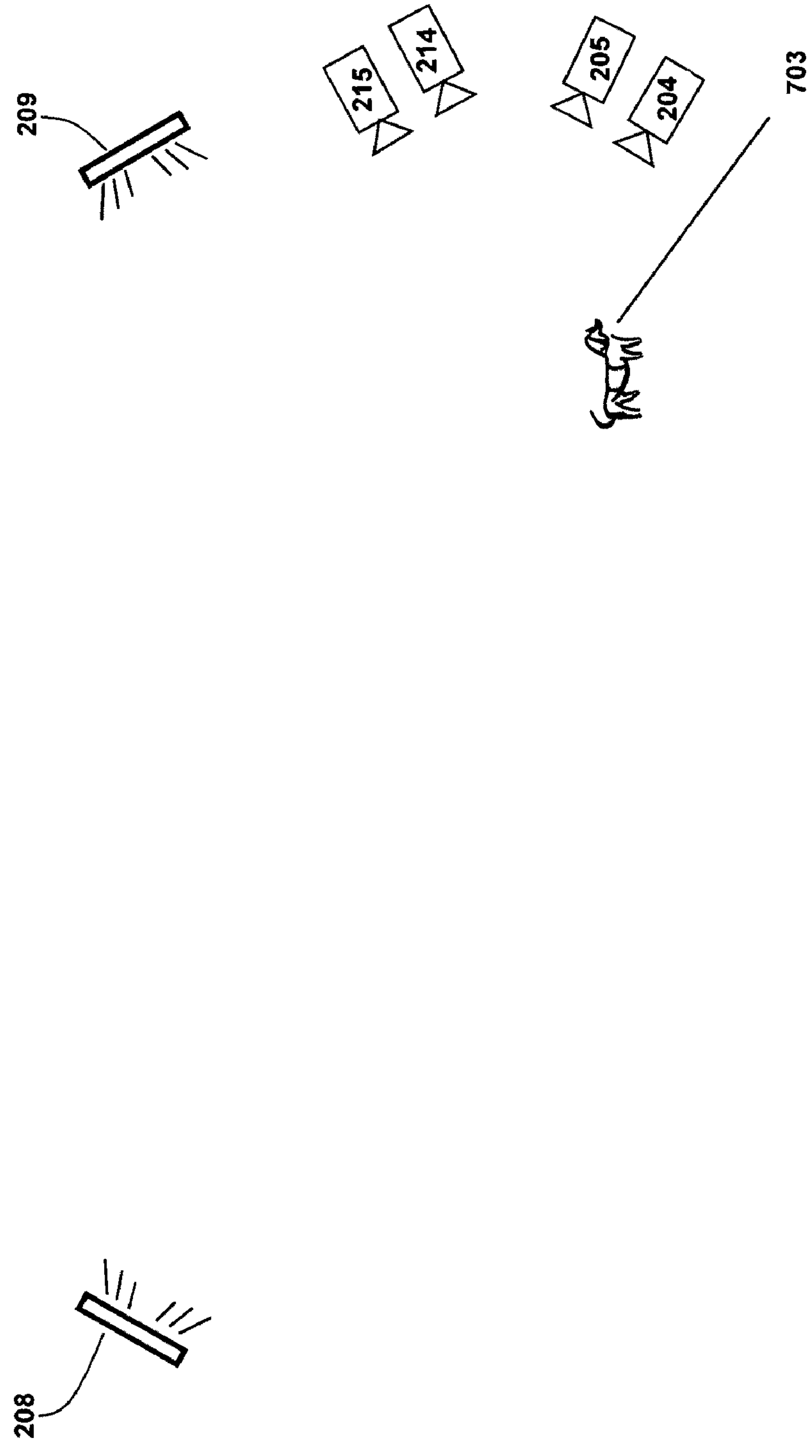


Fig. 7e

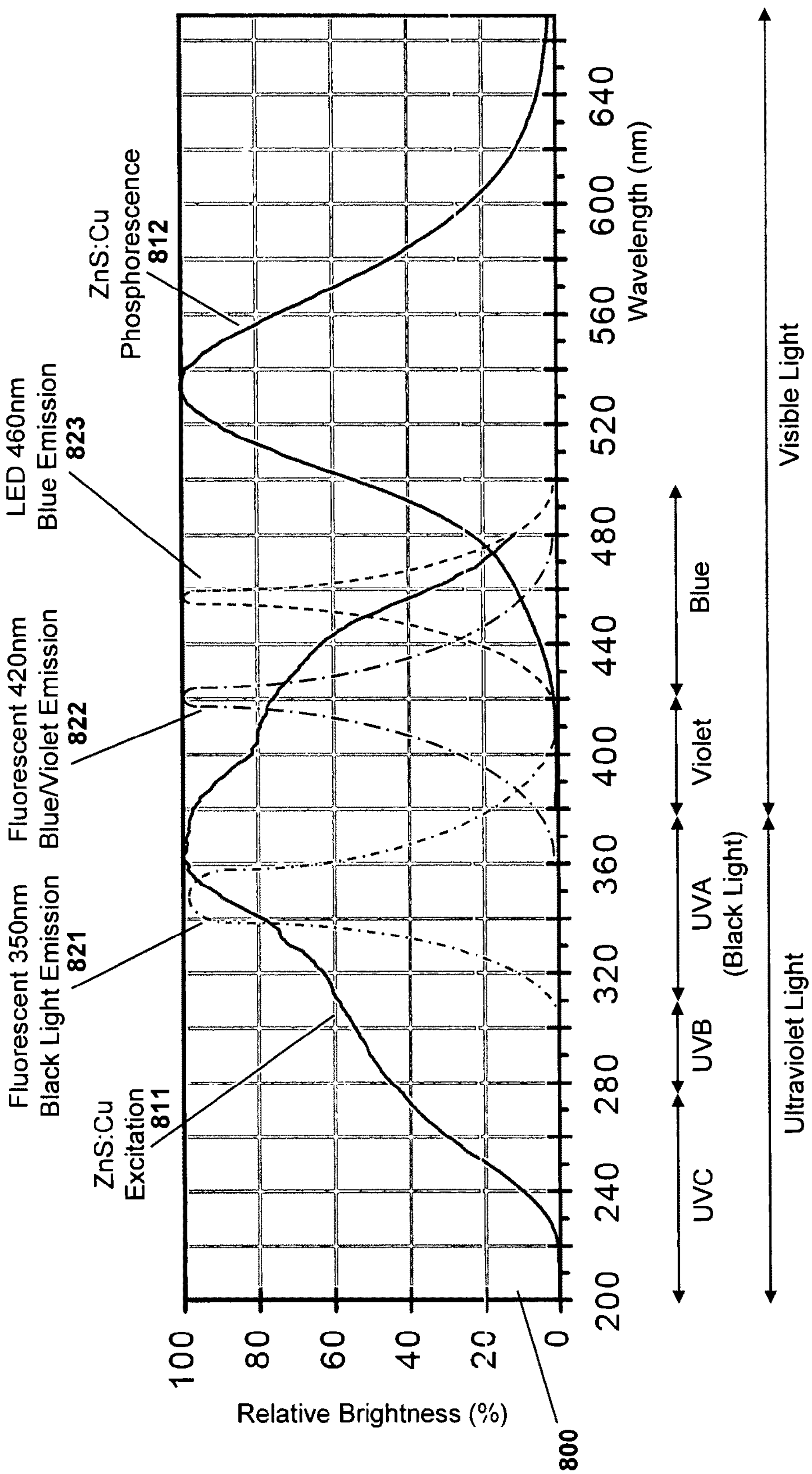

ZnS:Cu Phosphorescence 812
LED 460nm Blue Emission 823
Fluorescent 420nm Blue/Violet Emission 822
Fluorescent 350nm Black Light Emission 821
ZnS:Cu Excitation 811
Wavelength (nm)
200 240 280 320 360 400 440 480 520 560 600 640
Relative Brightness (%)
100 80 60 40 20 0
800
UVC
UVB
UVA (Black Light)
Violet
Blue
Ultraviolet Light
Visible Light

Fig. 8

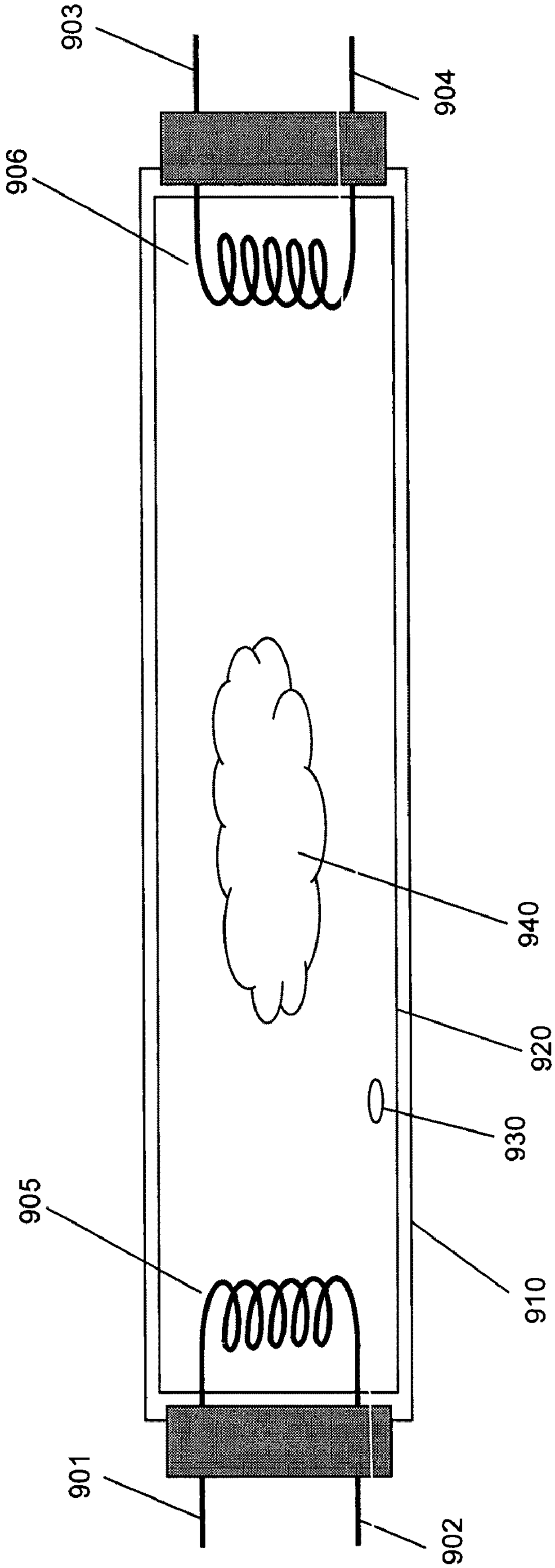


FIG. 9
(Prior Art)

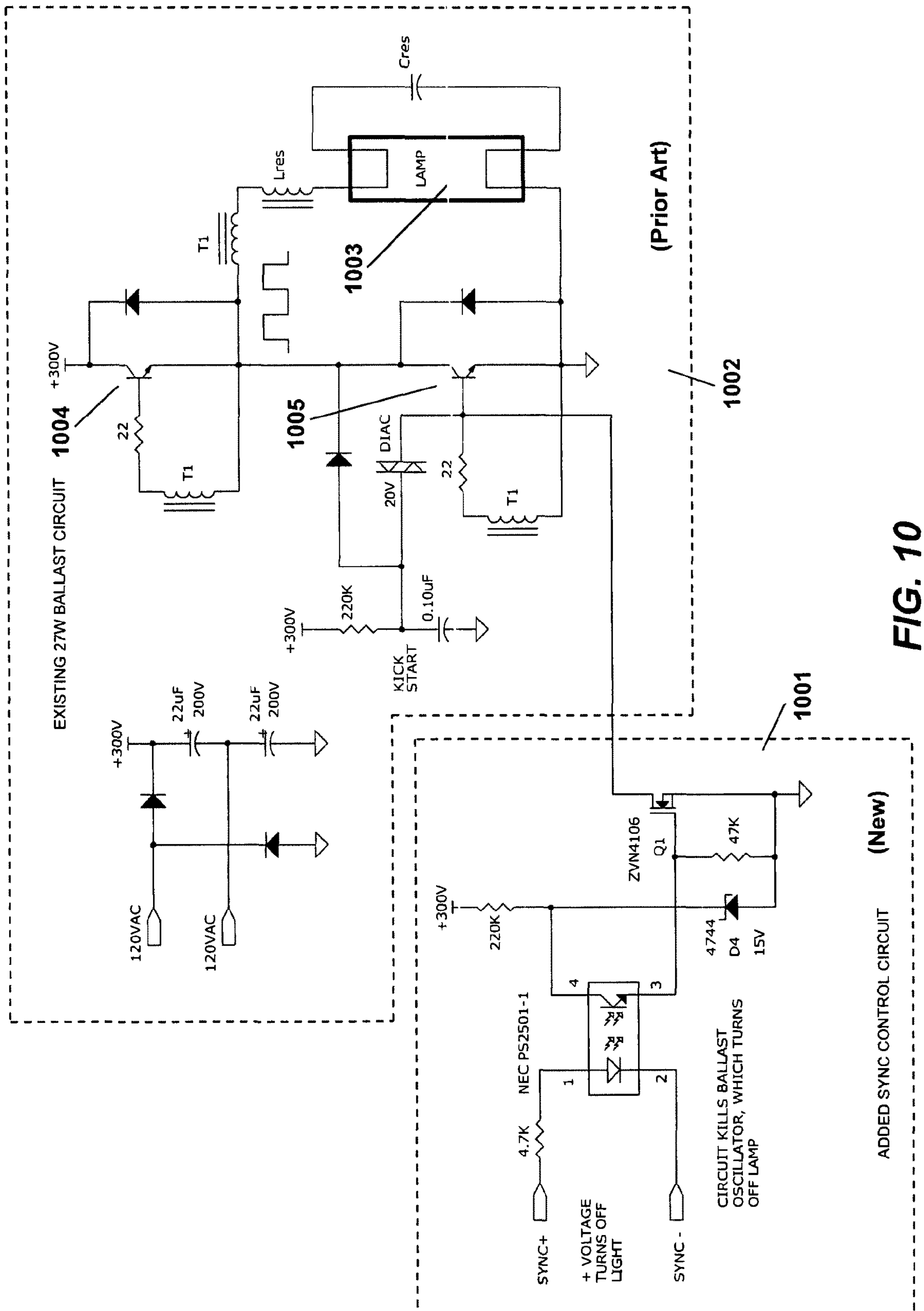
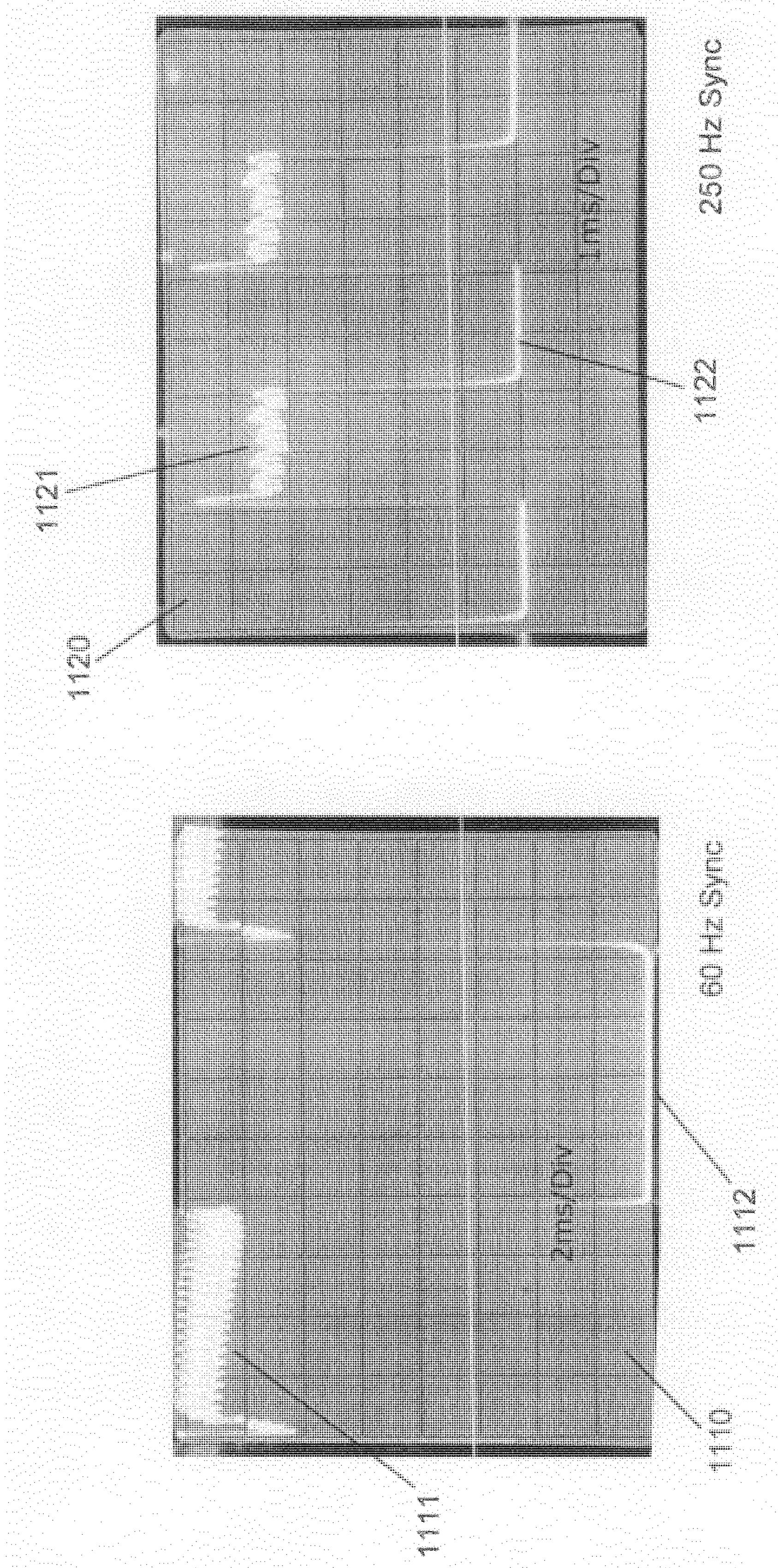

EXISTING 27W BALLAST CIRCUIT
1004
1005
1003
1002
1001
(Prior Art)
(New)
LAMP
Lres
Cres
T1
22
DIAC
20V
+300V
220K
0.10uF
KICK START
22uF 200V
120VAC
ZVN4106
Q1
47K
4744
D4
15V
NEC PS2501-1
4.7K
SYNC+
+ VOLTAGE TURNS OFF LIGHT
SYNC -
CIRCUIT KILLS BALLAST OSCILLATOR, WHICH TURNS OFF LAMP
ADDED SYNC CONTROL CIRCUIT

FIG. 10



250 Hz Sync
1ms/Div
1121
1122
1120
60 Hz Sync
2ms/Div
1112
1111
1110

FIG. 11

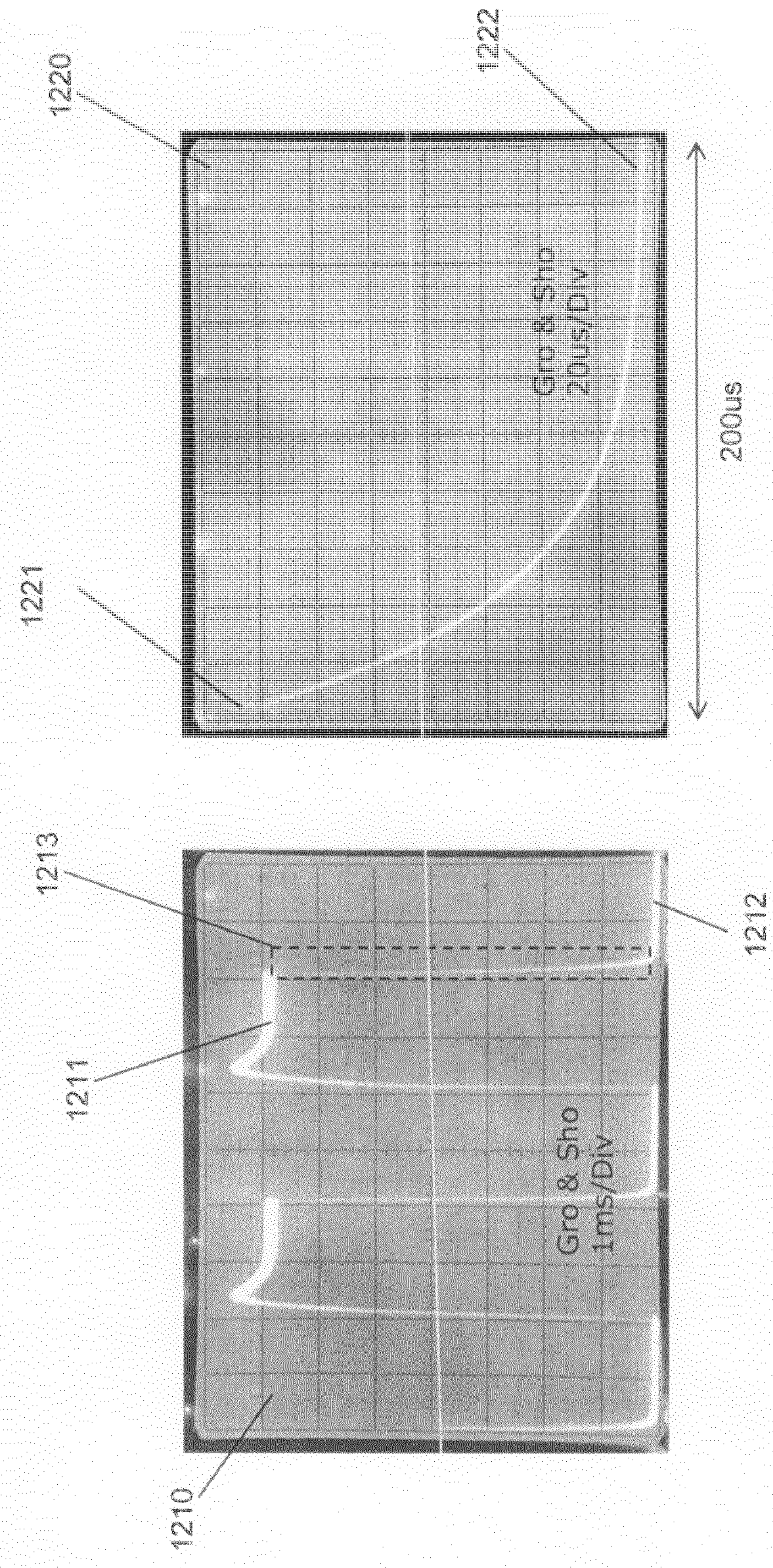

1220
1222
1221
Gro & Sho
20us/Div
200us
1213
1211
1212
Gro & Sho
1ms/Div
1210

FIG. 12

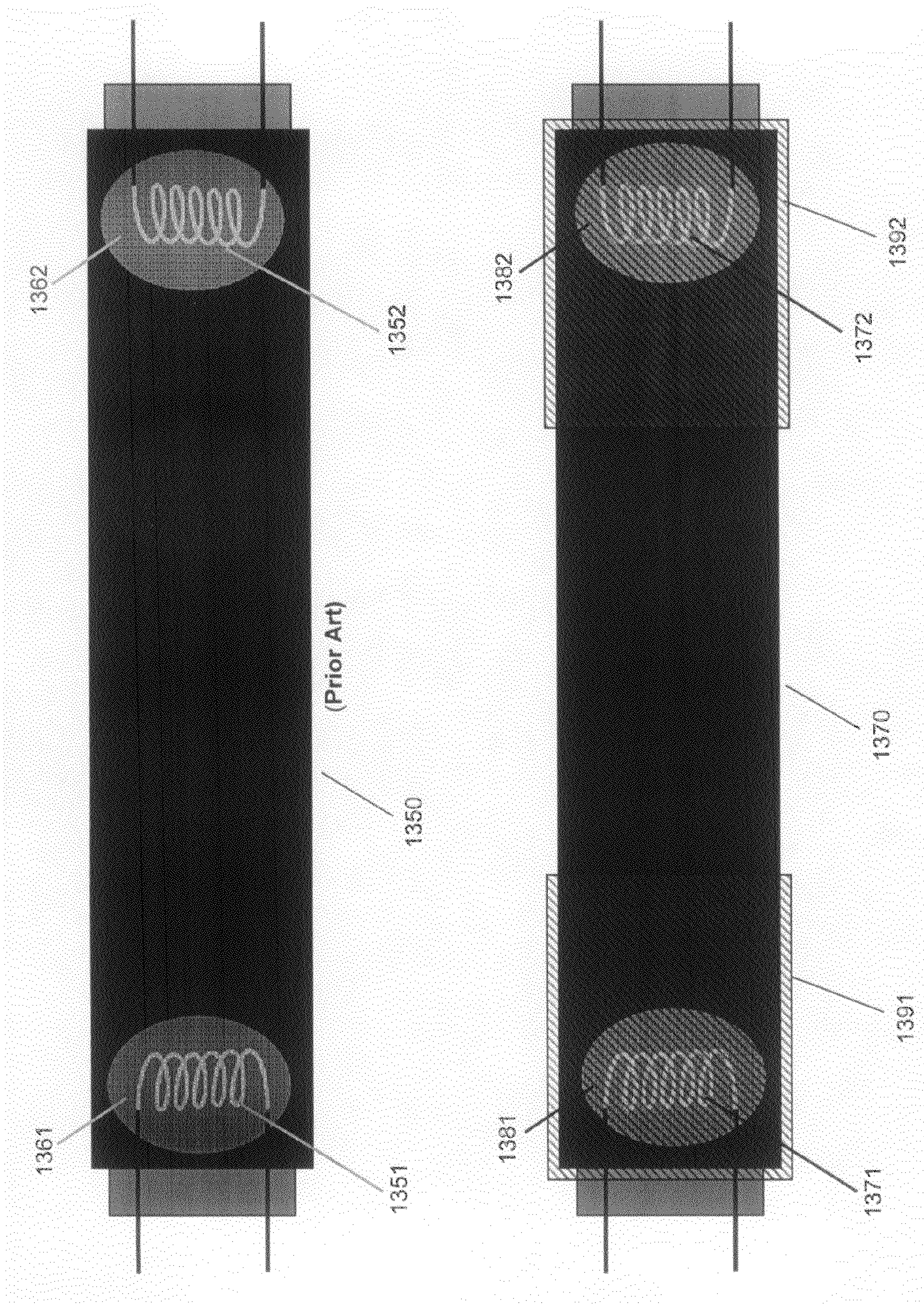

1362
1352
1350
(Prior Art)
1361
1351
1382
1392
1372
1370
1391
1381
1371

FIG. 13

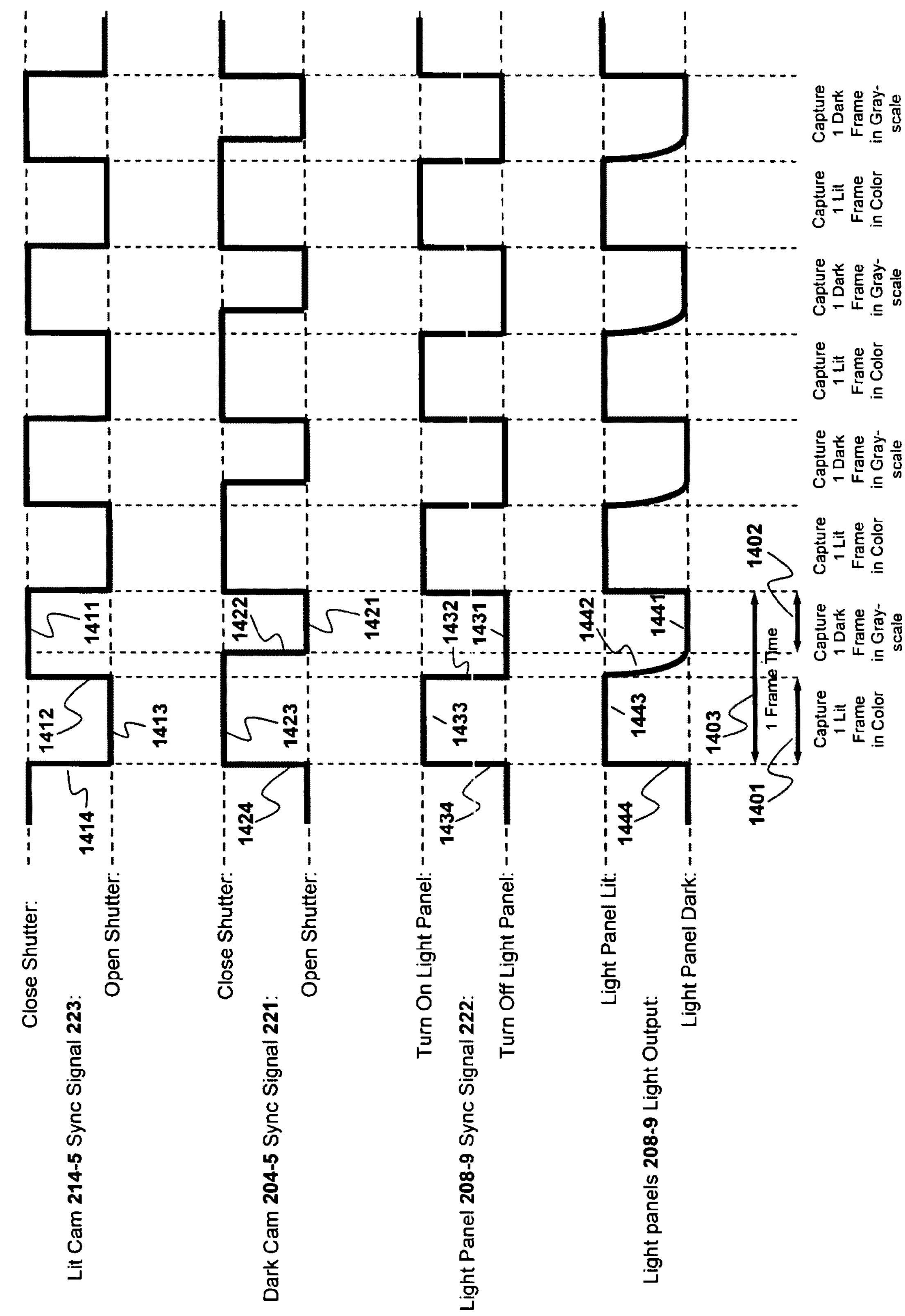

Close Shutter:
Lit Cam 214-5 Sync Signal 223:
Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
1411
1412
1413
1414
1421
1422
1423
1424
1431
1432
1433
1434
1441
1442
1443
1444
1401
1402
1403
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 14

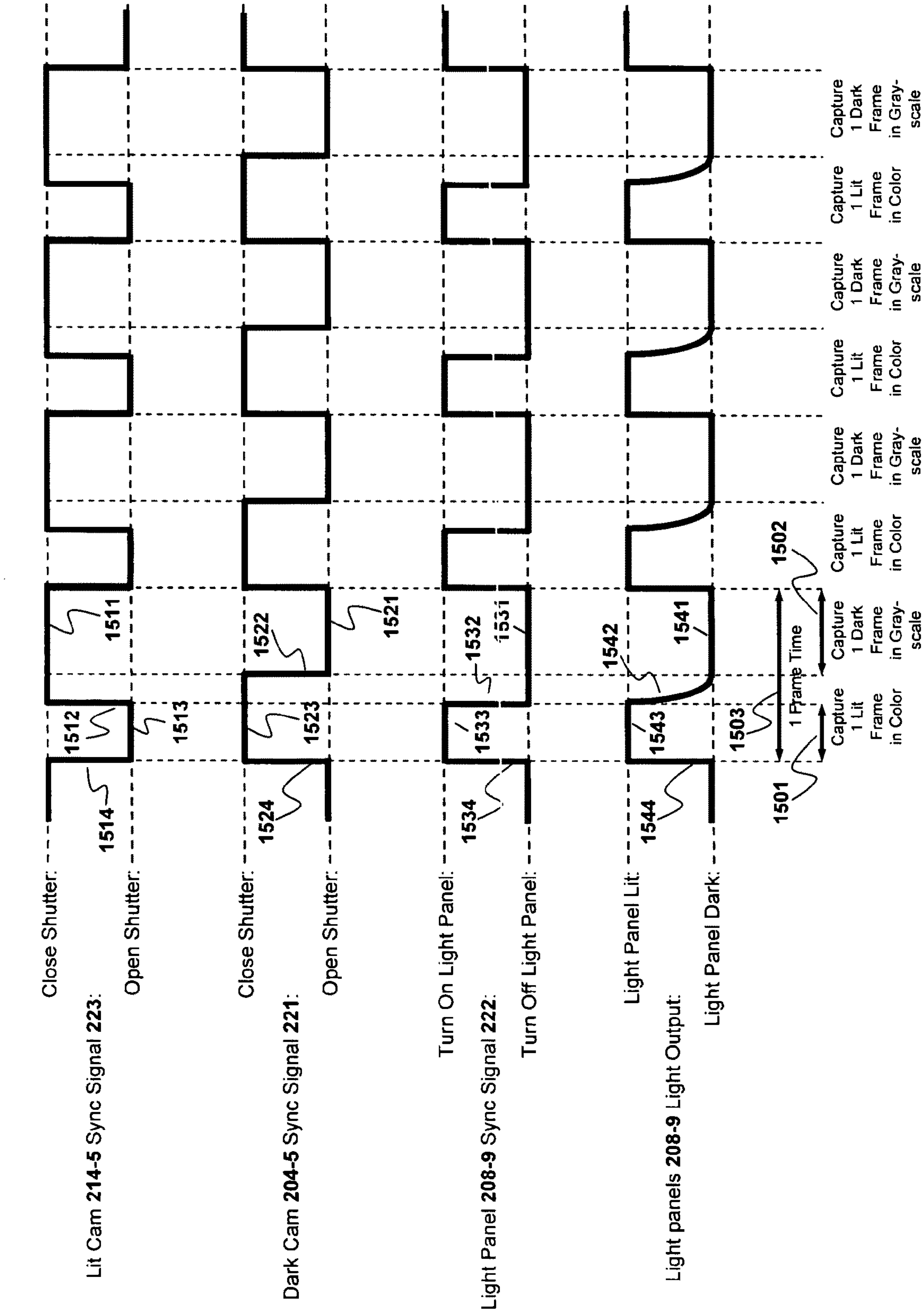

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
1511
1512
1513
1514
1521
1522
1523
1524
1531
1532
1533
1534
1541
1542
1543
1544
1501
1502
1503
1 Frame Time
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 15

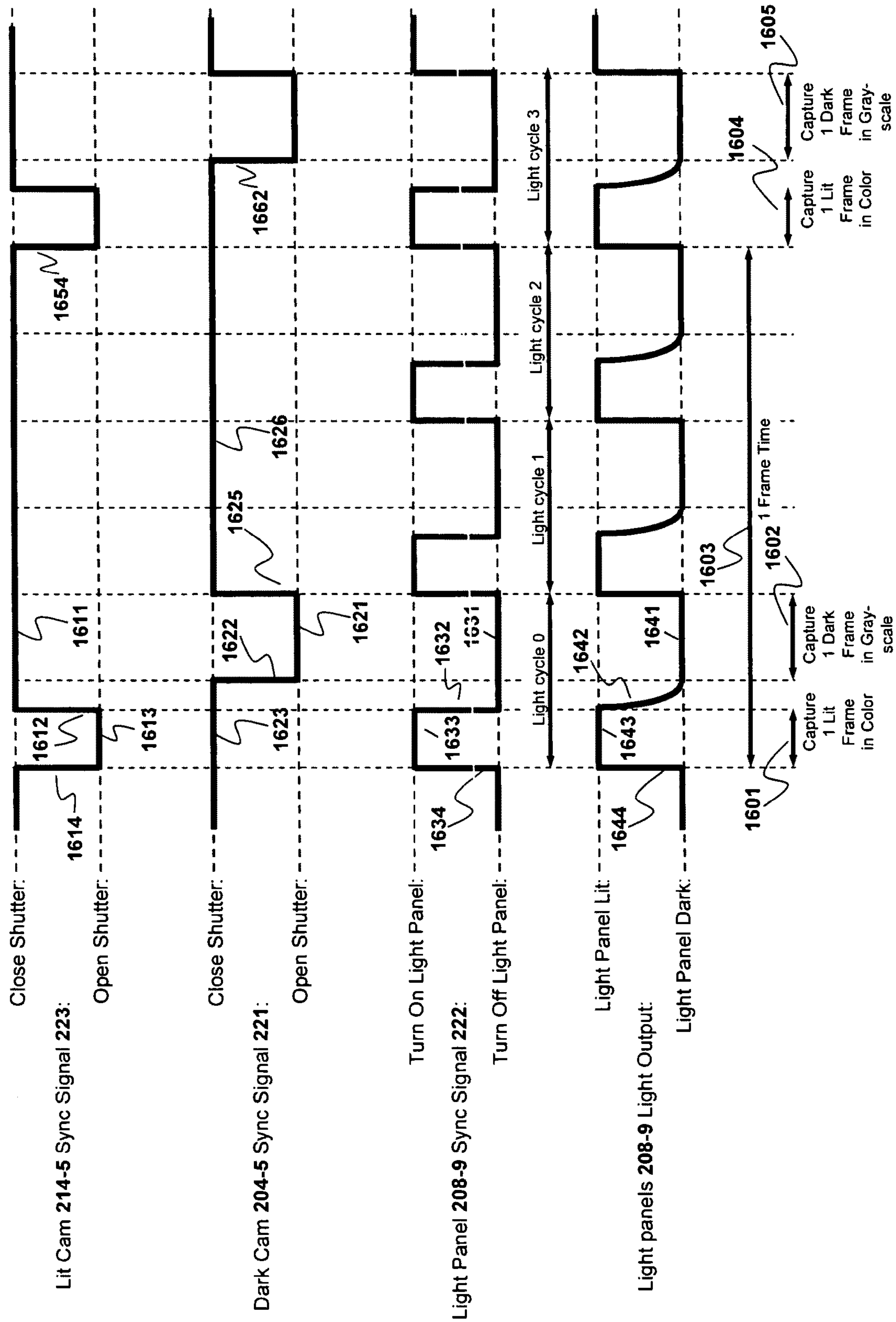
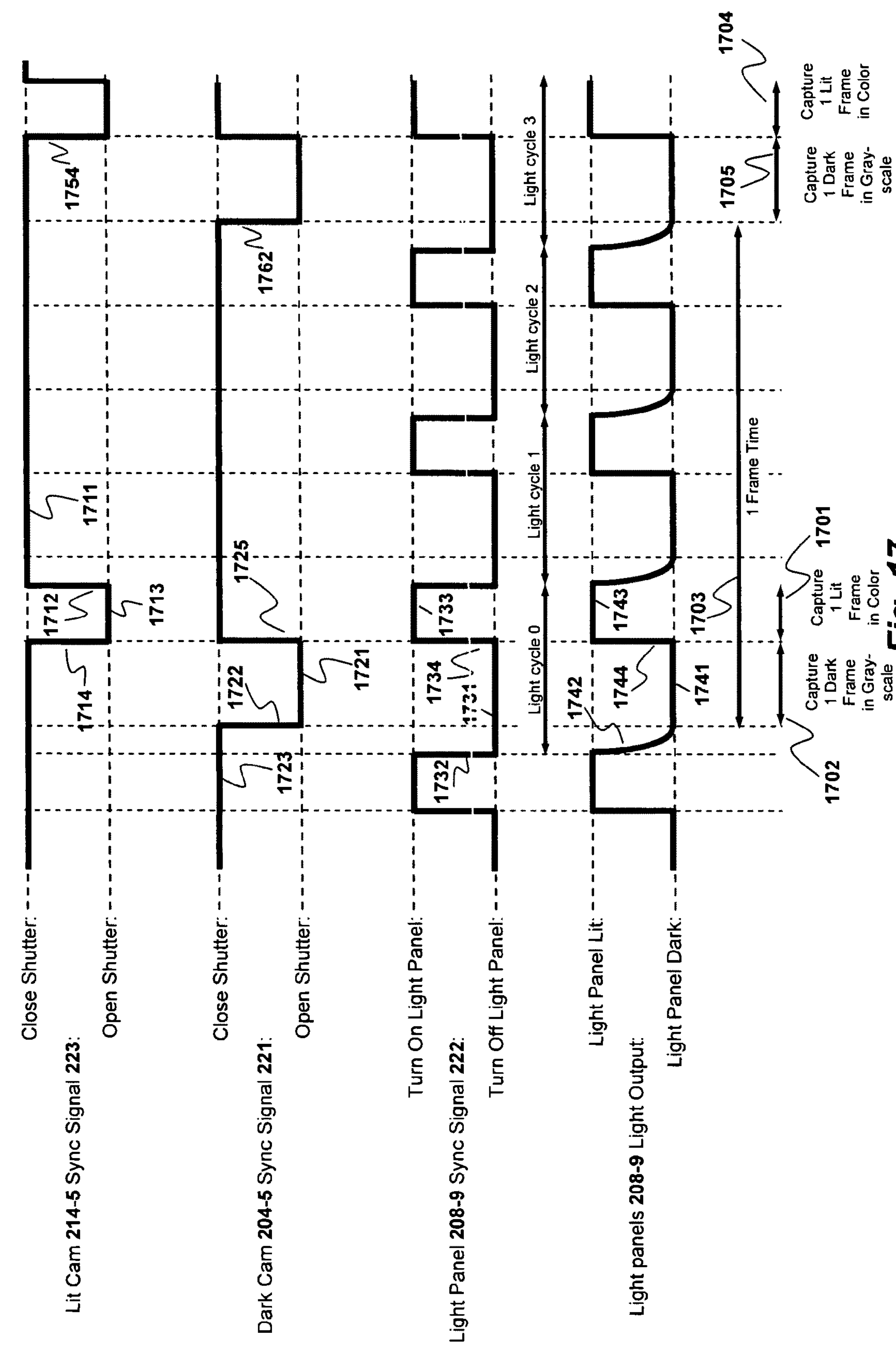

Close Shutter:
Lit Cam 214-5 Sync Signal 223:
Open Shutter:
Close Shutter:
Dark Cam 204-5 Sync Signal 221:
Open Shutter:
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
1611
1612
1613
1614
1654
1621
1622
1623
1625
1626
1662
1631
1632
1633
1634
1641
1642
1643
1644
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
1601
1602
1603
1604
1605
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale

Fig. 16



Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
1711
1712
1713
1714
1721
1722
1723
1725
1731
1732
1733
1734
1741
1742
1743
1744
1754
1762
1701
1702
1703
1704
1705

Fig. 17

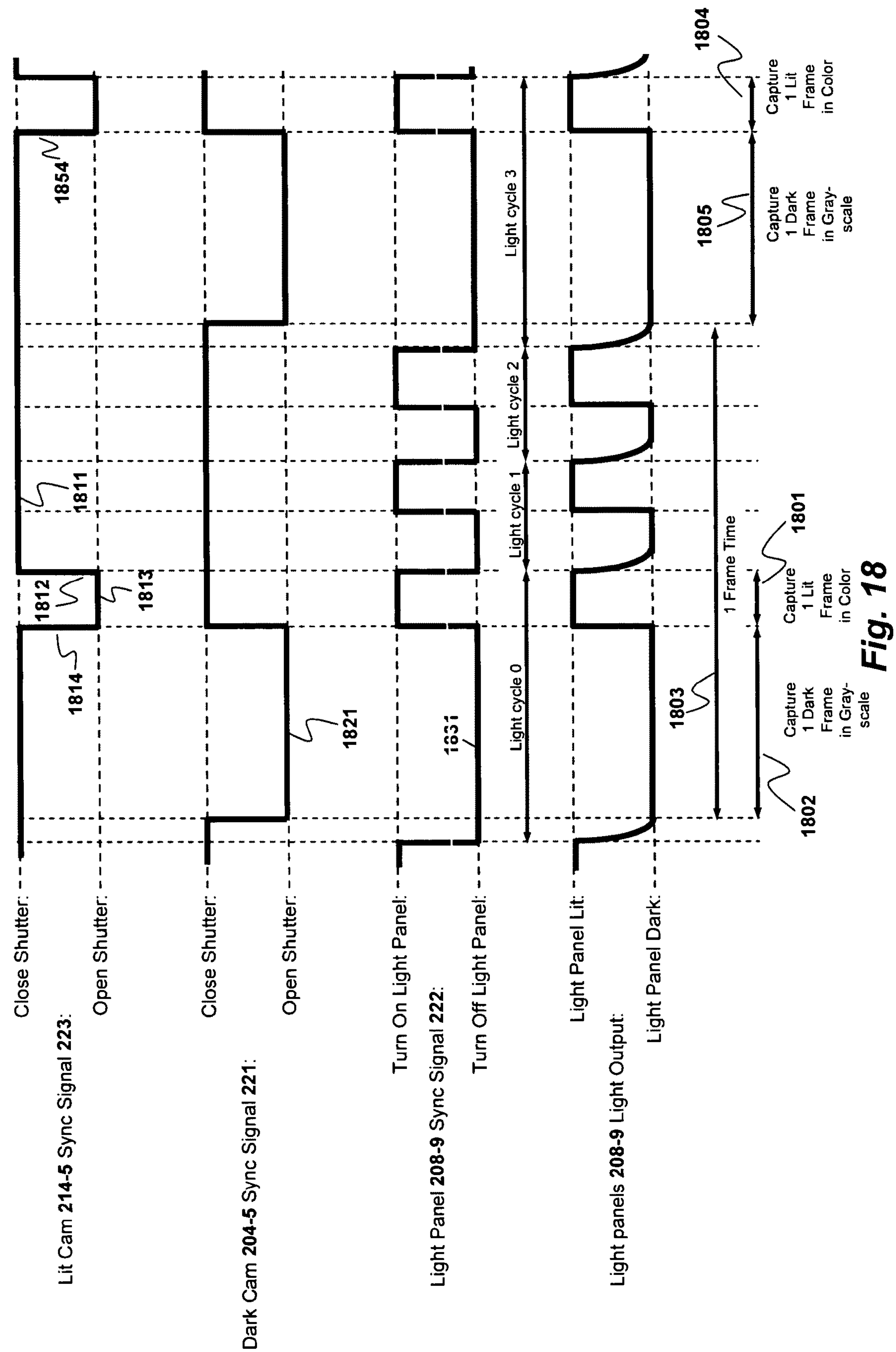

Lit Cam 214-5 Sync Signal 223:
Close Shutter:
Open Shutter:
Dark Cam 204-5 Sync Signal 221:
Close Shutter:
Open Shutter:
Light Panel 208-9 Sync Signal 222:
Turn On Light Panel:
Turn Off Light Panel:
Light panels 208-9 Light Output:
Light Panel Lit:
Light Panel Dark:
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color
1801
1802
1803
1804
1805
1811
1812
1813
1814
1821
1831
1854

Fig. 18

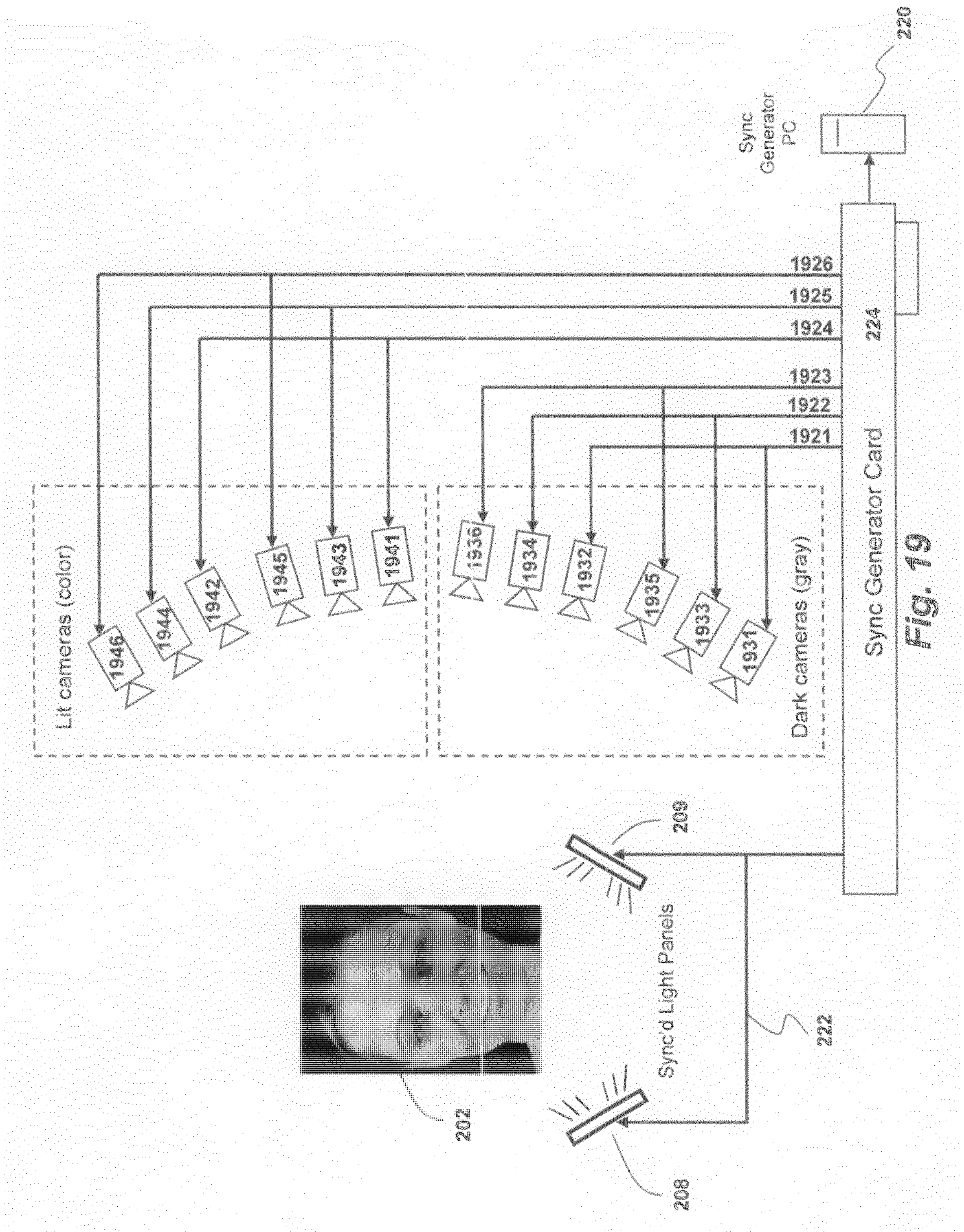

Sync Generator PC
220
Sync Generator Card
224
1926
1925
1924
1923
1922
1921
Lit cameras (color)
1946
1944
1942
1945
1943
1941
Dark cameras (gray)
1936
1934
1932
1935
1933
1931
209
208
Sync'd Light Panels
222
202

Fig. 19

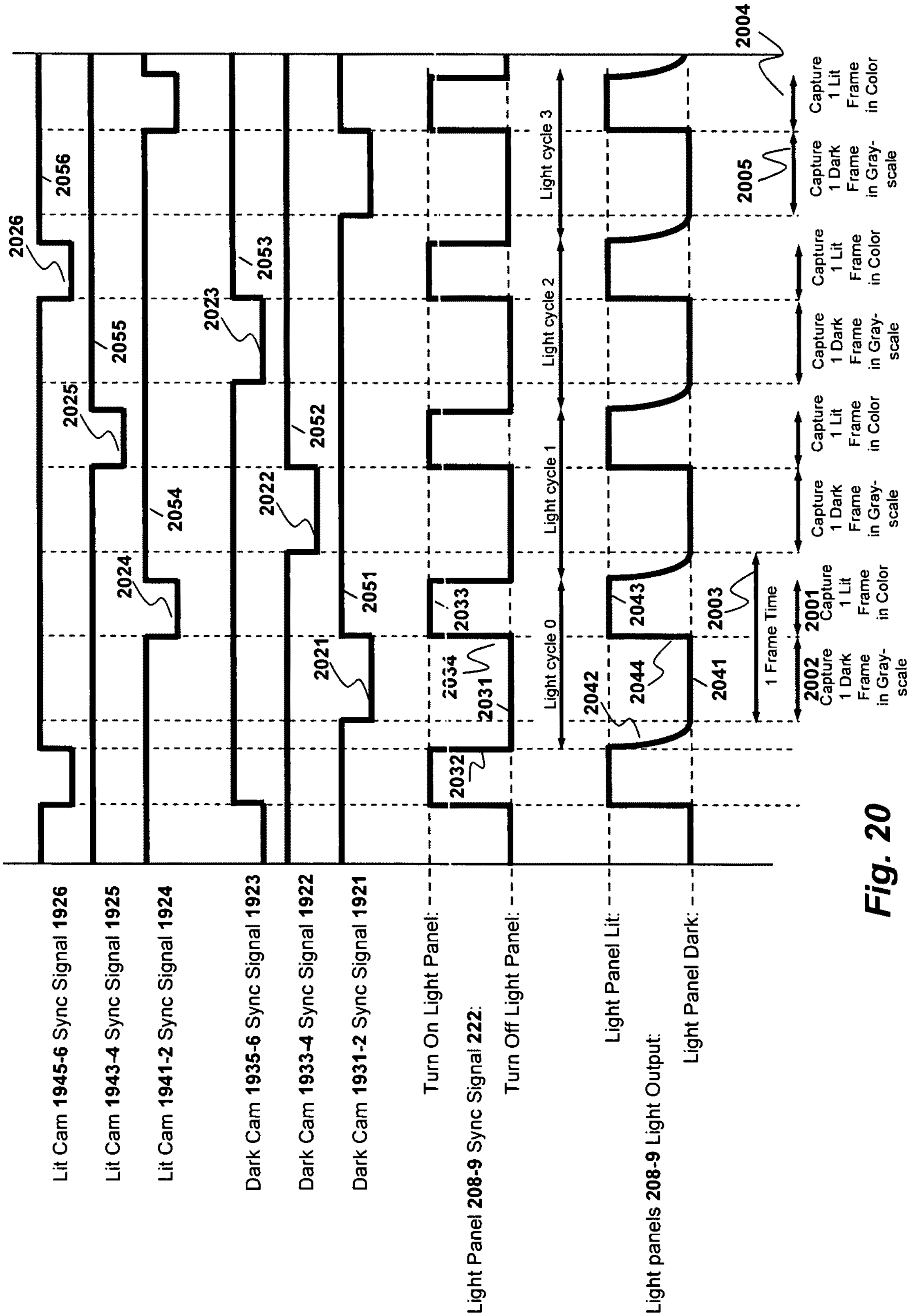
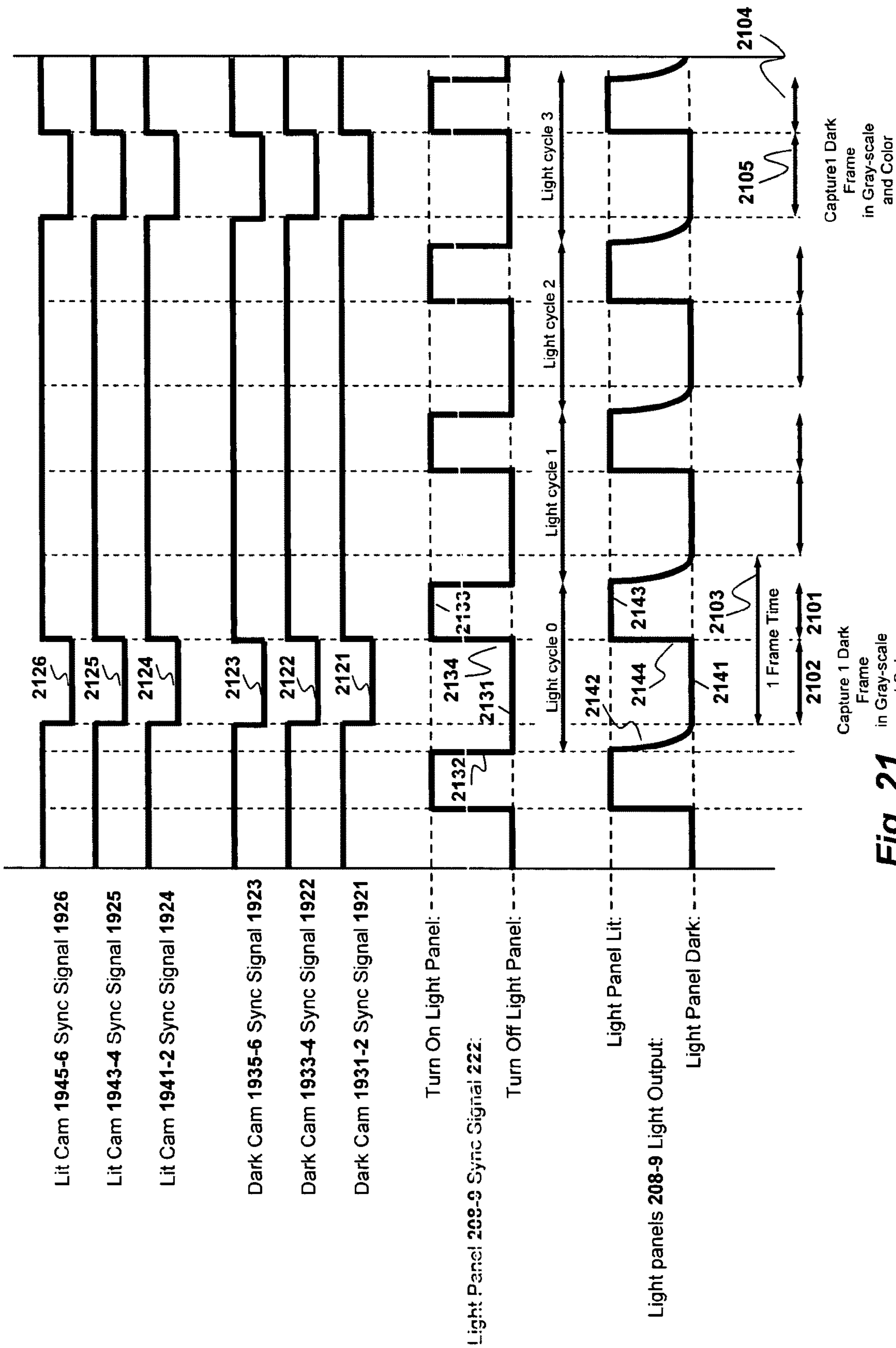

Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
2026
2056
2025
2055
2024
2054
2023
2053
2022
2052
2021
2051
2034
2033
2032
2031
2043
2042
2044
2041
2003
2004
2005
2001
2002
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
1 Frame Time
Capture 1 Dark Frame in Gray-scale
Capture 1 Lit Frame in Color

Fig. 20



Lit Cam 1945-6 Sync Signal 1926
Lit Cam 1943-4 Sync Signal 1925
Lit Cam 1941-2 Sync Signal 1924
Dark Cam 1935-6 Sync Signal 1923
Dark Cam 1933-4 Sync Signal 1922
Dark Cam 1931-2 Sync Signal 1921
Turn On Light Panel:
Light Panel 208-9 Sync Signal 222:
Turn Off Light Panel:
Light Panel Lit:
Light panels 208-9 Light Output:
Light Panel Dark:
2126
2125
2124
2123
2122
2121
2132
2134
2131
2133
Light cycle 0
Light cycle 1
Light cycle 2
Light cycle 3
2142
2144
2143
2141
2103
2105
2104
1 Frame Time
2102
2101
Capture 1 Dark Frame in Gray-scale and Color
Capture1 Dark Frame in Gray-scale and Color

Fig. 21

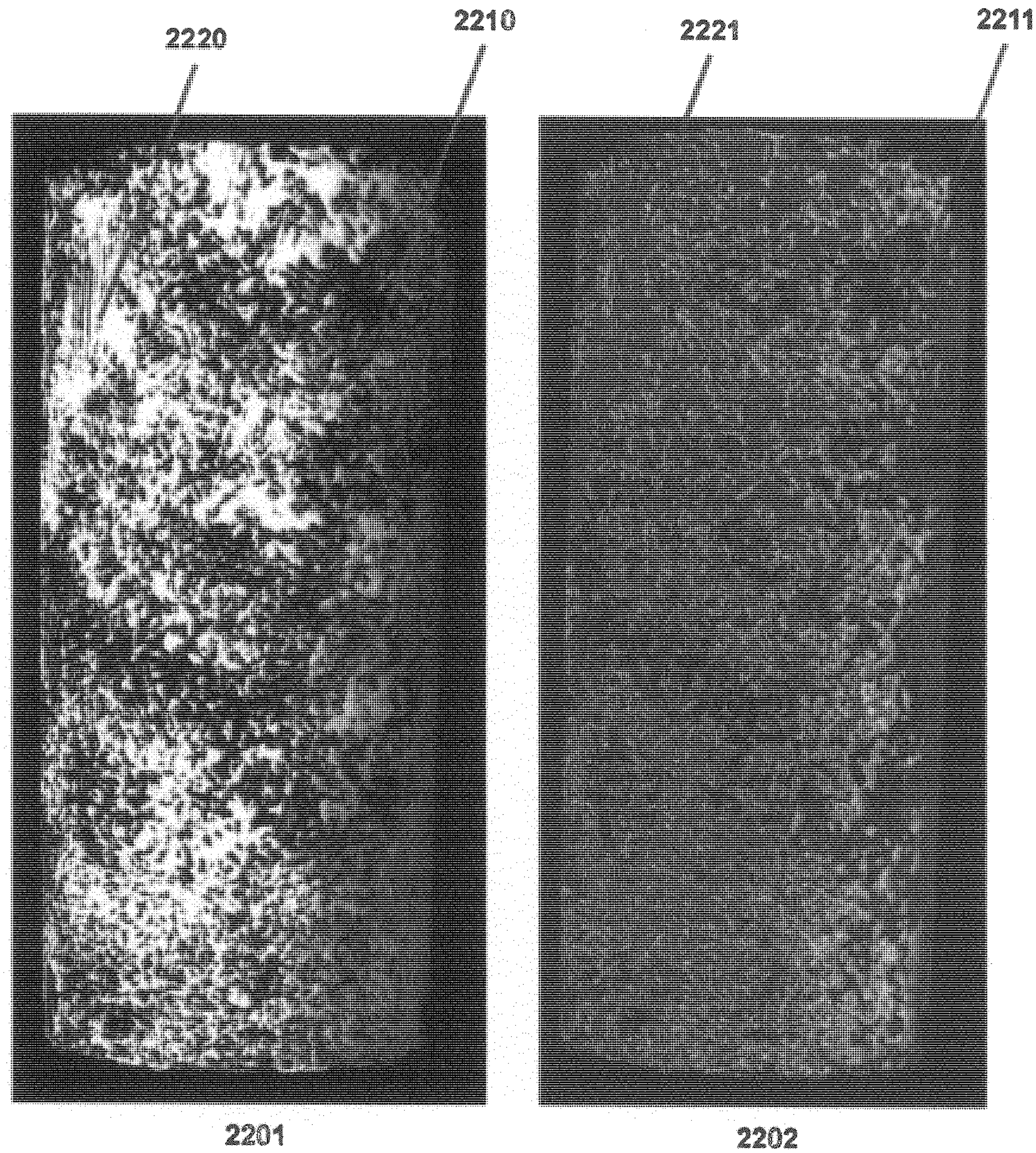


Fig. 22

Weighting as function of distance from surface

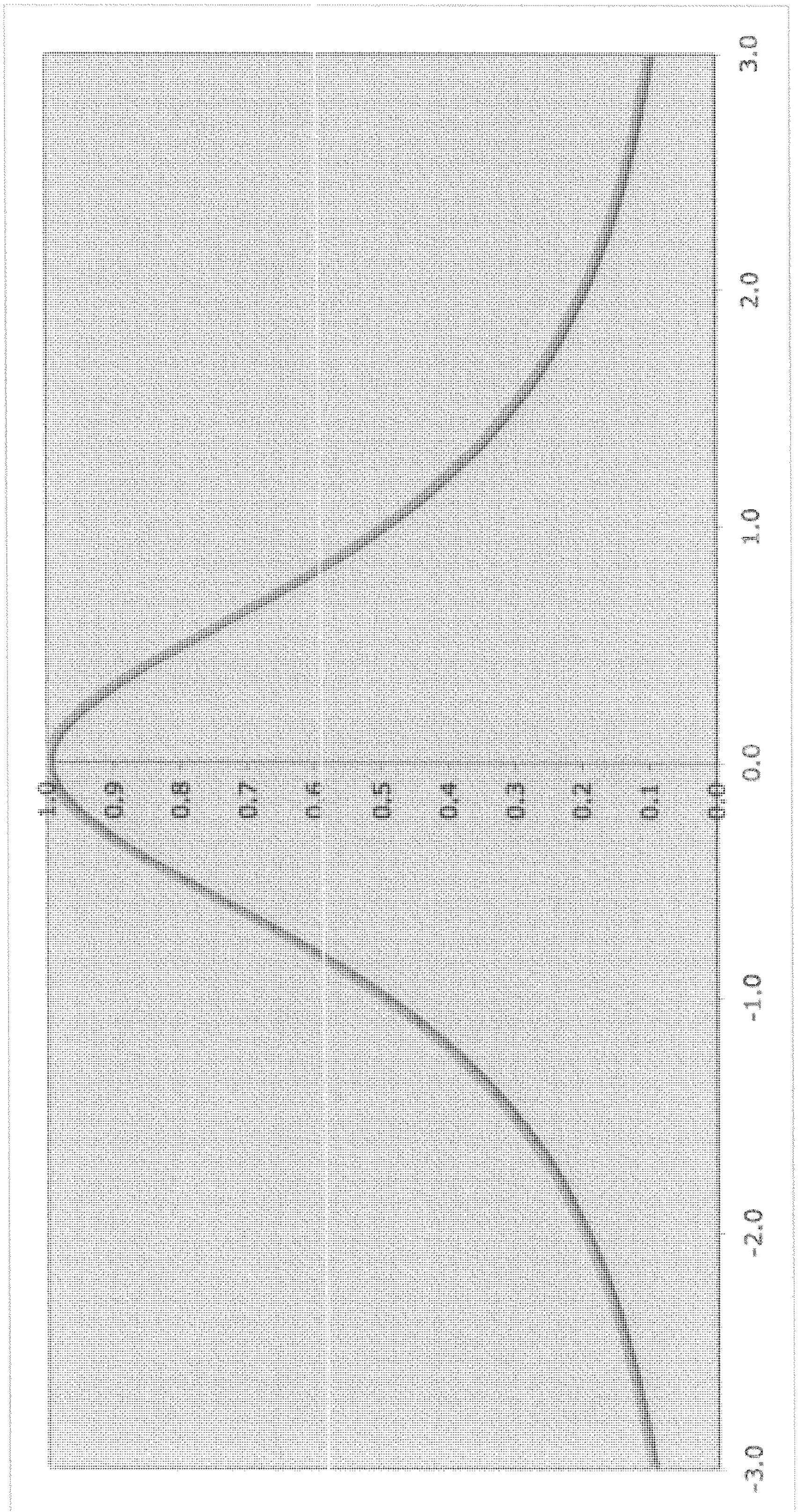
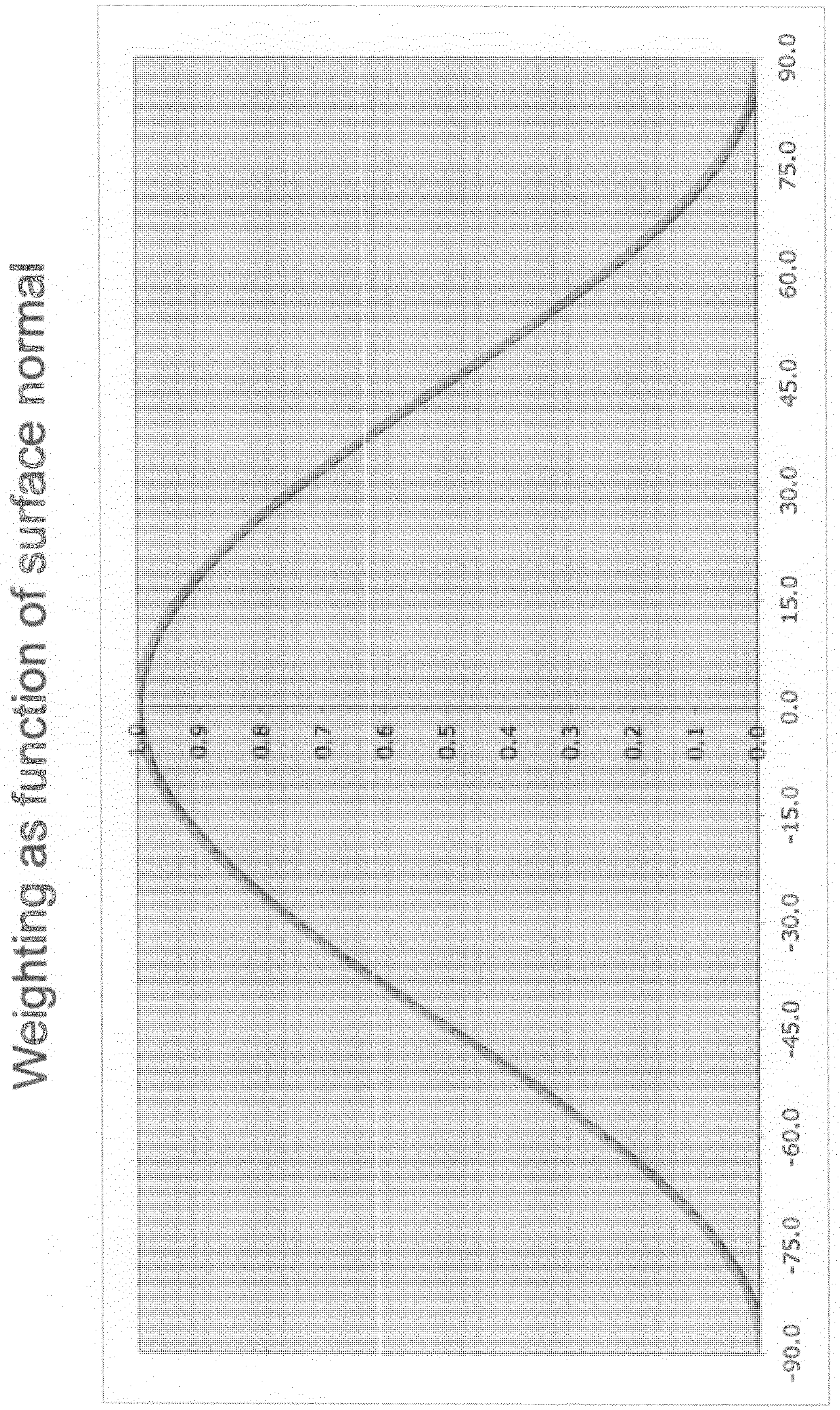


Fig. 23



Weighting as function of surface normal
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-90.0
-75.0
-60.0
-45.0
-30.0
-15.0
0.0
15.0
30.0
45.0
60.0
75.0
90.0

Fig. 24

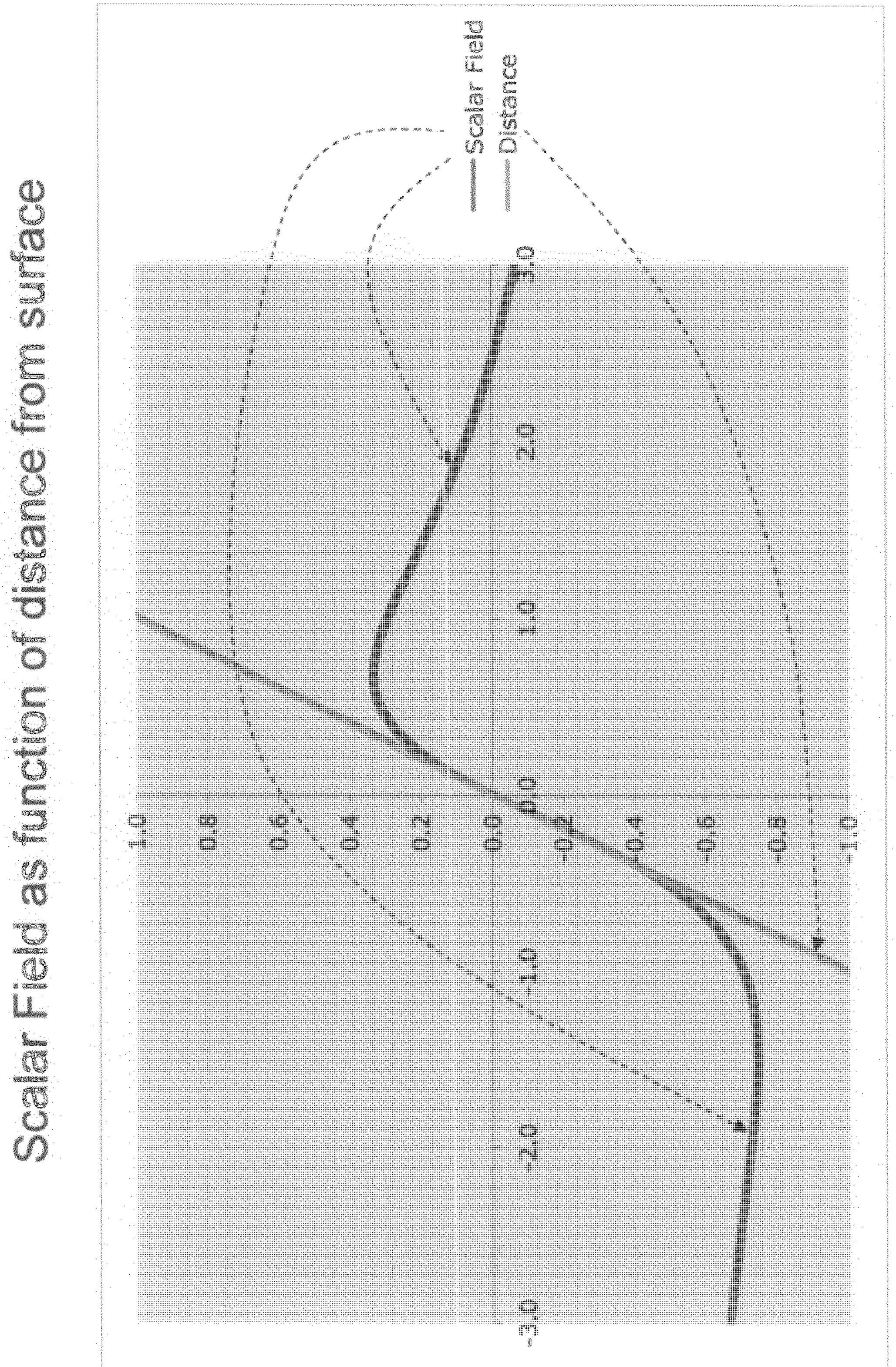

Scalar Field as function of distance from surface
Scalar Field
Distance
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0

Fig. 25

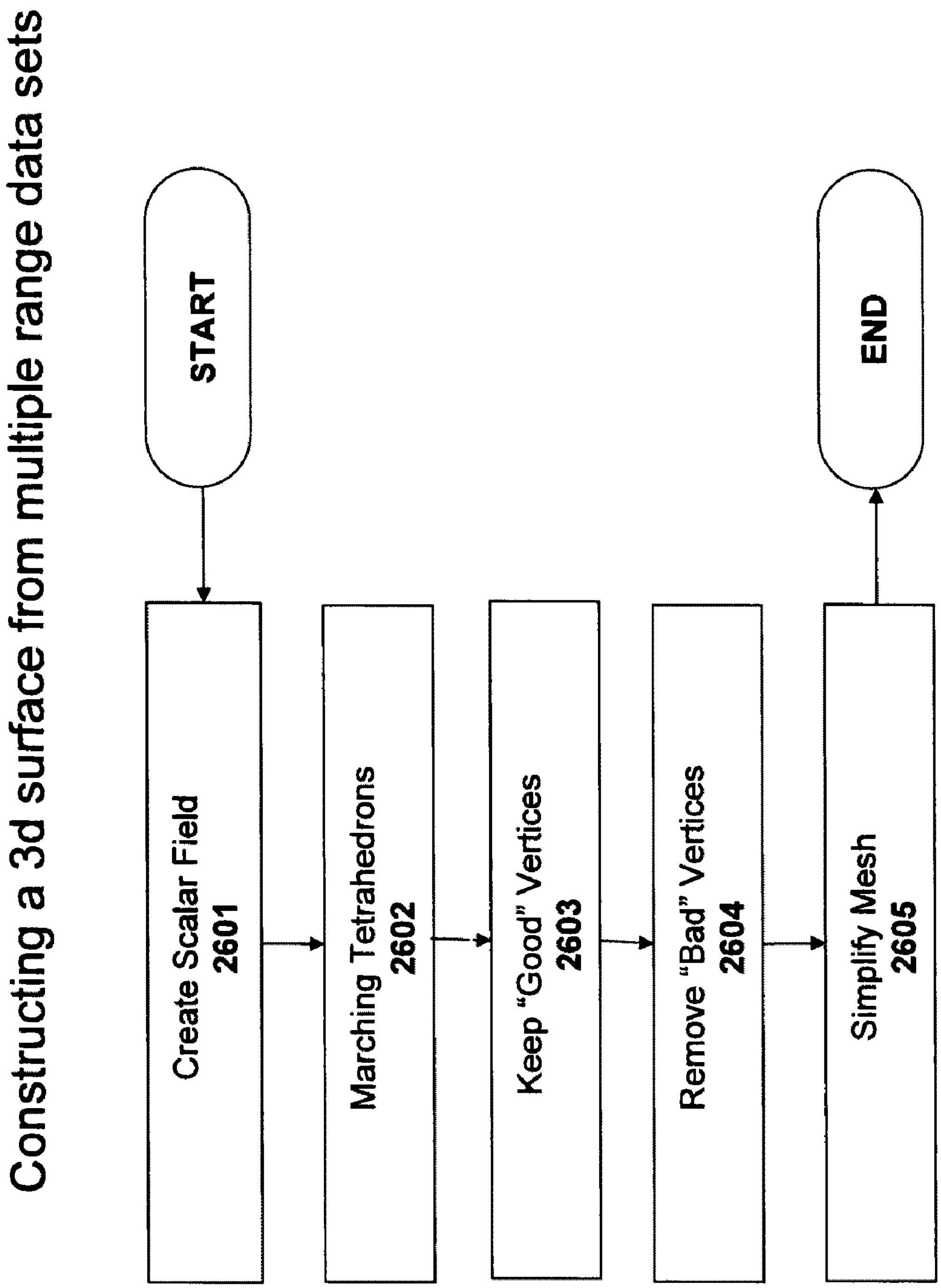

Constructing a 3d surface from multiple range data sets
START
Create Scalar Field
2601
Marching Tetrahedrons
2602
Keep "Good" Vertices
2603
Remove "Bad" Vertices
2604
Simplify Mesh
2605
END

Fig. 26

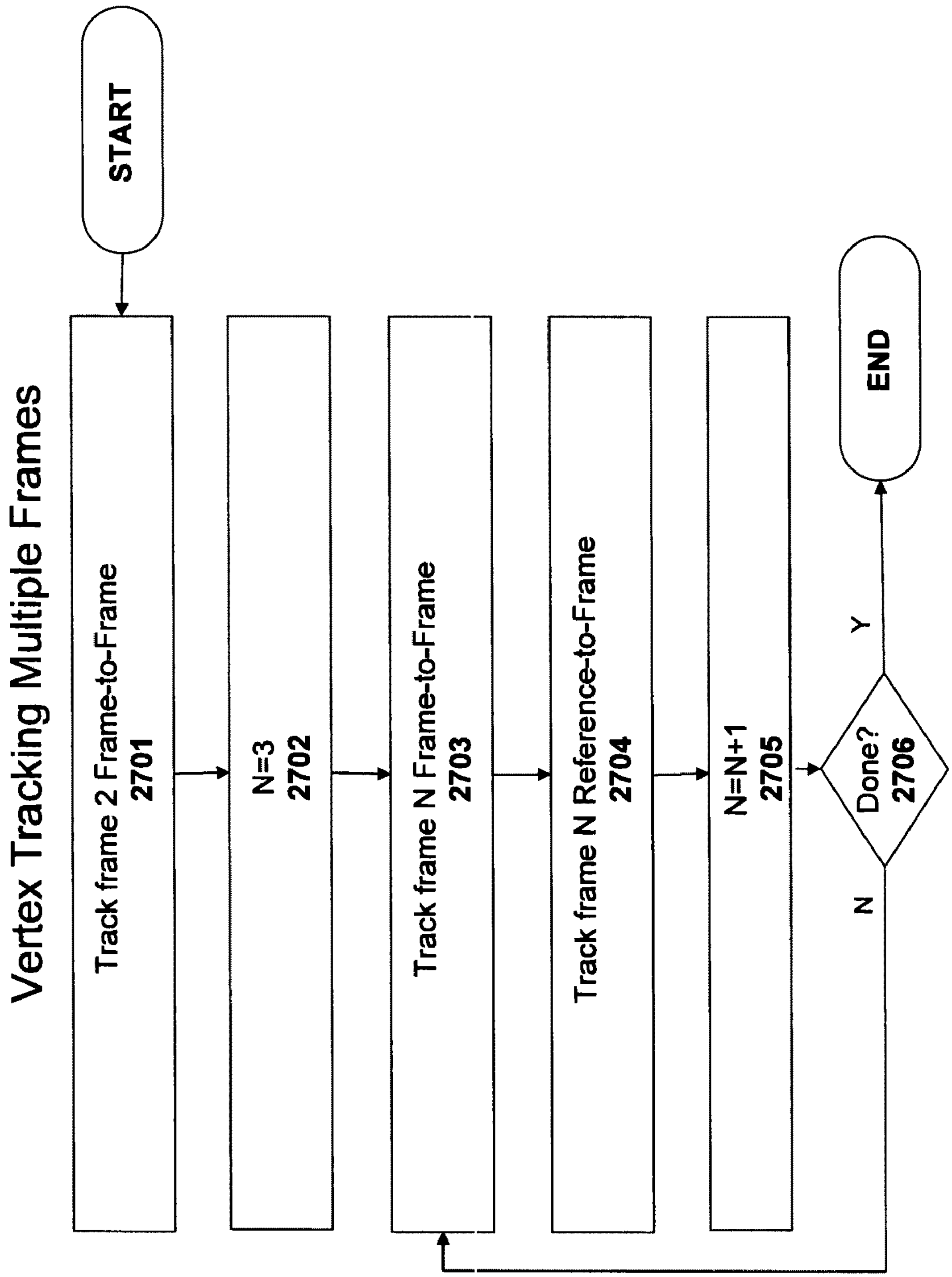

Vertex Tracking Multiple Frames
START
Track frame 2 Frame-to-Frame
2701
N=3
2702
Track frame N Frame-to-Frame
2703
Track frame N Reference-to-Frame
2704
N=N+1
2705
Done?
2706
Y
N
END

Fig. 27

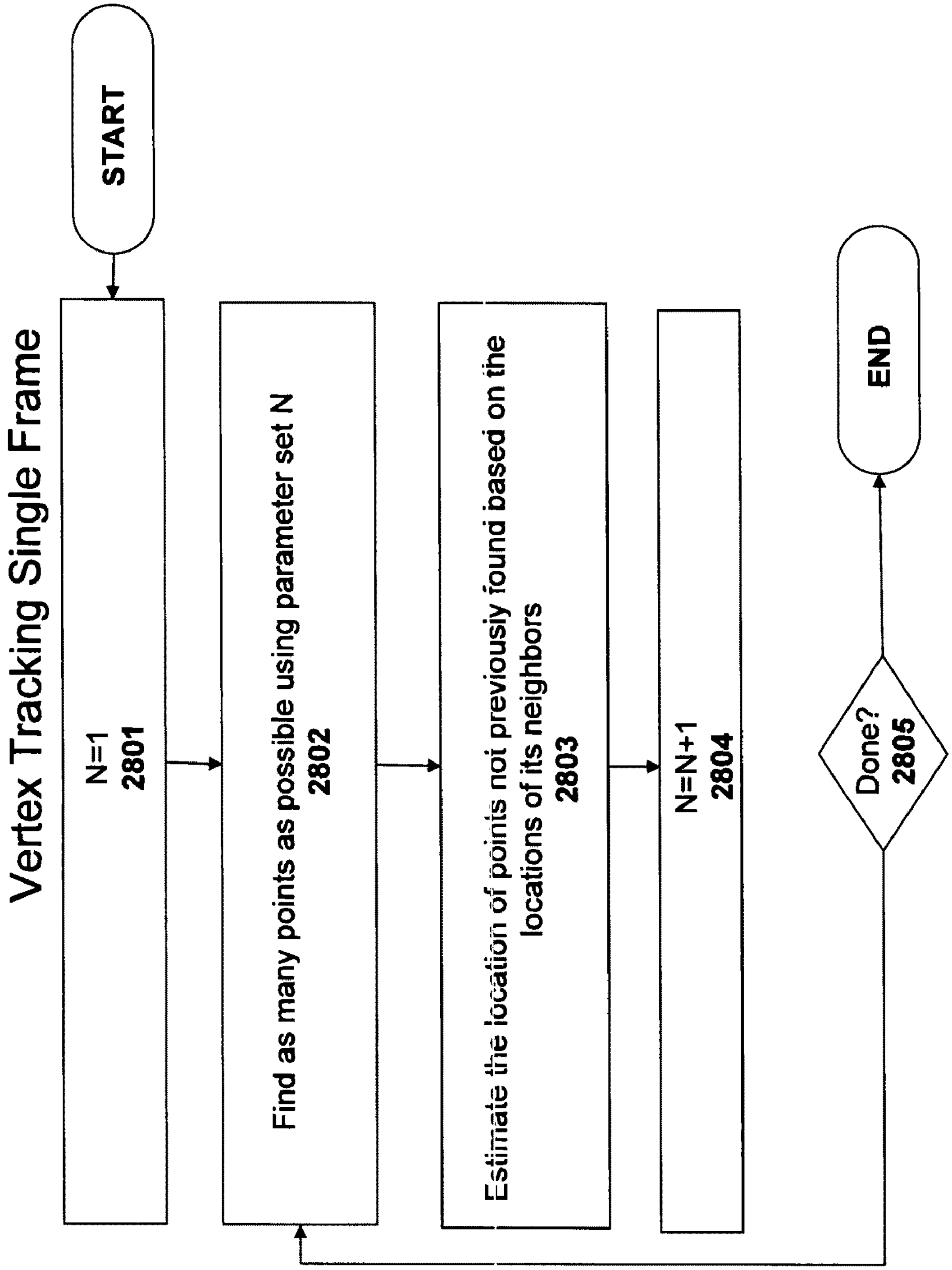

Vertex Tracking Single Frame
START
N=1
2801
Find as many points as possible using parameter set N
2802
Estimate the location of points not previously found based on the locations of its neighbors
2803
N=N+1
2804
Done?
2805
END

Fig. 28

SYSTEM AND METHOD FOR PERFORMING MOTION CAPTURE AND IMAGE RECONSTRUCTION

PRIORITY CLAIM

This application claims the benefit of U.S. Provisional Application No. 60/834,771 entitled, "System and Method For Performing Motion", filed on Jul. 31, 2006.

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent publication with color drawing(s) will be provided by the U.S. Patent and Trademark Office upon request and payment of the necessary fee.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of motion capture. More particularly, the invention relates to an improved apparatus and method for performing motion capture and image reconstruction.

2. Description of the Related Art

"Motion capture" refers generally to the tracking and recording of human and animal motion. Motion capture systems are used for a variety of applications including, for example, video games and computer-generated movies. In a typical motion capture session, the motion of a "performer" is captured and translated to a computer-generated character.

As illustrated in FIG. **1** in a motion capture system, a plurality of motion tracking "markers" (e.g., markers **101**, **102**) are attached at various points on a performer's **100**'s body. The points are selected based on the known limitations of the human skeleton. Different types of motion capture markers are used for different motion capture systems. For example, in a "magnetic" motion capture system, the motion markers attached to the performer are active coils which generate measurable disruptions x, y, z and yaw, pitch, roll in a magnetic field.

By contrast, in an optical motion capture system, such as that illustrated in FIG. **1**, the markers **101**, **102** are passive spheres comprised of retro-reflective material, i.e., a material which reflects light back in the direction from which it came, ideally over a wide range of angles of incidence. A plurality of cameras **120**, **121**, **122**, each with a ring of LEDs **130**, **131**, **132** around its lens, are positioned to capture the LED light reflected back from the retro-reflective markers **101**, **102** and other markers on the performer. Ideally, the retro-reflected LED light is much brighter than any other light source in the room. Typically, a thresholding function is applied by the cameras **120**, **121**, **122** to reject all light below a specified level of brightness which, ideally, isolates the light reflected off of the reflective markers from any other light in the room and the cameras **120**, **121**, **122** only capture the light from the markers **101**, **102** and other markers on the performer.

A motion tracking unit **150** coupled to the cameras is programmed with the relative position of each of the markers **101**, **102** and/or the known limitations of the performer's body. Using this information and the visual data provided from the cameras **120-122**, the motion tracking unit **150** generates artificial motion data representing the movement of the performer during the motion capture session.

A graphics processing unit **152** renders an animated representation of the performer on a computer display **160** (or similar display device) using the motion data. For example, the graphics processing unit **152** may apply the captured motion of the performer to different animated characters and/or to include the animated characters in different computer-generated scenes. In one implementation, the motion tracking unit **150** and the graphics processing unit **152** are programmable cards coupled to the bus of a computer (e.g., such as the PCI and AGP buses found in many personal computers). One well known company which produces motion capture systems is Motion Analysis Corporation (see, e.g., www.motionanalysis.com).

SUMMARY

A system and method are described for performing motion capture on a subject using fluorescent lamps. For example, a system according to one embodiment of the invention comprises: a synchronization signal generator to generate one or more synchronization signals; one or more fluorescent lamps configured to strobe on and off responsive to a first one of the one or more synchronization signals, the fluorescent lamps charging phosphorescent makeup, paint or dye applied to a subject for a motion capture session; and a plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture images of the phosphorescent paint, wherein the shutters are open when the light source is off and the shutters are closed when the light source is on.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention can be obtained from the following detailed description in conjunction with the drawings, in which:

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent publication with color drawing(s) will be provided by the U.S. Patent and Trademark Office upon request and payment of the necessary fee.

FIG. **1** illustrates a prior art motion tracking system for tracking the motion of a performer using retro-reflective markers and cameras.

FIG. **2***a* illustrates one embodiment of the invention during a time interval when the light panels are lit.

FIG. **2***b* illustrates one embodiment of the invention during a time interval when the light panels are dark.

FIG. **3** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **4** is images of heavily-applied phosphorescent makeup on a model during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **5** is images of phosphorescent makeup mixed with base makeup on a model both during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **6** is images of phosphorescent makeup applied to cloth during lit and dark time intervals, as well as the resulting reconstructed 3D surface and textured 3D surface.

FIG. **7***a* illustrates a prior art stop-motion animation stage.

FIG. **7***b* illustrates one embodiment of the invention where stop-motion characters and the set are captured together.

FIG. **7***c* illustrates one embodiment of the invention where the stop-motion set is captured separately from the characters.

FIG. **7***d* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **7***e* illustrates one embodiment of the invention where a stop-motion character is captured separately from the set and other characters.

FIG. **8** is a chart showing the excitation and emission spectra of ZnS:Cu phosphor as well as the emission spectra of certain fluorescent and LED light sources.

FIG. **9** is an illustration of a prior art fluorescent lamp.

FIG. **10** is a circuit diagram of a prior art fluorescent lamp ballast as well as one embodiment of a synchronization control circuit to modify the ballast for the purposes of the present invention.

FIG. **11** is oscilloscope traces showing the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **12** is oscilloscope traces showing the decay curve of the light output of a fluorescent lamp driven by a fluorescent lamp ballast modified by the synchronization control circuit of FIG. **9**.

FIG. **13** is a illustration of the afterglow of a fluorescent lamp filament and the use of gaffer's tape to cover the filament.

FIG. **14** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **15** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **16** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **17** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **18** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **19** illustrates one embodiment: of the camera, light panel, and synchronization subsystems of the invention during a time interval when the light panels are lit.

FIG. **20** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **21** is a timing diagram illustrating the synchronization between the light panels and the shutters according to one embodiment of the invention.

FIG. **22** illustrates one embodiment of the invention where color is used to indicate phosphor brightness.

FIG. **23** illustrates weighting as a function of distance from surface.

FIG. **24** illustrates weighting as a function of surface normal.

FIG. **25** illustrates scalar field as a function of distance from surface

FIG. **26** illustrates one embodiment of a process for constructing a 3-D surface from multiple range data sets.

FIG. **27** illustrates one embodiment of a method for vertex tracking for multiple frames.

FIG. **28** illustrates one embodiment of a method for vertex tracking of a single frame.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Described below is an improved apparatus and method for performing motion capture using shutter synchronization and/or phosphorescent makeup, paint or dye. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form to avoid obscuring the underlying principles of the invention.

The assignee of the present application previously developed a system for performing color-coded motion capture and a system for performing motion capture using a series of reflective curves painted on a performer's face. These systems are described in the co-pending applications entitled "Apparatus and Method for Capturing the Motion and/or Expression of a Performer," Ser. Nos. 10/942,609, and 10/942,413, filed Sep. 15, 2004. These applications are assigned to the assignee of the present application and are incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture of random patterns applied to surfaces. This system is described in the co-pending applications entitled "Apparatus and Method for Performing Motion Capture Using A Random Pattern On Capture Surfaces," Ser. No. 11/255,854, Filed Oct. 20, 2005. This application is assigned to the assignee of the present application and is incorporated herein by reference.

The assignee of the present application also previously developed a system for performing motion capture using shutter synchronization and phosphorescent paint. This system is described in the co-pending application entitled "Apparatus and Method for Performing Motion Capture Using Shutter Synchronization," Ser. No. 11/077,628, Filed Mar. 10, 2005 (hereinafter "Shutter Synchronization" application). Briefly, in the Shutter Synchronization application, the efficiency of the motion capture system is improved by using phosphorescent paint or makeup and by precisely controlling synchronization between the motion capture cameras' shutters and the illumination of the painted curves. This application is assigned to the assignee of the present application and is incorporated herein by reference.

System Overview

As described in these co-pending applications, by analyzing curves or random patterns applied as makeup on a performer's face rather than discrete marked points or markers on a performer's face, the motion capture system is able to generate significantly more surface data than traditional marked point or marker-based tracking systems. The random patterns or curves are painted on the face of the performer using retro-reflective, non-toxic paint or theatrical makeup. In one embodiment of the invention, non-toxic phosphorescent makeup is used to create the random patterns or curves. By utilizing phosphorescent paint or makeup combined with synchronized lights and camera shutters, the motion capture system is able to better separate the patterns applied to the performer's face from the normally-illuminated image of the face or other artifacts of normal illumination such as highlights and shadows.

FIGS. **2***a* and **2***b* illustrate an exemplary motion capture system described in the co-pending applications in which a random pattern of phosphorescent makeup is applied to a performer's face and motion capture is system is operated in a light-sealed space. When the synchronized light panels **208**-**209** are on as illustrated FIG. **2***a*, the performers' face looks as it does in image **202** (i.e. the phosphorescent makeup is only slightly visible). When the synchronized light panels **208**-**209** (e.g. LED arrays) are off as illustrated in FIG. **2***b*, the performers' face looks as it does in image **203** (i.e. only the glow of the phosphorescent makeup is visible).

Grayscale dark cameras **204-205** are synchronized to the light panels **208-209** using the synchronization signal generator PCI Card **224** (an exemplary PCI card is a PCI-6601 manufactured by National Instruments of Austin, Tex.) coupled to the PCI bus of synchronization signal generator PC **220** that is coupled to the data processing system **210** and so that all of the systems are synchronized together. Light Panel Sync signal **222** provides a TTL-level signal to the light panels **208-209** such that when the signal **222** is high (i.e. ≧2.0V), the light panels **208-209** turn on, and when the signal **222** is low (i.e. ≦0.8V), the light panels turn off. Dark Cam Sync signal **221** provides a TTL-level signal to the grayscale dark cameras **204-205** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller PCs **205**. The synchronization timing (explained in detail below) is such that the (camera **204-205** shutters open to capture a frame when the light panels **208-209** are off (the "dark" interval). As a result, grayscale dark cameras **204-205** capture images of only the output of the phosphorescent makeup. Similarly, Lit Cam Sync **223** provides TTL-level signal to color lit cameras **214-215** such that when signal **221** is low the camera **204-205** shutters open and each camera **204-205** captures an image, and when signal **221** is high the shutters close and the cameras transfer the captured images to camera controller computers **225**. Color lit cameras **214-215** are synchronized (as explained in detail below) such that their shutters open to capture a frame when the light panels **208-209** are on (the "lit" interval). As a result, color lit cameras **214-215** capture images of the performers' face illuminated by the light panels.

As used herein, grayscale cameras **204-205** may be referenced as "dark cameras" or "dark cams" because their shutters normally only when the light panels **208-209** are dark. Similarly, color cameras **214-215** may be referenced as "lit cameras" or "lit cams" because normally their shutters are only open when the light panels **208-209** are lit. While grayscale and color cameras are used specifically for each lighting phase in one embodiment, either grayscale or color cameras can be used for either light phase in other embodiments.

In one embodiment, light panels **208-209** are flashed rapidly at 90 flashes per second (as driven by a 90 Hz square wave from Light Panel Sync signal **222**), with the cameras **204-205** and **214-205** synchronized to them as previously described. At 90 flashes per second, the light panels **208-209** are flashing at a rate faster than can be perceived by the vast majority of humans, and as a result, the performer (as well as any observers of the motion capture session) perceive the room as being steadily illuminated and are unaware of the flashing, and the performer is able to proceed with the performance without distraction from the flashing light panels **208-209**.

As described in detail in the co-pending applications, the images captured by cameras **204-205** and **214-215** are recorded by camera controllers **225** (coordinated by a centralized motion capture controller **206**) and the images and images sequences so recorded are processed by data processing system **210**. The images from the various grayscale dark cameras are processed so as to determine the geometry of the 3D surface of the face **207**. Further processing by data processing system **210** can be used to map the color lit images captured onto the geometry of the surface of the face **207**. Yet further processing by the data processing system **210** can be used to track surface points on the face from frame-to-frame.

In one embodiment, each of the camera controllers **225** and central motion capture controller **206** is implemented using a separate computer system. Alternatively, the camera controllers and motion capture controller may be implemented as software executed on a single computer system or as any combination of hardware and software. In one embodiment, the camera controller computers **225** are rack-mounted computers, each using a 945GT Speedster-A4R motherboard from MSI Computer Japan Co., Ltd. (C&K Bldg. 6F 1-17-6, Higashikanda, Chiyoda-ku, Tokyo 101-0031 Japan) with 2 Gbytes of random access memory (RAM) and a 2.16 GHz Intel Core Duo central processing unit from Intel Corporation, and a 300 GByte SATA hard disk from Western Digital, Lake Forest Calif. The cameras **204-205** and **214-215** interface to the camera controller computers **225** via IEEE 1394 cables.

In another embodiment the central motion capture controller **206** also serves as the synchronization signal generator PC **220**. In yet another embodiment the synchronization signal generator PCI card **224** is replaced by using the parallel port output of the synchronization signal generator PC **220**. In such an embodiment, each of the TTL-level outputs of the parallel port are controlled by an application running on synchronization signal generator PC **220**, switching each TTL-level output to a high state or a low state in accordance with the desired signal timing. For example, bit **0** of the PC **220** parallel port is used to drive synchronization signal **221**, bit **1** is used to drive signal **222**, and bit **2** is used to drive signal **224**. However, the underlying principles of the invention are not limited to any particular mechanism for generating the synchronization signals.

The synchronization between the light sources and the cameras employed in one embodiment of the invention is illustrated in FIG. **3**. In this embodiment, the Light Panel and Dark Cam Sync signals **221** and **222** are in phase with each other, while the Lit Cam Sync Signal **223** is the inverse of signals **221**/**222**. In one embodiment, the synchronization signals cycle between 0 to 5 Volts. In response to the synchronization signal **221** and **223**, the shutters of the cameras **204-205** and **214-215**, respectively, are periodically opened and closed as shown in FIG. **3**. In response to sync signal **222**, the light panels are periodically turned off and on, respectively as shown in FIG. **3**. For example, on the falling edge **314** of sync signal **223** and on the rising edges **324** and **334** of sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are opened and the dark camera **204-215** shutters are closed and the light panels are illuminated as shown by rising edge **344**. The shutters remain in their respective states and the light panels remain illuminated for time interval **301**. Then, on the rising edge **312** of sync signal **223** and falling edges **322** and **332** of the sync signals **221** and **222**, respectively, the lit camera **214-215** shutters are closed, the dark camera **204-215** shutters are opened and the light panels are turned off as shown by falling edge **342**. The shutters and light panels are left in this state for time interval **302**. The process then repeats for each successive frame time interval **303**.

As a result, during the first time interval **301**, a normally-lit image is captured by the color lit cameras **214-215**, and the phosphorescent makeup is illuminated (and charged) with light from the light panels **208-209**. During the second time interval **302**, the light is turned off and the grayscale dark cameras **204-205** capture an image of the glowing phosphorescent makeup on the performer. Because the light panels are off during the second time interval **302**, the contrast between the phosphorescent makeup and any surfaces in the room without phosphorescent makeup is extremely high (i.e., the rest of the room is pitch black or at least quite dark, and as a result there is no significant light reflecting off of surfaces in the room, other than reflected light from the phosphorescent emissions), thereby improving the ability of the system to differentiate the various patterns applied to the performer's face. In addition, because the light panels are on half of the time, the performer will be able to see around the room during the performance, and also the phosphorescent makeup is constantly recharged. The frequency of the synchronization signals is 1/(time interval **303**) and may be set at such a high rate that the performer will not even notice that the light panels are being turned on and off. For example, at a flashing rate of 90 Hz or above, virtually all humans are unable to perceive that a light is flashing and the light appears to be continuously illuminated. In psychophysical parlance, when a high frequency flashing light is perceived by humans to be continuously illuminated, it is said that "fusion" has been achieved. In one embodiment, the light panels are cycled at 120 Hz; in another embodiment, the light panels are cycled at 140 Hz, both frequencies far above the fusion threshold of any human. However, the underlying principles of the invention are not limited to any particular frequency.

Surface Capture of Skin Using Phosphorescent Random Patterns

FIG. **4** shows images captured using the methods described above and the 3D surface and textured 3D surface reconstructed from them. Prior to capturing the images, a phosphorescent makeup was applied to a Caucasian model's face with an exfoliating sponge. Luminescent zinc sulfide with a copper activator (ZnS:Cu) is the phosphor responsible for the makeup's phosphorescent properties. This particular formulation of luminescent Zinc Sulfide is approved by the FDA color additives regulation 21 CFR Part 73 for makeup preparations. The particular brand is Fantasy F/XT Tube Makeup; Product #: FFX; Color Designation: GL; manufactured by Mehron Inc. of 100 Red Schoolhouse Rd. Chestnut Ridge, N.Y. 10977. The motion capture session that produced these images utilized 8 grayscale dark cameras (such as cameras **204-205**) surrounding the model's face from a plurality, of angles and 1 color lit camera (such as cameras **214-215**) pointed at the model's face from an angle to provide the view seen in Lit Image **401**. The grayscale cameras were model A311 f from Basler A G, An der Strusbek 60-62, 22926 Ahrensburg, Germany, and the color camera was a Basler model A311fc. The light panels **208-209** were flashed at a rate of 72 flashes per second.

Lit Image **401** shows an image of the performer captured by one of the color lit cameras **214-215** during lit interval **301**, when the light panels **208-209** are on and the color lit camera **214-215** shutters are open. Note that the phosphorescent makeup is quite visible on the performer's face, particularly the lips.

Dark Image **402** shows an image of the performer captured by one of the grayscale dark cameras **204-205** during dark interval **302**, when the light panels **208-209** are off and the grayscale dark camera **204-205** shutters are open. Note that only random pattern of phosphorescent makeup is visible on the surfaces where it is applied. All other surfaces in the image, including the hair, eyes, teeth, ears and neck of the performer are completely black.

3D Surface **403** shows a rendered image of the surface reconstructed from the Dark Images **402** from grayscale dark cameras **204-205** (in this example, 8 grayscale dark cameras were used, each producing a single Dark Image **402** from a different angle) pointed at the model's face from a plurality of angles. One reconstruction process which may be used to create this image is detailed in co-pending application Apparatus and Method for Performing Motion Capture Using A Random Pattern On Capture Surfaces, Ser. No. 11/255,854, Filed Oct. 20, 2005. Note that 3D Surface **403** was only reconstructed from surfaces where there was phosphorescent makeup applied. Also, the particular embodiment of the technique that was used to produce the 3D Surface **403** fills in cavities in the 3D surface (e.g., the eyes and the mouth in this example) with a flat surface.

Textured 3D Surface **404** shows the Lit Image **401** used as a texture map and mapped onto 3D Surface **403** and rendered at an angle. Although Textured 3D Surface **404** is a computer-generated 3D image of the model's face, to the human eye it appears real enough that when it is rendered at an angle, such as it is in image **404**, it creates the illusion that the model is turning her head and actually looking at an angle. Note that no phosphorescent makeup was applied to the model's eyes and teeth, and the image of the eyes and teeth are mapped onto flat surfaces that fill those cavities in the 3D surface. Nonetheless, the rest of the 3D surface is reconstructed so accurately, the resulting Textured 3D Surface **404** approaches photorealism. When this process is applied to create successive frames of Textured 3D Surfaces **404**, when the frames are played back in real-time, the level of realism is such that, to the untrained eye, the successive frames look like actual video of the model, even though it is a computer-generated 3D image of the model viewed from side angle.

Since the Textured 3D Surfaces **404** produces computer-generated 3D images, such computer-generated images can manipulated with far more flexibility than actual video captured of the model. With actual video it is often impractical (or impossible) to show the objects in the video from any camera angles other than the angle from which the video was shot. With computer-generated 3D, the image can be rendered as if it is viewed from any camera angle. With actual video it is generally necessary to use a green screen or blue screen to separate an object from its background (e.g. so that a TV meteorologist can be composited in front of a weather map), and then that green- or blue-screened object can only be presented from the point of view of the camera shooting the object. With the technique just described, no green/blue screen is necessary. Phosphorescent makeup, paint, or dye is applied to the areas desired to be captured (e.g. the face, body and clothes of the meteorologist) and then the entire background will be separated from the object. Further, the object can be presented from any camera angle. For example, the meteorologist can be shown from a straight-on shot, or from an side angle shot, but still composited in front of the weather map.

Further, a 3D generated image can be manipulated in 3D. For example, using standard 3D mesh manipulation tools (such as those in Maya, sold by Autodesk, Inc.) the nose can be shortened or lengthened, either for cosmetic reasons if the performer feels her nose would look better in a different size, or as a creature effect, to make the performer look like a fantasy character like Gollum of "Lord of the Rings." More extensive 3D manipulations could add wrinkles to the performers face to make her appear to be older, or smooth out wrinkles to make her look younger. The face could also be manipulated to change the performer's expression, for Example, from a smile to a frown. Although some 2D manipulations are possible with conventional 2D video capture, they are generally limited to manipulations from the point of view of the camera. If the model turns her head during the video sequence, the 2D manipulations applied when the head is facing the camera would have to be changed when the head is turned. 3D manipulations do not need to be changed, regardless of which way the head is turned. As a result, the techniques described above for creating successive frames of Textured 3D Surface **404** in a video sequence make it possible to capture objects that appear to look like actual video, but nonetheless have the flexibility of manipulation as computer-generated 3D objects, offering enormous advantages in production of video, motion pictures, and also video games (where characters may be manipulated by the player in 3D).

Note that in FIG. **4** the phosphorescent makeup is visible on the model's face in Lit Image **401** and appears like a yellow powder has been spread on her face. It is particularly prominent on her lower lip, where the lip color is almost entirely changed from red to yellow. These discolorations appear in Textured 3D Surface **404**, and they would be even more prominent on a dark-skinned model who is, for example, African in race. Many applications (e.g. creating a fantasy 3D character like Gollum) only require 3D Surface **403**, and Textured 3D Surface **404** would only serve as a reference to the director of the motion capture session or as a reference to 3D animators manipulating the 3D Surface **403**. But in some applications, maintaining the actual skin color of the model's skin is important and the discolorations from the phosphorescent makeup are not desirable.

Surface Capture Using Phosphorescent Makeup Mixed with Base

FIG. **5** shows a similar set of images as FIG. **4**, captured and created under the same conditions: with 8 grayscale dark cameras (such as **204-205**), 1 color camera (such as **214-215**), with the Lit Image **501** captured by the color lit camera during the time interval when the Light Array **208-9** is on, and the Dark Image **502** captured by one of the 8 grayscale dark cameras when the Light Array **208-9**. 3D Surface **503** is reconstructed from the 8 Dark Images **502** from the 8 grayscale dark cameras, and Textured 3D Surface **504** is a rendering of the Lit Image **501** texture-mapped onto 3D Surface **503** (and unlike image **404**, image **504** is rendered from a camera angle similar to the camera angle of the color lit camera that captured Lit Image **501**).

However, there is a notable differences between the images of FIG. **5** and FIG. **4**: The phosphorescent makeup that is noticeably visible in Lit Image **401** and Textured 3D Surface **404** is almost invisible in Lit Image **501** and Textured 3D Surface **504**. The reason for this is that, rather than applying the phosphorescent makeup to the model in its pure form, as was done in the motion capture session of FIG. **4**, in the embodiment illustrated in FIG. **5** the phosphorescent makeup was mixed with makeup base and was then applied to the model. The makeup base used was "Clean Makeup" in "Buff Beige" color manufactured by Cover Girl, and it was mixed with the same phosphorescent makeup used in the FIG. **4** shoot in a proportion of 80% phosphorescent makeup and 20% base makeup.

Note that mixing the phosphorescent makeup with makeup base does reduce the brightness of the phosphorescence during the Dark interval **302**. Despite this, the phosphorescent brightness is still sufficient to produce Dark Image **502**, and there is enough dynamic range in the dark images from the 8 grayscale dark cameras to reconstruct 3D Surface **503**. As previously noted, some applications do not require an accurate capture of the skin color of the model, and in that case it is advantageous to not mix the phosphorescent makeup with base, and then get the benefit of higher phosphorescent brightness during the Dark interval **302** (e.g. higher brightness allows for a smaller aperture setting on the camera lens, which allows for larger depth of field). But some applications do require an accurate capture of the skin color of the model. For such applications, it is advantageous to mix the phosphorescent makeup with base (in a color suited for the model's skin tone) makeup, and work within the constraints of lower phosphorescent brightness. Also, there are applications where some phosphor visibility is acceptable, but not the level of visibility seen in Lit Image **401**. For such applications, a middle ground can be found in terms of skin color accuracy and phosphorescent brightness by mixing a higher percentage of phosphorescent makeup relative to the base.

In another embodiment, luminescent zinc sulfide (ZnS:Cu) in its raw form is mixed with base makeup and applied to the model's face.

Surface Capture of Fabric with Phosphorescent Random Patterns

In another embodiment, the techniques described above are used to capture cloth. FIG. **6** shows a capture of a piece of cloth (part of a silk pajama top) with the same phosphorescent makeup used in FIG. **4** sponged onto it. The capture was done under the exact same conditions with 8 grayscale dark cameras (such as **204-205**) and 1 color lit camera (such as **214-215**). The phosphorescent makeup can be seen slightly discoloring the surface of Lit Frame **601**, during lit interval **301**, but it can be seen phosphorescing brightly in Dark Frame **602**, during dark interval **302**. From the 8 cameras of Dark Frame **602**, 3D Surface **603** is reconstructed using the same techniques used for reconstructing the 3D Surfaces **403** and **503**. And, then Lit Image **601** is texture-mapped onto 3D Surface **603** to produce Textured 3D Surface **604**.

FIG. **6** shows a single frame of captured cloth, one of hundreds of frames that were captured in a capture session while the cloth was moved, folded and unfolded. And in each frame, each area of the surface of the cloth was captured accurately, so long as at least 2 of the 8 grayscale cameras had a view of the area that was not overly oblique (e.g. the camera optical axis was within 30 degrees of the area's surface normal). In some frames, the cloth was contorted such that there were areas within deep folds in the cloth (obstructing the light from the light panels **208-209**), and in some frames the cloth was curved such that there were areas that reflected back the light from the light panels **208-209** so as to create a highlight (i.e. the silk fabric was shiny). Such lighting conditions would make it difficult, if not impossible, to accurately capture the surface of the cloth using reflected light during lit interval **301** because shadow areas might be too dark for an accurate capture (e.g. below the noise floor of the camera sensor) and some highlights might be too bright for an accurate capture (e.g. oversaturating the sensor so that it reads the entire area as solid white). But, during the dark interval **302**, such areas are readily captured accurately because the phosphorescent makeup emits light quite uniformly, whether deep in a fold or on an external curve of the cloth.

Because the phosphor charges from any light incident upon it, including diffused or reflected light that is not directly from the light panels **208-209**, even phosphor within folds gets charged (unless the folds are so tightly sealed no light can get into them, but in such cases it is unlikely that the cameras can see into the folds anyway). This illustrates a significant advantage of utilizing phosphorescent makeup (or paint or dye) for creating patterns on (or infused within) surfaces to be captured: the phosphor is emissive and is not subject to highlights and shadows, producing a highly uniform brightness level for the patterns seen by the grayscale dark cameras **204-205**, that neither has areas too dark nor areas too bright.

Another advantage of dyeing or painting a surface with phosphorescent dye or paint, respectively, rather than applying phosphorescent makeup to the surface is that with dye or paint the phosphorescent pattern on the surface can be made permanent throughout a motion capture session. Makeup, by its nature, is designed to be removable, and a performer will normally remove phosphorescent makeup at the end of a day's motion capture shoot, and if not, almost certainly before going to bed. Frequently, motion capture sessions extend across several days, and as a result, normally a fresh application of phosphorescent makeup is applied to the performer each day prior to the motion capture shoot. Typically, each fresh application of phosphorescent makeup will result in a different random pattern. One of the techniques disclosed in co-pending applications is the tracking of vertices ("vertex tracking") of the captured surfaces. Vertex tracking is accomplished by correlating random patterns from one captured frame to the next. In this way, a point on the captured surface can be followed from frame-to-frame. And, so long as the random patterns on the surface stay the same, a point on a captured surface even can be tracked from shot-to-shot. In the case of random patterns made using phosphorescent makeup, it is typically practical to leave the makeup largely undisturbed (although it is possible for some areas to get smudged, the bulk of the makeup usually stays unchanged until removed) during one day's-worth of motion capture shooting, but as previously mentioned it normally is removed at the end of the day. So, it is typically impractical to maintain the same phosphorescent random pattern (and with that, vertex tracking based on tracking a particular random pattern) from day-to-day. But when it comes to non-skin objects like fabric, phosphorescent dye or paint can be used to create a random pattern. Because dye and paint are essentially permanent, random patterns will not get smudged during the motion capture session, and the same random patterns will be unchanged from day-to-day. This allows vertex tracking of dyed or painted objects with random patterns to track the same random pattern through the duration of a multi-day motion capture session (or in fact, across multiple motion capture sessions spread over long gaps in time if desired).

Skin is also subject to shadows and highlights when viewed with reflected light. There are many concave areas (e.g., eye sockets) that often are shadowed. Also, skin may be shiny and cause highlights, and even if the skin is covered with makeup to reduce its shininess, performers may sweat during a physical performance, resulting in shininess from sweaty skin. Phosphorescent makeup emits uniformly both from shiny and matte skin areas, and both from convex areas of the body (e.g. the nose bridge) and concavities (e.g. eye sockets). Sweat has little impact on the emission brightness of phosphorescent makeup. Phosphorescent makeup also charges while folded up in areas of the body that fold up (e.g. eyelids) and when it unfolds (e.g. when the performer blinks) the phosphorescent pattern emits light uniformly.

Returning back to FIG. **6**, note that the phosphorescent makeup can be seen on the surface of the cloth in Lit Frame **601** and in Textured 3D Surface **604**. Also, while this is not apparent in the images, although it may be when the cloth is in motion, the phosphorescent makeup has a small impact on the pliability of the silk fabric. In another embodiment, instead of using phosphorescent makeup (which of course is formulated for skin application) phosphorescent dye is used to create phosphorescent patterns on cloth. Phosphorescent dyes are available from a number of manufacturers. For example, it is common to find t-shirts at novelty shops that have glow-in-the-dark patterns printed onto them with phosphorescent dyes. The dyes can also can be formulated manually by mixing phosphorescent powder (e.g. ZnS:Cu) with off-the-shelf clothing dyes, appropriate for the given type of fabric. For example, Dharma Trading Company with a store at 1604 Fourth Street, San Rafael, Calif. stocks a large number of dyes, each dye designed for certain fabrics types (e.g. Dharma Fiber Reactive Procion Dye is for all natural fibers, Sennelier Tinfix Design—French Silk Dye is for silk and wool), as well as the base chemicals to formulate such dyes. When phosphorescent powder is used as the pigment in such formulations, then a dye appropriate for a given fabric type is produced and the fabric can be dyed with phosphorescent pattern while minimizing the impact on the fabric's pliability.

Surface Capture of Stop-Motion Animation Characters with Phosphorescent Random Patterns

In another embodiment, phosphor is embedded in silicone or a moldable material such as modeling clay in characters, props and background sets used for stop-motion animation. Stop-motion animation is a technique used in animated motion pictures and in motion picture special effects. An exemplary prior art stop-motion animation stage is illustrated in FIG. 7*a*. Recent stop-motion animations are feature films Wallace & Gromit in The Curse of the Were-Rabbit (Academy Award-winning best animated feature film released in 2005) (hereafter referenced as WG) and Corpse Bride (Academy Award-nominated best animated feature film released in 2005) (hereafter referred to as CB). Various techniques are used in stop-motion animation. In WG the characters **702-703** are typically made of modeling clay, often wrapped around a metal armature to give the character structural stability. In CB the characters **702-703** are created from puppets with mechanical armatures which are then covered with molded silicone (e.g. for a face), or some other material (e.g. for clothing). The characters **702-703** in both films are placed in complex sets **701** (e.g. city streets, natural settings, or in buildings), the sets are lit with lights such as **708-709**, a camera such as **705** is placed in position, and then one frame is shot by the camera **705** (in modern stop-motion animation, typically, a digital camera). Then the various characters (e.g. the man with a leash **702** and the dog **703**) that are in motion in the scene are moved very slightly. In the case of WB, often the movement is achieved by deforming the clay (and potentially the armature underneath it) or by changing a detailed part of a character **702-703** (e.g. for each frame swapping in a different mouth shape on a character **702-703** as it speaks). In the case of CB, often motion is achieved by adjusting the character puppet **702-703** armature (e.g. a screwdriver inserted in a character puppet's **702-703** ear might turn a screw that actuates the armature causing the character's **702-703** mouth to open). Also, if the camera **705** is moving in the scene, then the camera **705** is placed on a mechanism that allows it to be moved, and it is moved slightly each frame time. After all the characters **702-703** and the camera **705** in a scene have been moved, another frame is captured by the camera **705**. This painstaking process continues frame-by-frame until the shot is completed.

There are many difficulties with the stop-motion animation process that both limit the expressive freedom of the animators, limit the degree of realism in motion, and add to the time and cost of production. One of these difficulties is animating many complex characters **702-703** within a complex set **701** on a stop-motion animation stage such as that shown in FIG. 7*a*. The animators often need to physically climb into the sets, taking meticulous care not to bump anything inadvertently, and then make adjustments to character **702-703** expressions, often with sub-millimeter precision. When characters **702-703** are very close to each other, it gets even more difficult. Also, sometimes characters **702-703** need to be placed in a pose where a character **702-703** can easily fall over (e.g. a character **702-703** is doing a hand stand or a character **702-**

703 is flying). In these cases the character **702-703** requires some support structure that may be seen by the camera **705**, and if so, needs to be erased from the shot in post-production.

In one embodiment illustrated by the stop-motion animation stage in FIG. **7***b*, phosphorescent phosphor (e.g. zinc sulfide) in powder form can be mixed (e.g. kneaded) into modeling clay resulting in the clay surface phosphorescing in darkness with a random pattern. Zinc sulfide powder also can be mixed into liquid silicone before the silicone is poured into a mold, and then when the silicone dries and solidifies, it has zinc sulfide distributed throughout. In another embodiment, zinc sulfide powder can be spread onto the inner surface of a mold and then liquid silicone can be poured into the mold to solidify (with the zinc sulfide embedded on the surface). In yet another embodiment, zinc sulfide is mixed in with paint that is applied to the surface of either modeling clay or silicone. In yet another embodiment, zinc sulfide is dyed into fabric worn by characters **702-703** or mixed into paint applied to props or sets **701**. In all of these embodiments the resulting effect is that the surfaces of the characters **702-703**, props and sets **701** in the scene phosphoresce in darkness with random surface patterns.

At low concentrations of zinc sulfide in the various embodiments described above, the zinc sulfide is not significantly visible under the desired scene illumination when light panels **208-208** are on. The exact percentage of zinc sulfide depends on the particular material it is mixed with or applied to, the color of the material, and the lighting circumstances of the character **702-703**, prop or set **701**. But, experimentally, the zinc sulfide concentration can be continually reduced until it is no longer visually noticeable in lighting situations where the character **702-703**, prop or set **701** is to be used. This may result in a very low concentration of zinc sulfide and very low phosphorescent emission. Although this normally would be a significant concern with live action frame capture of dim phosphorescent patterns, with stop-motion animation, the dark frame capture shutter time can be extremely long (e.g. 1 second or more) because by definition, the scene is not moving. With a long shutter time, even very dim phosphorescent emission can be captured accurately.

Once the characters **702-703**, props and the set **701** in the scene are thus prepared, they look almost exactly as they otherwise would look under the desired scene illumination when light panels **208-209** are on, but they phosphoresce in random patterns when the light panels **208-209** are turned off. At this point all of the characters **702-703**, props and the set **701** of the stop-motion animation can now be captured 3D using a configuration like that illustrated in FIGS. **2***a* and **2***b* and described in the co-pending applications. (FIGS. **7***b*-**7***e* illustrate stop-motion animation stages with light panels **208-209**, dark cameras **204-205** and lit cameras **214-215** from FIGS. **2***a* and **2***b* surrounding the stop-motion animation characters **702-703** and set **701**. For clarity, the connections to devices **208-209**, **204-205** and **214-215** have been omitted from FIGS. **7***b*-**7***e*, but in they would be hooked up as illustrated in FIGS. **2***a* and **2***b*.) Dark cameras **204-205** and lit cameras **214-215** are placed around the scene illustrated in FIG. **7***b* so as to capture whatever surfaces will be needed to be seen in the final animation. And then, rather than rapidly switching sync signals **221-223** at a high capture frame rate (e.g. 90 fps), the sync signals are switched very slowly, and in fact may be switched by hand.

In one embodiment, the light panels **208-209** are left on while the animators adjust the positions of the characters **702-703**, props or any changes to the set **701**. Note that the light panels **208-209** could be any illumination source, including incandescent lamps, because there is no requirement in stop-motion animation for rapidly turning on and off the illumination source. Once the characters **702-703**, props and set **701** are in position for the next frame, lit cam sync signal **223** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the lit cameras **214-215** capture a frame for a specified duration based on the desired exposure time for the captured frames. In other embodiments, different cameras may have different exposure times based on individual exposure requirements.

Next, light panels **208-209** are turned off (either by sync signal **222** or by hand) and the lamps are allowed to decay until the scene is in complete darkness (e.g. incandescent lamps may take many seconds to decay). Then, dark cam sync signal **221** is triggered (by a falling edge transition in the presently preferred embodiment) and all of the dark cameras **208-209** capture a frame of the random phosphorescent patterns for a specified duration based on the desired exposure time for the captured frames. Once again, different cameras have different exposure times based on individual exposure requirements. As previously mentioned, in the case of very dim phosphorescent emissions, the exposure time may be quite long (e.g., a second or more). The upper limit of exposure time is primarily limited by the noise accumulation of the camera sensors. The captured dark frames are processed by data processing system **210** to produce 3D surface **207** and then to map the images captured by the lit cameras **214-215** onto the 3D surface **207** to create textured 3D surface **217**. Then, the light panels, **208-9** are turned back on again, the characters **702-703**, props and set **701** are moved again, and the process described in this paragraph is repeated until the entire shot is completed.

The resulting output is the successive frames of textured 3D surfaces of all of the characters **702-703**, props and set **701** with areas of surfaces embedded or painted with phosphor that are in view of at least 2 dark cameras **204-205** at a non-oblique angle (e.g., <30 degrees from the optical axis of a camera). When these successive frames are played back at the desired frame rate (e.g., 24 fps), the animated scene will come to life, but unlike frames of a conventional stop-motion animation, the animation will be able to be viewed from any camera position, just by rendering this textured 3D surfaces from a chosen camera position. Also, if the camera position of the final animation is to be in motion during a frame sequence (e.g. if a camera is following a character **702-703**), it is not necessary to have a physical camera moving in the scene. Rather, for each successive frame, the textured 3D surfaces of the scene are simply rendered from the desired camera position for that frame, using a 3D modeling/animation application software such as Maya (from Autodesk, Inc.).

In another embodiment, illustrated in FIGS. **7***c*-**7***e*, some or all of the different characters **702-703**, props, and/or sets **701** within a single stop-motion animation scene are shot separately, each in a configuration such as FIGS. **2***a* and **2***b*. For example, if a scene had man with leash **702** and his dog **703** walking down a city street set **701**, the city street set **701**, the man with leash **702**, and the dog **703** would be shot individually, each with separate motion capture systems as illustrated in FIG. **7***c* (for city street set **701**, FIG. **7***d* (for man with leash **702**) and FIG. **7***e* (for dog **703**)a. The stop-motion animation of the 2 characters **702-703** and 1 set **701** would each then be separately captured as individual textured 3D surfaces **217**, in the manner described above. Then, with a 3D modeling and/or animation application software the 2 characters **702-703** and 1 set **701** would be rendered together into a 3D scene. In one embodiment, the light panel **208-209** lighting the characters **702-703** and the set **701** could be configured to be the same, so the man with leash **702** and the dog **703** appear to be illuminated in the same environment as the set **701**. In another embodiment, flat lighting (i.e. uniform lighting to minimize shadows and highlights) is used, and then lighting (including shadows and highlights) is simulated by the 3D modeling/animation application software. Through the 3D modeling/animation application software the animators will be able to see how the characters **702-703** look relative to each other and the set **701**, and will also be able to look at the characters **702-703** and set **701** from any camera angle they wish, without having to move any of the physical cameras **204-205** or **214-215** doing the capture.

This approach provides significant advantages to stop-motion animation. The following are some of the advantages of this approach: (a) individual characters **702-703** may be manipulated individually without worrying about the animator bumping into another character **702-703** or the characters **702-703** bumping into each other, (b) the camera position of the rendered frames may be chosen arbitrarily, including having the camera position move in successive frames, (c) the rendered camera position can be one where it would not be physically possible to locate a camera **705** in a conventional stop-motion configuration (e.g. directly between 2 characters **702-703** that are close together, where there is no room for a camera **705**), (d) the lighting, including highlights and shadows can be controlled arbitrarily, including creating lighting situations that are not physically possible to realize (e.g. making a character glow), (e) special effects can be applied to the characters **702-703** (e.g. a ghost character **702-703** can be made translucent when it is rendered into the scene), (f) a character **702-703** can remain in a physically stable position on the ground while in the scene it is not (e.g. a character **702-703** can be captured in an upright position, while it is rendered into the scene upside down in a hand stand, or rendered into the scene flying above the ground), (g) parts of the character **702-703** can be held up by supports that do not have phosphor on them, and as such will not be captured (and will not have to be removed from the shot later in post-production), (h) detail elements of a character **702-703**, like mouth positions when the character **702-703** is speaking, can be rendered in by the 3D modeling/animation application, so they do not have be attached and then removed from the character **702-703** during the animation, (i) characters **702-703** can be rendered into computer-generated 3D scenes (e.g. the man with leash **702** and dog **703** can be animated as clay animations, but the city street set **701** can be a computer-generated scene), (j) 3D motion blur can be applied to the objects as they move (or as the rendered camera position moves), resulting in a smoother perception of motion to the animation, and also making possible faster motion without the perception of jitter.

Additional Phosphorescent Phosphors

In another embodiment, different phosphors other than ZnS:Cu are used as pigments with dyes for fabrics or other non-skin objects. ZnS:Cu is the preferred phosphor to use for skin applications because it is FDA-approved as a cosmetic pigment. But a large variety of other phosphors exist that, while not approved for use on the skin, are in some cases approved for use within materials handled by humans. One such phosphor is $SrAl_2O_4:Eu^{2+},Dy^{3+}$. Another is $SrAl_2O_4:Eu^{2+}$. Both phosphors have a much longer afterglow than ZnS:Cu for a given excitation.

Optimizing Phosphorescent Emission

Many phosphors that phosphoresce in visible light spectra are charged more efficiently by ultraviolet light than by visible light. This can be seen in chart **800** of FIG. **8** which show approximate excitation and emission curves of ZnS:Cu (which we shall refer to hereafter as "zinc sulfide") and various light sources. In the case of zinc sulfide, its excitation curve **811** spans from about 230 nm to 480 nm, with its peak at around 360 nm. Once excited by energy in this range, its phosphorescence curve **812** spans from about 420 nm to 650 nm, producing a greenish glow. The zinc sulfide phosphorescence brightness **812** is directly proportional to the excitation energy **811** absorbed by the zinc sulfide. As can be seen by excitation curve **811**, zinc sulfide is excited with varying degrees of efficiency depending on wavelength. For example, at a given brightness from an excitation source (i.e. in the case of the presently preferred embodiment, light energy from light panels **208-209**) zinc sulfide will absorb only 30% of the energy at 450 nm (blue light) that it will absorb at 360 nm (UVA light, commonly called "black light"). Since it is desirable to get the maximum phosphorescent emission **812** from the zinc sulfide (e.g. brighter phosphorescence will allow for smaller lens apertures and longer depth of field), clearly it is advantageous to excite the zinc sulfide with as much energy as possible. The light panels **208-209** can only produce up to a certain level of light output before the light becomes uncomfortable for the performers. So, to maximize the phosphorescent emission output of the zinc sulfide, ideally the light panels **208-209** should output light at wavelengths that are the most efficient for exciting zinc sulfide.

Other phosphors that may be used for non-skin phosphorescent use (e.g. for dyeing fabrics) also are excited best by ultraviolet light. For example, $SrAl_2O_4:Eu^{2+},Dy^{3+}$ and $SrAl_2O_4:Eu^{2+}$ are both excited more efficiently with ultraviolet light than visible light, and in particular, are excited quite efficiently by UVA (black light).

As can be seen in FIG. **3**, a requirement for a light source used for the light panels **208-209** is that the light source can transition from completely dark to fully lit very quickly (e.g. on the order of a millisecond or less) and from fully lit to dark very quickly (e.g. also on the order of a millisecond or less). Most LEDs fulfill this requirement quite well, typically turning on an off on the order of microseconds. Unfortunately, though, current LEDs present a number of issues for use in general lighting. For one thing, LEDs currently available have a maximum light output of approximately 35 W. The BL-43F0-0305 from Lamina Ceramics, 120 Hancock Lane, Westampton, N.J. 08060 is one such RGB LED unit. For another, currently LEDs have special power supply requirements (in the case of the BL-43F0-0305, different voltage supplies are need for different color LEDs in the unit). In addition, current LEDs require very large and heavy heatsinks and produce a great deal of heat. Each of these issues results in making LEDs expensive and somewhat unwieldy for lighting an entire motion capture stage for a performance. For example, if 3500 Watts were needed to light a stage, 100 35 W LED units would be needed.

But, in addition to these disadvantages, the only very bright LEDs currently available are white or RGB LEDs. In the case of both types of LEDs, the wavelengths of light emitted by the LED does not overlap with wavelengths where the zinc sulfide is efficiently excited. For example, in FIG. **8** the emission curve **823** of the blue LEDs in the BL-43F0-0305 LED unit is centered around 460 nm. It only overlaps with the tail end of the zinc sulfide excitation curve **811** (and the Red and Green LEDs don't excite the zinc sulfide significantly at all). So, even if the blue LEDs are very bright (to the point where they are as bright as is comfortable to the performer), only a small percentage of that light energy will excite the zinc sulfide, resulting in a relatively dim phosphorescence. Violet and

UVA ("black light") LEDs do exist, which would excite the zinc sulfide more efficiently, but they only currently are available at very low power levels, on the order of 0.1 Watts. To achieve 3500 Watts of illumination would require 35,000 such 0.1 Watt LEDs, which would be quite impractical and prohibitively expensive.

Fluorescent Lamps As a Flashing Illumination Source

Other lighting sources exist that output light at wavelengths that are more efficiently absorbed by zinc sulfide. For example, fluorescent lamps (e.g. 482-S9 from Kino-Flo, Inc. 2840 North Hollywood Way, Burbank, Calif. 91505) are available that emit UVA (black light) centered around 350 nm with an emission curve similar to **821**, and Blue/violet fluorescent lamps (e.g. 482-S10-S from Kino-Flo) exist that emit bluish/violet light centered around 420 nm with an emission curve similar to **822**. The emission curves **821** and **822** are much closer to the peak of the zinc sulfide excitation curve **811**, and as a result the light energy is far more efficiently absorbed, resulting in a much higher phosphorescent emission **812** for a given excitation brightness. Such fluorescent bulbs are quite inexpensive (typically $15/bulb for a 48" bulb), produce very little heat, and are very light weight. They are also available in high wattages. A typical 4-bulb fluorescent fixture produces 160 Watts or more. Also, theatrical fixtures are readily available to hold such bulbs in place as staging lights. (Note that UVB and UVC fluorescent bulbs are also available, but UVB and UVC exposure is known to present health hazards under certain conditions, and as such would not be appropriate to use with human or animal performers without suitable safety precautions.)

The primary issue with using fluorescent lamps is that they are not designed to switch on and off quickly. In fact, ballasts (the circuits that ignite and power fluorescent lamps) typically turn the lamps on very slowly, and it is common knowledge that fluorescent lamps may take a second or two until they are fully illuminated.

FIG. **9** shows a diagrammatic view of a prior art fluorescent lamp. The elements of the lamp are contained within a sealed glass bulb **910** which, in this example, is in the shape of a cylinder (commonly referred to as a "tube"). The bulb contains an inert gas **940**, typically argon, and a small amount of mercury **930**. The inner surface of the bulb is coated with a phosphor **920**. The lamp has 2 electrodes **905-906**, each of which is coupled to a ballast through connectors **901-904**. When a large voltage is applied across the electrodes **901-904**, some of the mercury in the tube changes from a liquid to a gas, creating mercury vapor, which, under the right electrical circumstances, emits ultraviolet light. The ultraviolet light excites the phosphor coating the inner surface of the bulb. The phosphor then fluoresces light at a higher wavelength than the excitation wavelength. A wide range of phosphors are available for fluorescent lamps with different wavelengths. For example, phosphors that are emissive at UVA wavelengths and all visible light wavelengths are readily available off-the-shelf from many suppliers.

Standard fluorescent ballasts are not designed to switch fluorescent lamps on and off quickly, but it is possible to modify an existing ballast so that it does. FIG. **10** is a circuit diagram of a prior art 27 Watt fluorescent lamp ballast **1002** modified with an added sync control circuit **1001** of the present invention.

For the moment, consider only the prior art ballast circuit **1002** of FIG. **10** without the modification **1001**. Prior art ballast **1002** operates in the following manner: A voltage doubler circuit converts 120 VAC from the power line into 300 volts DC. The voltage is connected to a half bridge oscillator/driver circuit, which uses two NPN power transistors **1004-1005**. The half bridge driver, in conjunction with a multi-winding transformer, forms an oscillator. Two of the transformer windings provide high drive current to the two power transistors **1004-1005**. A third winding of the transformer is in line with a resonant circuit, to provide the needed feedback to maintain oscillation. The half bridge driver generates a square-shaped waveform, which swings from +300 volts during one half cycle, to zero volts for the next half cycle. The square wave signal is connected to an "LC" (i.e. inductor-capacitor) series resonant circuit. The frequency of the circuit is determined by the inductance Lres and the capacitance Cres. The fluorescent lamp **1003** is connected across the resonant capacitor. The voltage induced across the resonant capacitor from the driver circuit provides the needed high voltage AC to power the fluorescent lamp **1003**. To kick the circuit into oscillation, the base of the power transistor **1005** is connected to a simple relaxation oscillator circuit. Current drawn from the 300 v supply is routed through a resistor and charges up a 0.1 uF capacitor. When the voltage across the capacitor reaches about 20 volts, a DIAC (a bilateral trigger diode) quickly switches and supplies power transistor **1005** with a current spike. This spike kicks the circuit into oscillation.

Synchronization control circuit **1001** is added to modify the prior art ballast circuit **1002** described in the previous paragraph to allow rapid on-and-off control of the fluorescent lamp **1003** with a sync signal. In the illustrated embodiment in FIG. **10**, a sync signal, such as sync signal **222** from FIG. **2**, is electrically coupled to the SYNC+ input. SYNC− is coupled to ground. Opto-isolator NEC PS2501-1 isolates the SYNC+ and SYNC− inputs from the high voltages in the circuit. The opto-isolator integrated circuit consists of a light emitting diode (LED) and a phototransistor. The voltage differential between SYNC+ and SYNC− when the sync signal coupled to SYNC+ is at a high level (e.g. ≧2.0V) causes the LED in the opto-isolator to illuminate and turn on the phototransistor in the opto-isolator. When this phototransistor is turned on, voltage is routed to the gate of an n-channel MOSFET Q1 (Zetex Semiconductor ZVN4106F DMOS FET). MOSFET Q1 functions as a low resistance switch, shorting out the base-emitter voltage of power transistor **1005** to disrupt the oscillator, and turn off fluorescent lamp **1003**. To turn the fluorescent lamp back on, the sync signal (such as **222**) is brought to a low level (e.g. <0.8V), causing the LED in the opto-isolator to turn off, which turns off the opto-isolator phototransistor, which turns off MOSFET Q1 so it no longer shorts out the base-emitter voltage of power transistor **1005**. This allows the kick start circuit to initialize ballast oscillation, and the fluorescent lamp **1003** illuminates.

This process repeats as the sync signal coupled to SYNC+ oscillates between high and low level. The synch control circuit **1001** combined with prior art ballast **1002** will switch fluorescent lamp **1003** on and off reliably, well in excess of 120 flashes per second. It should be noted that the underlying principles of the invention are not limited to the specific set of circuits illustrated in FIG. **10**.

FIG. **11** shows the light output of fluorescent lamp **1003** when synch control circuit **1001** is coupled to prior art ballast **1002** and a sync signal **222** is coupled to circuit **1001** as described in the previous paragraph. Traces **1110** and **1120** are oscilloscope traces of the output of a photodiode placed on the center of the bulb of a fluorescent lamp using the prior art ballast circuit **1002** modified with the sync control circuit **1001** of the present invention. The vertical axis indicates the brightness of lamp **1003** and the horizontal axis is time. Trace **1110** (with 2 milliseconds/division) shows the light output of fluorescent lamp **1003** when sync signal **222** is producing a 60 Hz square wave. Trace **1120** (with the oscilloscope set to 1 millisecond/division and the vertical brightness scale reduced by 50%) shows the light output of lamp **1003** under the same test conditions except now sync signal **222** is producing a 250 Hz square wave. Note that the peak **1121** and minimum **1122** (when lamp **1003** is off and is almost completely dark) are still both relatively flat, even at a much higher switching frequency. Thus, the sync control circuit **1001** modification to prior art ballast **1002** produces dramatically different light output than the unmodified ballast **1002**, and makes it possible to achieve on and off switching of fluorescent lamps at high frequencies as required by the motion capture system illustrated in FIG. **2** with timing similar to that of FIG. **3**.

Although the modified circuit shown in FIG. **10** will switch a fluorescent lamp **1003** on and off rapidly enough for the requirements of a motion capture system such as that illustrated in FIG. **2**, there are certain properties of fluorescent lamps that may be modified for use in a practical motion capture system.

FIG. **12** illustrates one of these properties. Traces **1210** and **1220** are the oscilloscope traces of the light output of a General Electric Gro and Sho fluorescent lamp **1003** placed in circuit **1002** modified by circuit **1001**, using a photodiode placed on the center of the bulb. Trace **1210** shows the light output at 1 millisecond/division, and Trace **1220** shows the light output at 20 microseconds/division. The portion of the waveform shown in Trace **1220** is roughly the same as the dashed line area **1213** of Trace **1210**. Sync signal **222** is coupled to circuit **1002** as described previously and is producing a square wave at 250 Hz. Peak level **1211** shows the light output when lamp **1003** is on and minimum **1212** shows the light output when lamp **1003** is off. While Trace **1210** shows the peak level **1211** and minimum **1212** as fairly flat, upon closer inspection with Trace **1220**, it can be seen that when the lamp **1003** is turned off, it does not transition from fully on to completely off instantly. Rather, there is a decay curve of approximately 200 microseconds (0.2 milliseconds) in duration. This is apparently due to the decay curie of the phosphor coating the inside of the fluorescent bulb (i.e. when the lamp **1003** is turned off, the phosphor continues to fluoresce for a brief period of time). So, when sync signal **222** turns off the modified ballast **1001-1002**, unlike LED lights which typically switch off within a microsecond, fluorescent lamps take a short interval of time until they decay and become dark.

There exists a wide range of decay periods for different brands and types of fluorescent lamps, from as short as 200 microseconds, to as long as over a millisecond. To address this property of fluorescent lamps, one embodiment of the invention adjusts signals **221-223**. This embodiment will be discussed shortly.

Another property of fluorescent lamps that impacts their usability with a motion capture system such as that illustrated in FIG. **2** is that the electrodes within the bulb are effectively incandescent filaments that glow when they carry current through them, and like incandescent filaments, they continue to glow for a long time (often a second or more) after current is removed from them. So, even if they are switched on and off rapidly (e.g. at 90 Hz) by sync signal **222** using ballast **1002** modified by circuit **1001**, they continue to glow for the entire dark interval **302**. Although the light emitted from the fluorescent bulb from the glowing electrodes is very dim relative to the fully illuminated fluorescent bulb, it is still is a significant amount of light, and when many fluorescent bulbs are in use at once, together the electrodes add up to a significant amount of light contamination during the dark interval **302**, where it is advantageous for the room to be as dark as possible.

FIG. **13** illustrates one embodiment of the invention which addresses this problem. Prior art fluorescent lamp **1350** is shown in a state 10 milliseconds after the lamp as been shut off. The mercury vapor within the lamp is no longer emitting ultraviolet light and the phosphor lining the inner surface of the bulb is no longer emitting a significant amount of light. But the electrodes **1351-1352** are still glowing because they are still hot. This electrode glowing results in illuminated regions **1361-1362** near the ends of the bulb of fluorescent lamp **1350**.

Fluorescent lamp **1370** is a lamp in the same state as prior art lamp **1350**, 10 milliseconds after the bulb **1370** has been shut off, with its electrodes **1371-1372** still glowing and producing illuminated regions **1381-1382** near the ends of the bulb of fluorescent lamp **1370**, but unlike prior art lamp **1350**, wrapped around the ends of lamp **1370** is opaque tape **1391** and **1392** (shown as see-through with slanted lines for the sake of illustration). In the presently preferred embodiment black gaffers' tape is used, such as 4" P-665 from Permacel, A Nitto Denko Company, US Highway No. 1, P.O. Box 671, New Brunswick, N.J. 08903. The opaque tape **1391-1392** serves to block almost all of the light from glowing electrodes **1371-1372** while blocking only a small amount of the overall light output of the fluorescent lamp when the lamp is on during lit interval **301**. This allows the fluorescent lamp to become much darker during dark interval **302** when being flashed on and off at a high rate (e.g. 90 Hz). Other techniques can be used to block the light from the glowing electrodes, including other types of opaque tape, painting the ends of the bulb with an opaque paint, or using an opaque material (e.g. sheets of black metal) on the light fixtures holding the fluorescent lamps so as to block the light emission from the parts of the fluorescent lamps containing electrodes.

Returning now to the light decay property of fluorescent lamps illustrated in FIG. **12**, if fluorescent lamps are used for light panels **208-209**, the synchronization signal timing shown in FIG. **3** will not produce optimal results because when Light Panel sync signal **222** drops to a low level on edge **332**, the fluorescent light panels **208-209** will take time to become completely dark (i.e. edge **342** will gradually drop to dark level). If the Dark Cam Sync Signal triggers the grayscale cameras **204-205** to open their shutters at the same time as edge **322**, the grayscale camera will capture some of the scene lit by the afterglow of light panels **208-209** during its decay interval. Clearly, FIG. **3**'s timing signals and light output behavior is more suited for light panels **208-209** using a lighting source like LEDs that have a much faster decay than fluorescent lamps.

Synchronization Timing for Fluorescent Lamps

FIG. **14** shows timing signals which are better suited for use with fluorescent lamps and the resulting light panel **208-209** behavior (note that the duration of the decay curve **1442** is exaggerated in this and subsequent timing diagrams for illustrative purposes). The rising edge **1434** of sync signal **222** is roughly coincident with rising edge **1414** of lit cam sync signal **223** (which opens the lit camera **214-215** shutters) and with falling edge **1424** of dark cam sync signal **223** (which closes the dark camera **204-205** shutters). It also causes the fluorescent lamps in the light panels **208-209** to illuminate quickly. During lit time interval **1401**, the lit cameras **214-215** capture a color image illuminated by the fluorescent lamps, which are emitting relatively steady light as shown by light output level **1443**.

At the end of lit time interval **1401**, the falling edge **1432** of sync signal **222** turns off light panels **208-209** and is roughly coincident with the rising edge **1412** of lit cam sync signal **223**, which closes the shutters of the lit cameras **214-215**. Note, however, that the light output of the light panels **208-209** does not drop from lit to dark immediately, but rather slowly drops to dark as the fluorescent lamp phosphor decays as shown by edge **1442**. When the light level of the fluorescent lamps finally reaches; dark level **1441**, dark cam sync signal **221** is dropped from high to low as shown by edge **1422**, and this opens the shutters of dark cameras **204-205**. This way the dark cameras **204-205** only capture the emissions from the phosphorescent makeup, paint or dye, and do not capture the reflection of light from any objects illuminated by the fluorescent lamps during the decay interval **1442**. So, in this embodiment the dark interval **1402** is shorter than the lit interval **1401**, and the dark camera **204-205** shutters are open for a shorter period of time than the lit camera **214-205** shutters.

Another embodiment is illustrated in FIG. **15** where the dark interval **1502** is longer than the lit interval **1501**. The advantage of this embodiment is it allows for a longer shutter time for the dark cameras **204-205**. In this embodiment, light panel sync signal **222** falling edge **1532** occurs earlier which causes the light panels **208-209** to turn off. Lit cam sync signal **223** rising edge **1512** occurs roughly coincident with falling edge **1532** and closes the shutters on the lit cameras **214-5**. The light output from the light panel **208-209** fluorescent lamps begins to decay as shown by edges **1542** and finally reaches dark level **1541**. At this point dark cam sync signal **221** is transitions to a low state on edge **1522**, and the dark cameras **204-205** open their shutters and capture the phosphorescent emissions.

Note that in the embodiments shown in both FIGS. **14** and **15** the lit camera **214-215** shutters were only open while the light output of the light panel **208-209** fluorescent lamps was at maximum. In another embodiment, the lit camera **214-215** shutters can be open during the entire time the fluorescent lamps are emitting any light, so as to maximize the amount of light captured. In this situation, however, the phosphorescent makeup, paint or dye in the scene will become more prominent relative to the non-phosphorescent areas in the scene because the phosphorescent areas will continue to emit light fairly steadily during the fluorescent lamp decay while the non-phosphorescent areas will steadily get darker. The lit cameras **214-215** will integrate this light during the entire time their shutters are open.

In yet another embodiment the lit cameras **214-215** leave their shutters open for some or all of the dark time interval **1502**. In this case, the phosphorescent areas in the scene will appear very prominently relative to the non-phosphorescent areas since the lit cameras **214-215** will integrate the light during the dark time interval **1502** with the light from the lit time interval **1501**.

Because fluorescent lamps are generally not sold with specifications detailing their phosphor decay characteristics, it is necessary to determine the decay characteristics of fluorescent lamps experimentally. This can be readily done by adjusting the falling edge **1522** of sync signal **221** relative to the falling edge **1532** of sync signal **222**, and then observing the output of the dark cameras **204-205**. For example, in the embodiment shown in FIG. **15**, if edge **1522** falls too soon after edge **1532** during the fluorescent light decay **1542**, then non-phosphorescent objects will be captured in the dark cameras **204-205**. If the edge **1522** is then slowly delayed relative to edge **1532**, the non-phosphorescent objects in dark camera **204-205** will gradually get darker until the entire image captured is dark, except for the phosphorescent objects in the image. At that point, edge **1522** will be past the decay interval **1542** of the fluorescent lamps. The process described in this paragraph can be readily implemented in an application on a general-purpose computer that controls the output levels of sync signals **221-223**.

In another embodiment the decay of the phosphor in the fluorescent lamps is such that even after edge **1532** is delayed as long as possible after **1522** to allow for the dark cameras **204-205** to have a long enough shutter time to capture a bright enough image of phosphorescent patterns in the scene, there is still a small amount of light from the fluorescent lamp illuminating the scene such that non-phosphorescent objects in the scene are slightly visible. Generally, this does not present a problem for the pattern processing techniques described in the co-pending applications identified above. So long as the phosphorescent patterns in the scene are substantially brighter than the dimly-lit non-fluorescent objects in the scene, the pattern processing techniques will be able to adequately correlate and process the phosphorescent patterns and treat the dimly lit non-fluorescent objects as noise.

Synchronizing Cameras with Lower Frame Rates than The Light Panel Flashing Rate

In another embodiment the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. For example, the capture frame rate may be 30 frames per second (fps), but so as to keep the flashing of the light panels **208-209** about the threshold of human perception, the light panels **208-209** are flashed at 90 flashes per second. This situation is illustrated in FIG. **16**. The sync signals **221-3** are controlled the same as the are in FIG. **15** for lit time interval **1601** and dark time interval **1602** (light cycle **0**), but after that, only light panel **208-9** sync signal **222** continues to oscillate for light cycles **1** and **2**. Sync signals **221** and **223** remain in constant high state **1611** and **1626** during this interval. Then during light cycle **3**, sync signals **221** and **223** once again trigger with edges **1654** and **1662**, opening the shutters of lit cameras **214-215** during lit time interval **1604**, and then opening the shutters of dark cameras **204-205** during dark time interval **1605**.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, sync signal **223** causes the lit cameras **214-215** to open their shutters after sync signal **221** causes the dark cameras **204-205** to open their shutters. This is illustrated in FIG. **17**. An advantage of this timing arrangement over that of FIG. **16** is the fluorescent lamps transition from dark to lit (edge **1744**) more quickly than they decay from lit to dark (edge **1742**). This makes it possible to abut the dark frame interval **1702** more closely to the lit frame interval **1701**. Since captured lit textures are often used to be mapped onto 3D surfaces reconstructed from dark camera images, the closer the lit and dark captures occur in time, the closer the alignment will be if the captured object is in motion.

In another embodiment where the lit cameras **214-215** and dark cameras **204-205** are operated at a lower frame rate than the flashing rate of the light panels **208-209**, the light panels **208-209** are flashed with varying light cycle intervals so as to allow for longer shutter times for either the dark cameras **204-205** or lit cameras **214-215**, or to allow for longer shutters times for both cameras. An example of this embodiment is illustrated in FIG. **18** where the light panels **208-209** are flashed at **3** times the frame rate of cameras **204-205** and **214-215**, but the open shutter interval **1821** of the dark cameras **204-205** is equal to almost half of the entire frame time **1803**. This is accomplished by having light panel **208-209** sync signal **222** turn off the light panels **208-209** for a long dark interval **1802** while dark cam sync signal **221** opens the dark shutter for the duration of long dark interval **1802**. Then sync signal **222** turns the light panels **208-209** on for a brief lit interval **1801**, to complete light cycle **0** and then rapidly flashes the light panels **208-209** through light cycles **1** and **2**. This results in the same number of flashes per second as the embodiment illustrated in FIG. **17**, despite the much longer dark interval **1802**. The reason this is a useful configuration is that the human visual system will still perceive rapidly flashing lights (e.g. at 90 flashes per second) as being lit continuously, even if there are some irregularities to the flashing cycle times. By varying the duration of the lit and dark intervals of the light panels **208-209**, the shutter times of either the dark cameras **204-205**, lit cameras **214-215** or both can be lengthened or shortened, while still maintaining the human perception that light panels **208-209** are continuously lit.

High Aggregate Frame Rates from Cascaded Cameras

FIG. **19** illustrates another embodiment where lit cameras **1941-1946** and dark cameras **1931-1936** are operated at a lower frame rate than the flashing rate of the light panels **208-209**. FIG. **19** illustrates a similar motion capture system configuration as FIG. **2***a*, but given space limitations in the diagram only the light panels, the cameras, and the synchronization subsystem is shown. The remaining components of FIG. **2***a* that are not shown (i.e. the interfaces from the cameras to their camera controllers and the data processing subsystem, as well as the output of the data processing subsystem) are a part of the full configuration that is partially shown in FIG. **19**, and they are coupled to the components of FIG. **19** in the same manner as they are to the components of FIG. **2***a*. Also, FIG. **19** shows the Light Panels **208-209** in their "lit" state. Light Panels **208-209** can be switched off by sync signal **222** to their "dark" state, in which case performer **202** would no longer be lit and only the phosphorescent pattern applied to her face would be visible, as it is shown in FIG. **2***b*.

FIG. **19** shows 6 lit cameras **1941-1946** and 6 dark cameras **1931-1936**. In the presently preferred embodiment color cameras are used for the lit cameras **1941-1946** and grayscale cameras are used for the dark camera **1931-1936**, but either type could be used for either purpose. The shutters on the cameras **1941-1946** and **1931-1936** are driven by sync signals **1921-1926** from sync generator PCI card **224**. The sync generator card is installed in sync generator PC **220**, and operates as previously described. (Also, in another embodiment it may be replaced by using the parallel port outputs of sync generator PC **220** to drive sync signals **1921-1926**, and in this case, for example, bit **0** of the parallel port would drive sync signal **222**, and bits **1-6** of the parallel port would drive sync signals **1921-1926**, respectively.)

Unlike the previously described embodiments, where there is one sync signal **221** for the dark cameras and one sync signal **223** for the lit cameras, in the embodiment illustrated in FIG. **19**, there are 3 sync signals **1921-1923** for the dark cameras and 3 sync signals **1924-1926** for the dark cameras. The timing for these sync signals **1921-1926** is shown in FIG. **20**. When the sync signals **1921-1926** are in a high state they causes the shutters of the cameras attached to them to be closed, when the sync signals are in a low state, they cause the shutters of the cameras attached to them to be open.

In this embodiment, as shown in FIG. **20**, the light panels **208-209** are flashed at a uniform **90** flashes per second, as controlled by sync signal **222**. The light output of the light panels **208-209** is also shown, including the fluorescent lamp decay **2042**. Each camera **1931-1936** and **1941-1946** captures images at 30 frames per second (fps), exactly at a 1:3 ratio with the 90 flashes per second rate of the light panels. Each camera captures one image per each 3 flashes of the light panels, and their shutters are sequenced in a "cascading" order, as illustrated in FIG. **20**. A sequence of 3 frames is captured in the following manner:

Sync signal **222** transitions with edge **2032** from a high to low state **2031**. Low state **2031** turns off light panels **208-209**, which gradually decay to a dark state **2041** following decay curve **2042**. When the light panels are sufficiently dark for the purposes of providing enough contrast to separate the phosphorescent makeup, paint, or dye from the non-phosphorescent surfaces in the scene, sync signal **1921** transitions to low state **2021**. This causes dark cameras **1931-1932** to open their shutters and capture a dark frame. After the time interval **2002**, sync signal **222** transitions with edge **2034** to high state **2033** which causes the light panels **208-209** to transition with edge **2044** to lit state **2043**. Just prior to light panels **208-209** becoming lit, sync signal **1921** transitions to high state **2051** closing the shutter of dark cameras **1931-1932**. Just after the light panels **208-209** become lit, sync signal **1924** transition to low state **2024**, causing the shutters on the lit cameras **1941-1942** to open during time interval **2001** and capture a lit frame. Sync signal **222** transitions to a low state, which turns off the light panels **208-9**, and sync signal **1924** transitions to a high state at the end of time interval **2001**, which closes the shutters on lit cameras **1941-1942**.

The sequence of events described in the preceding paragraphs repeats 2 more times, but during these repetitions sync signals **1921** and **1924** remain high, keeping their cameras shutters closed. For the first repetition, sync signal **1922** opens the shutter of dark cameras **1933-1934** while light panels **208-209** are dark and sync signal **1925** opens the shutter of lit cameras **1943-1944** while light panels **208-209** are lit. For the second repetition, sync signal **1923** opens the shutter of dark cameras **1935-1936** while light panels **208-209** are dark and sync signal **1926** opens the shutter of lit cameras **1945-1946** while light panels **208-209** are lit.

Then, the sequence of events described in the prior 2 paragraphs continues to repeat while the motion capture session illustrated in FIG. **19** is in progress, and thus a "cascading" sequence of camera captures allows 3 sets of dark and 3 sets of lit cameras to capture motion at 90 fps (i.e. equal to the light panel flashing rate of 90 flashes per second), despite the fact each cameras is only capturing images at 30 fps. Because each camera only captures 1 of every 3 frames, the captured frames stored by the data processing system **210** are then interleaved so that the stored frame sequence at 90 fps has the frames in proper order in time. After that interleaving operation is complete, the data processing system will output reconstructed 3D surfaces **207** and textured 3D surfaces **217** at 90 fps.

Although the "cascading" timing sequence illustrated in FIG. **20** will allow cameras to operate at 30 fps while capturing images at an aggregate rate of 90 fps, it may be desirable to be able to switch the timing to sometimes operate all of the cameras **1921-1923** and **1924-1926** synchronously. An example of such a situation is for the determination of the relative position of the cameras relative to each other. Precise knowledge of the relative positions of the dark cameras **1921-**

1923 is used for accurate triangulation between the cameras, and precise knowledge of the position of the lit cameras **1924-1926** relative to the dark cameras **1921-1923** is used for establishing how to map the texture maps captured by the lit cameras **1924-1926** onto the geometry reconstructed from the images captured by the dark cameras **1921-1923**. One prior art method (e.g. that is used to calibrate cameras for the motion capture cameras from Motion Analysis Corporation) to determine the relative position of fixed cameras is to place a known object (e.g. spheres on the ends of a rods in a rigid array) within the field of view of the cameras, and then synchronously (i.e. with the shutters of all cameras opening and closing simultaneously) capture successive frames of the image of that known object by all the cameras as the object is in motion. By processing successive frames from all of the cameras, it is possible to calculate the relative position of the cameras to each other. But for this method to work, all of the cameras need to be synchronized so that they capture images simultaneously. If the camera shutters do not open simultaneously, then when each non-simultaneous shutter opens, its camera will capture the moving object at a different position in space than other cameras whose shutters open at different times. This will make it more difficult (or impossible) to precisely determine the relative position of all the cameras to each other.

FIG. **21** illustrates in another embodiment how the sync signals **1921-6** can be adjusted so that all of the cameras **1931-1936** and **1941-1946** open their shutters simultaneously. Sync signals **1921-1926** all transition to low states **2121-2126** during dark time interval **2102**. Although the light panels **208-209** would be flashed 90 flashes a second, the cameras would be capturing frames synchronously to each other at 30 fps. (Note that in this case, the lit cameras **1941-1946** which, in the presently preferred embodiment are color cameras, also would be capturing frames during the dark interval **2102** simultaneously with the dark cameras **1931-1936**.) Typically, this synchronized mode of operation would be done when a calibration object (e.g. an array of phosphorescent spheres) was placed within the field of view of some or all of the cameras, and potentially moved through successive frames, usually before or after a motion capture of a performer. In this way, the relative position of the cameras could determined while the cameras are running synchronously at 30 fps, as shown in FIG. **21**. Then, the camera timing would be switched to the "cascading" timing shown in FIG. **20** to capture a performance at 90 fps. When the 90 fps frames are reconstructed by data processing system **210**, then camera position information, determined previously (or subsequently) to the 90 fps capture with the synchronous mode time shown in FIG. **21**, will be used to both calculate the 3D surface **207** and map the captured lit frame textures onto the 3D surface to create textured 3D surface **217**

When a scene is shot conventionally using prior art methods and cameras are capturing only 2D images of that scene, the "cascading" technique to use multiple slower frame rate cameras to achieve a higher aggregate frame rate as illustrated in FIGS. **19** and **20** will not produce high-quality results. The reason for this is each camera in a "cascade" (e.g. cameras **1931**, **1933** and **1935**) will be viewing the scene from a different point of view. If the captured 30 fps frames of each camera are interleaved together to create a 90 fps sequence of successive frames in time, then when the 90 fps sequence is viewed, it will appear to jitter, as if the camera was rapidly jumping amongst multiple positions. But when slower frame rate cameras are "cascaded" to achieve a higher aggregate frame rate as illustrate in FIGS. **19** and **20** for the purpose capturing the 3D surfaces of objects in a scene, as described herein and in combination with the methods described in the co-pending applications, the resulting 90 fps interleaved 3D surfaces **207** and textured 3D surfaces **217** do not exhibit jitter at all, but rather look completely stable. The reason is the particular position of the cameras **1931-1936** and **1941-1946** does not matter in the reconstruction 3D surfaces, just so long as the at least a pair of dark cameras **1931-1936** during each dark frame interval **2002** has a non-oblique view (e.g. <30 degrees) of the surface area (with phosphorescent makeup, paint or dye) to be reconstructed. This provides a significant advantage over conventional prior art 2D motion image capture (i.e. commonly known as video capture), because typically the highest resolution sensors commercially available at a given time have a lower frame rate than commercially available lower resolution sensors. So, 2D motion image capture at high resolutions is limited to the frame rate of a single high resolution sensor. A 3D motion surface capture at high resolution, under the principles described herein, is able to achieve n times the frames rate of a single high resolution sensor, where n is the number of camera groups "cascaded" together, per the methods illustrated in FIGS. **19** and **20**.

Color Mapping of Phosphor Brightness

Ideally, the full dynamic range, but not more, of dark cameras **204-205** should be utilized to achieve the highest quality pattern capture. For example, if a pattern is captured that is too dark, noise patterns in the sensors in cameras **204-205** may become as prominent as captured patterns, resulting in incorrect 3D reconstruction. If a pattern is too bright, some areas of the pattern may exceed the dynamic range of the sensor, and all pixels in such areas will be recorded at the maximum brightness level (e.g. 255 in an 8-bit sensor), rather than at the variety or brightness levels that actually make up that area of the pattern. This also will result in incorrect 3D reconstruction. So, prior to capturing a pattern, per the techniques described herein, it is advantageous to try to make sure the brightness of the pattern throughout is not too dark, nor too bright (e.g. not reaching the maximum brightness level of the camera sensor).

When phosphorescent makeup is applied to a performer, or when phosphorescent makeup, paint or dye is applied to an object, it is difficult for the human eye to evaluate whether the phosphor application results in a pattern captured by the dark cameras **204-205** that is bright enough in all locations or too bright in some locations. FIG. **22** image **2201** shows a cylinder covered in a random pattern of phosphor. It is difficult, when viewing this image on a computer display (e.g. an LCD monitor) to determine precisely if there are parts of the pattern that are too bright (e.g. location **2220**) or too dark (e.g. location **2210**). There are many reasons for this. Computer monitors often do not have the same dynamic range as a sensor (e.g. a computer monitor may only display 128 unique gray levels, while the sensor captures 256 gray levels). The brightness and/or contrast may not be set correctly on the monitor. Also, the human eye may have trouble determining what constitutes a maximum brightness level because the brain may adapt to the brightness it sees, and consider whatever is the brightest area on the screen to be the maximum brightness. For all of these reasons, it is helpful to have an objective measure of brightness that humans can readily evaluate when applying phosphorescent makeup, paint or dye. Also, it is helpful to have an objective measure brightness as the lens aperture and/or gain is adjusted on dark cameras **204-205** and/or the brightness of the light panels **208-209** is adjusted.

Image **2202** shows such an objective measure. It shows the same cylinder as image **2201**, but instead of showing the brightness of each pixel of the image as a grayscale level (in this example, from 0 to 255), it shows it as a color. Each color represents a range of brightness. For example, in image **2202** blue represents brightness ranges 0-32, orange represents brightness ranges 192-223 and dark red represents brightness ranges 224-255. Other colors represent other brightness ranges. Area **2211**, which is blue, is now clearly identifiable as an area that is very dark, and area **2221**, which is dark red, is now clearly identifiable as an area that is very bright. These determinations can be readily made by the human eye, even if the dynamic range of the display monitor is less than that of the sensor, or if the display monitor is incorrectly adjusted, or if the brain of the observer adapts to the brightness of the display. With this information the human observer can change the application of phosphorescent makeup, dye or paint. The human observer can also adjust the aperture and/or the gain setting on the cameras **204-205** and/or the brightness of the light panels **208-209**.

In one embodiment image **2202** is created by application software running on one camera controller computer **225** and is displayed on a color LCD monitor attached to the camera controller computer **225**. The camera controller computer **225** captures a frame from a dark camera **204** and places the pixel values of the captured frame in an array in its RAM. For example, if the dark cameras **204** is a 640×480 grayscale camera with 8 bits/pixel, then the array would be a 640×480 array of 8-bit bytes in RAM. Then, the application takes each pixel value in the array and uses it as an index into a lookup table of colors, with as many entries as the number of possible pixel values. With 8 bits/pixel, the lookup table has 256 entries. Each of the entries in the lookup table is pre-loaded (by the user or the developer of the application) with the desired Red, Green, Blue (RGB) color value to be displayed for the given brightness level. Each brightness level may be given a unique color, or a range of brightness levels can share a unique color. For example, for image **2202**, lookup table entries **0-31** are all loaded with the RGB value for blue, entries **192-223** are loaded with the RGB value for orange and entries **224-255** are loaded with the RGB value for dark red. Other entries are loaded with different RGB color values. The application uses each pixel value from the array (e.g. 640×480 of 8-bit grayscale values) of the captured frame as an index into this color lookup take, and forms a new array (e.g. 640×480 of 24-bit RGB values) of the looked-up colors. This new array of look-up colors is then displayed, producing a color image such as **1102**.

If a color camera (either lit camera **214** or dark camera **204**) is used to capture the image to generate an image such as **2202**, then one step is first performed after the image is captured find before it is processed as described in the preceding paragraph. The captured RGB output of the camera is stored in an array in camera controller computer **225** RAM (e.g. 640×480 with 24 bits/pixel). The application running on camera controller computer **225** then calculates the average brightness of each pixel by averaging the Red, Green and Blue values of each pixel (i.e. Average=(R+G+B)/3), and places those averages in a new array (e.g. 640×480 with 8 bits/pixel). This array of Average pixel brightnesses (the "Average array") will soon be processed as if it were the pixel output of a grayscale camera, as described in the prior paragraph, to produce a color image such as **2202**. But, first there is one more step: the application examines each pixel in the captured RGB array to see if any color channel of the pixel (i.e. R, G, or B) is at a maximum brightness value (e.g. 255). If any channel is, then the application sets the value in the Average array for that pixel to the maximum brightness value (e.g. 255). The reason for this is that it is possible for one color channel of a pixel to be driven beyond maximum brightness (but only output a maximum brightness value), while the other color channels are driven by relatively dim brightness. This may result in an average calculated brightness for that pixel that is a middle-range level (and would not be considered to be a problem for good-quality pattern capture). But, if any of the color channels has been overdriven in a given pixel, then that will result in an incorrect pattern capture. So, by setting the pixel value in the Average array to maximum brightness, this produces a color images **2202** where that pixel is shown to be at the highest brightness, which would alert a human observer of image **1102** of the potential of a problem for a high-quality pattern capture.

It should be noted that the underlying principles of the invention are not limited to the specific color ranges and color choices illustrated in FIG. **22**. Also, other methodologies can be used to determine the colors in **2202**, instead of using only a single color lookup table. For example, in one embodiment the pixel brightness (or average brightness) values of a captured image is used to specify the hue of the color displayed. In another embodiment, a fixed number of lower bits (e.g. 4) of the pixel brightness (or average brightness) values of a captured image are set to zeros, and then the resulting numbers are used to specify the hue for each pixel. This has the effect of assigning each single hue to a range of brightnesses.

Surface Reconstruction from Multiple Range Data Sets

Correlating lines or random patterns captured by one camera with images from other cameras as described above provides range information for each camera. In one embodiment of the invention, range information from multiple cameras is combined in three steps: (1) treat the 3d capture volume as a scalar field; (2) use a "Marching Cubes" (or a related "Marching Tetrahedrons") algorithm to find the isosurface of the scalar field and create a polygon mesh representing the surface of the subject; and (3) remove false surfaces and simplify the mesh. Details associated with each of these steps is provided below.

The scalar value of each point in the capture volume (also called a voxel) is the weighted sum of the scalar values from each camera. The scalar value for a single camera for points near the reconstructed surface is the best estimate of the distance of that point to the surface. The distance is positive for points inside the object and negative for points outside the object. However, points far from the surface are given a small negative value even if they are inside the object.

The weight used for each camera has two components. Cameras that lie in the general direction of the normal to the surface are given a weight of 1. Cameras that lie 90 degrees to the normal are given a weight of 0. A function is used of the form: $n_i = \cos^2 a_i$, where n_i is the normal weighting function, and a_i is the angle between the camera's direction and the surface normal. This is illustrated graphically in FIG. **23**.

The second weighting component is a function of the distance. The farther the volume point is from the surface the less confidence there is in the accuracy of the distance estimate. This weight decreases significantly faster than the distance increases. A function is used of the form: $w_i = 1/(d_i^2 + 1)$, where w_i is the weight and d_i is the distance. This is illustrated graphically in FIG. **24**. This weight is also used to differentiate between volume points that are "near to" and "far from" the surface. The value of the scalar field for camera i, is a function of the form: $s_i = (d_i * w_i - k * (1 - w_i)) * n_i$, where d_i is the distance from the volume point to the surface, w_i is the distance weighting function, k is the scalar value for points "far away", and n_i is the normal weighting function. This is illustrated graphically in FIG. **25**. The value of the scalar field is the weighted sum of the scalar fields for all cameras: s=sum (s_i*w). See, e.g., A Volumetric Method for Building Complex Models from Range Images Brian Curless and Marc Levoy, Stanford University, http://graphics.stanford.edu/papers/volrange/paper1level/paper.html, which is incorporated herein by reference.

It should be noted that other known functions with similar characteristics to the functions described above may also be employed. For example, rather than a cosine-squared function as described above, a cosine squared function with a threshold may be employed. In fact, virtually any other function which produces a graph shaped similarly to those illustrated in FIGS. **23**-**25** may be used (e.g., a graph which falls towards zero at a high angle).

In one embodiment of the invention, the "Marching Cubes" algorithm and its variant "Marching Tetrahedrons" finds the zero crossings of a scalar field and generates a surface mesh. See, e.g., Lorensen, W. E. and Cline, H. E., Marching Cubes: a high resolution 3D surface reconstruction algorithm, Computer Graphics, Vol. 21, No. 4, pp 163-169 (Proc. of SIGGRAPH), 1987, which is incorporated herein by reference. A volume is divided up into cubes. The scalar field is known or calculated as above for each corner of a cube. When some of the corners have positive values and some have negative values it is known that the surface passes through the cube. The standard algorithm interpolates where the surface crosses each edge. One embodiment of the invention improves on this by using an improved binary search to find the crossing to a high degree of accuracy. In so doing, the scalar field is calculated for additional points. The computational load occurs only along the surface and greatly improves the quality of the resulting mesh. Polygons are added to the surface according to tables. The "Marching Tetrahedrons" variation divides each cube into six tetrahedrons. The tables for tetrahedrons are much smaller and easier to implement than the tables for cubes. In addition, Marching Cubes has an ambiguous case not present in Marching Tetrahedrons.

The resulting mesh often has a number of undesirable characteristics. Often there is a ghost surface behind this desired surface. There are often false surfaces forming a halo around the true surface. And finally the vertices in the mesh are not uniformly spaced. The ghost surface and most of the false surfaces can be identified and hence removed with two similar techniques. Each vertex in the reconstructed surface is checked against the range information from each camera. If the vertex is close to the range value for a sufficient number of cameras (e.g., 1-4 cameras) confidence is high that this vertex is good. Vertices that fail this check are removed. Range information generally doesn't exist for every point in the field of view of the camera. Either that point isn't on the surface or that part of the surface isn't painted. If a vertex falls in this "no data" region for too many cameras (e.g., 1-4 cameras), confidence is low that it should be part of the reconstructed surface. Vertices that fail this second test are also removed. This test makes assumptions about, and hence restrictions on, the general shape of the object to be reconstructed. It works well in practice for reconstructing faces, although the underlying principles of the invention are not limited to any particular type of surface. Finally, the spacing of the vertices is made more uniform by repeatedly merging the closest pair of vertices connected by an edge in the mesh. The merging process is stopped when the closest pair is separated by more than some threshold value. Currently, 0.5 times the grid spacing is known to provide good results.

FIG. **26** is a flowchart which provides an overview of foregoing process. At **2601**, the scalar field is created/calculated. At **2602**, the marching tetrahedrons algorithm and/or marching cubes algorithm are used to determine the zero crossings of the scalar field and generate a surface mesh. At **2603**, "good" vertices are identified based on the relative positioning of the vertices to the range values for a specified number of cameras. The good vertices are retained. At **2604**, "bad" vertices are removed based on the relative positioning of the vertices to the range values for the cameras and/or a determination as to whether the vertices fall into the "no data" region of a specified number of cameras (as described above). Finally, at **2605**, the mesh is simplified (e.g., the spacing of the vertices is made more uniform as described above) and the process ends.

Vertex Tracking Embodiments

"Vertex tracking" as used herein is the process of tracking the motion of selected points in a captured surfaces over time. In general, one embodiment utilizes two strategies to tracking vertices. The Frame-to-Frame method tracks the points by comparing images taken a very short time apart. The Reference-to-Frame method tracks points by comparing an image to a reference image that could have been captured at a very different time or possibly it was acquired by some other means. Both methods have strengths and weaknesses. Frame-to-Frame tracking does not give perfect results. Small tracking errors tend to accumulate over many frames. Points drift away from their nominal locations. In Reference-to-Frame, the subject in the target frame can be distorted from the reference. For example, the mouth in the reference image might be closed and in the target image it might be open. In some cases, it may not be possible to match up the patterns in the two images because it has been distorted beyond recognition.

To address the foregoing limitations, in one embodiment of the invention, a combination of Reference-to-Frame and Frame to Frame techniques are used. A flowchart describing this embodiment is illustrated in FIG. **27**. At **2701**, Frame-to-Frame tracking is used to find the points within the first and second frames. At **2703**, process variable N is set to 3 (i.e., representing frame **3**). Then, at **2704**, Reference-to-Frame tracking is used to counter the potential drift between the frames. At **2705**, the value of N is increased (i.e., representing the Nth frame) and, if another frame exists, determined at **2706**, the process returns to **2703** where Frame-to-Frame tracking is employed followed by Reference-to-Frame tracking at **2704**.

In one embodiment, for both Reference-to-Frame and Frame-to-Frame tracking, the camera closest to the normal of the surface is chosen. Correlation is used to find the new x,y locations of the points. See, e.g., APPARATUS AND METHOD FOR PERFORMING MOTION CAPTURE USING A RANDOM PATTERN ON CAPTURE SURFACES," Ser. No. 11/255,854, Filed Oct. 20, 2005, for a description of correlation techniques that may be employed. The z value is extracted from the reconstructed surface. The correlation technique has a number of parameters that can be adjusted to find as many points as possible. For example, the Frame-to-Frame method might search for the points over a relatively large area and use a large window function for matching points. The Reference-to-Frame method might search a smaller area with a smaller window. However, it is often the case that there is no discernible peak or that there are multiple peaks for a particular set of parameters. The point cannot be tracked with sufficient confidence using these parameters. For this reason, in one embodiment of the invention, multiple correlation passes are performed with different sets of parameters. In passes after the first, the search area can be shrunk by using a least squares estimate of the position of a point based on the positions of nearby points that were successfully tracked in previous passes. Care must be taken when selecting the nearby points. For example, points on the upper lip can be physically close to points on the lower lip in one frame but in later frames they can be separated by a substantial distance. Points on the upper lip are not good predictors of the locations of points on the lower lip. Instead of the spatial distance between points the geodesic distance between points when travel is restricted to be along edges of the mesh is a better basis for the weighting function of the least squares fitting. In the example, the path from the upper lip to the lower lip would go around the corners of the mouth—a much longer distance and hence a greatly reduced influence on the locations of points on the opposite lip.

FIG. **28** provides an overview of the foregoing operations. In **2801**, the first set of parameters is chosen. In **2802**, an attempt is made to track vertices given a set of parameters. Success is determined using the criteria described above. In **2802**, the locations of the vertices that were not successfully tracked are estimated from the positions of neighboring vertices that were successfully tracked. In **2804** and **2805**, the set of parameters is updated or the program is terminated. Thus, multiple correlation passes are performed using different sets of parameters.

At times the reconstruction of a surface is imperfect. It can have holes or extraneous bumps. The location of every point is checked by estimating its position from its neighbor's positions. If the tracked location is too different it is suspected that something has gone wrong with either the tracking or with the surface reconstruction. In either case the point is corrected to a best estimate location.

Retrospective Tracking Marker Selection

Many prior art motion capture systems (e.g. the Vicon MX40 motion capture system) utilize markers of one form or another that are attached to the objects whose motion is to be captured. For example, for capturing facial motion one prior art technique is to glue retroreflective markers to the face. Another prior art technique to capture facial motion is to paint dots or lines on the face. Since these markers remain in a fixed position relative to the locations where they are attached to the face, they track the motion of that part of the face as it moves.

Typically, in a production motion capture environment, locations on the face are chosen by the production team where they believe they will need to track the facial motion when they use the captured motion data in the future to drive an animation (e.g. they may place a marker on the eyelid to track the motion of blinking). The problem with this approach is that it often is not possible to determine the ideal location for the markers until after the animation production is in process, which may be months or even years after the motion capture session where the markers were captured. At such time, if the production team determines that one or more markers is in a sub-optimal location (e.g. located at a location on the face where there is a wrinkle that distorts the motion), it is often impractical to set up another motion capture session with the same performer and re-capture the data.

In one embodiment of the invention users specify the points on the capture surfaces that they wish to track after the motion capture data has been captured (i.e. retrospectively relative to the motion capture session, rather than prospectively). Typically, the number of points specified by a user to be tracked for production animation will be far fewer points than the number of vertices of the polygons captured in each frame using the surface capture system of the present embodiment. For example, while over 100,000 vertices may be captured in each frame for a face, typically 1000 tracked vertices or less is sufficient for most production animation applications.

For this example, a user may choose a reference frame, and then select 1000 vertices out of the more than 100,000 vertices on the surface to be tracked. Then, utilizing the vertex tracking techniques described previously and illustrated in FIGS. **27** and **28**, those 1000 vertices are tracked from frame-to-frame. Then, these 1000 tracked points are used by an animation production team for whatever animation they choose to do. If, at some point during this animation production process, the animation production team determines that they would prefer to have one or more tracked vertices moved to different locations on the face, or to have one or more tracked vertices added or deleted, they can specify the changes, and then using the same vertex tracking techniques, these new vertices will be tracked. In fact, the vertices to be tracked can be changed as many times as is needed. The ability to retrospectively change tracking markers (e.g. vertices) is an enormous improvement over prior approaches where all tracked points must be specified prospectively prior to a motion capture session and can not be changed thereafter.

Embodiments of the invention may include various steps as set forth above. The steps may be embodied in machine-executable instructions which cause a general-purpose or special-purpose processor to perform certain steps. Various elements which are not relevant to the underlying principles of the invention such as computer memory, hard drive, input devices, have been left out of the figures to avoid obscuring the pertinent aspects of the invention.

Alternatively, in one embodiment, the various functional modules illustrated herein and the associated steps may be performed by specific hardware components that contain hardwired logic for performing the steps, such as an application-specific integrated circuit ("ASIC") or by any combination of programmed computer components and custom hardware components.

Elements of the present invention may also be provided as a machine-readable medium for storing the machine-executable instructions. The machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, propagation media or other type of machine-readable media suitable for storing electronic instructions. For example, the present invention may be downloaded as a computer program which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Throughout the foregoing description, for the purposes of explanation, numerous specific details were set forth in order to provide a thorough understanding of the present system and method. It will be apparent, however, to one skilled in the art that the system and method may be practiced without some of these specific details. Accordingly, the scope and spirit of the present invention should be judged in terms of the claims which follow.

What is claimed is:

1. A computer-implemented system for performing motion capture of a subject comprising:

a plurality of cameras for capturing a sequence of image frames of the subject over a period of time, each frame having a plurality of vertices defining a captured surface of the subject;

a computing system for processing the sequence of image frames, the computing system having a memory for storing program code and a processor for processing the program code to perform the operations of:

establishing a reference frame having one or more of the plurality of vertices and specifying a location for each of the vertices;

performing frame-to-frame tracking to identify locations of vertices within an N'th frame based on locations of vertices within an (N−1)'th frame or an earlier frame;

performing reference-to-frame tracking to identify locations of vertices within the N'th frame based on the locations of vertices in the reference frame to counter potential drift between the frames;

storing the locations of vertices for use in subsequent reconstruction of the motion of the subject; and

performing the frame-to-frame and reference-to-frame tracking again using a different set of parameters, the parameters defining a search area for the vertices of each frame

wherein multiple correlation passes are performed with the different sets of parameters; and

wherein for passes after the first, the search area is shrunk by using an estimate of the position of a vertex based on the position of nearby vertices that were successfully tracked in the previous passes.

2. The system as in claim 1 wherein

a camera closest to a normal of the surface on which each vertex is located is selected to perform the frame-to-frame and reference-to-frame tracking.

3. The system as in claim 1 wherein the frame-to-frame tracking is performed using a relatively larger window for matching vertices and the reference-to-frame tracking is performed using a relatively smaller window for matching vertices.

4. The system as in claim 1 further comprising:

estimating the location of vertices not found in each frame N based on known locations of neighboring vertices.

5. The system as in claim 1 wherein the computing system includes additional program code executed by the processor to perform the additional operations of: correlating lines or random patterns captured by one of the plurality of cameras with images from other of the plurality of cameras.

6. The system as in claim 5 further comprising:

generating range information for each vertex based on the correlation.

7. The system as in claim 6 wherein range information from multiple cameras is combined by performing the operations of:

treating a 3-dimensional (3D) capture volume of the subject as a scalar field;

using a marching cubes or marching tetrahedrons process to locate an isosurface of the scalar field and create a polygon mesh representing the surface of the subject; and

removing false surfaces.

8. The system as in claim 7 wherein a scalar value of each point in the 3D capture volume is computed based on a weighted sum of scalar values from each of the plurality of cameras.

9. The system as in claim 8 wherein a first weighting component is associated with each camera based on an angle at which the camera is pointed relative to the isosurface normal.

10. The system as in claim 9 wherein a second weighting component is a function of distance of the vertex from the isosurface.

11. The system as in claim 1 wherein the subject is a performer and wherein a random pattern of material is applied to regions of the performer's face to create the vertices to be tracked.

12. The system as in claim 11 wherein the material is phosphorescent paint.

13. The system as in claim 11 further comprising:

a light source to be strobed on and off in response to control signals from the computer system, the light source charging the random pattern when on; and wherein shutters of the plurality of cameras are strobed synchronously with the strobing of the light source to capture sequences of images of the random pattern ("glow frames") as the performer moves or changes facial expressions during a performance, wherein the shutters of the plurality of cameras are open when the light source is off and the shutters are closed when the light source is on.

14. The system as in claim 13 further comprising:

a second plurality of cameras having shutters strobed synchronously with the strobing of the light source to capture images of the performer ("lit frames"), wherein the shutters of the second plurality of cameras are open when the light source is on and the shutters of the second plurality of cameras are closed when the light source is off.

15. The system as in claim 14 wherein the first plurality of cameras are grayscale cameras and the second plurality of cameras are color cameras.

16. The system as in claim 13 wherein the light source comprises a light emitting diode (LED) array.

17. The system as in claim 13 wherein strobing the shutters comprises opening the shutters for a first period of time and closing the shutters for a second period of time, the second period of time being of a different duration than the first period of time.

18. The system as in claim 17 wherein the first period of time is longer than the second period of time.

19. The system as in claim 14 wherein the lit frames and glow frames are separated to generate two separate sets of image data.

20. The system as in claim 14 wherein cameras capturing the lit frames have a sensitivity which is different from cameras capturing the glow frames.

21. The system as in claim 13 wherein the shutters are opened for a first period of time when the light source is on and for a second period of time when the light source is off, wherein the first and second periods of time are unequal.

22. The system as in claim 11 wherein applying the random pattern comprises:

applying phosphorescent material to a sponge; and

applying the sponge upon the performer's face.

23. The system as in claim 11 wherein applying the random pattern comprises:

spraying the random pattern on the performer's face with an airbrush.

24. The system as in claim 11 wherein applying the random pattern comprises:

applying paint to the performer's face through a stencil.

25. The system as in claim **11** wherein the material is phosphorescent paint and wherein applying the random pattern comprises flicking a wire brush containing the phosphorescent paint such that droplets of phosphorescent paint are splattered onto the performer's face.

26. The system as in claim **1** wherein the estimate comprises a least squares estimate.

* * * * *

Exhibit 7

United States of America
United States Patent and Trademark Office

MOVA

Reg. No. 3,843,152

Registered Aug. 31, 2010

MOVA, LLC (CALIFORNIA LIMITED LIABILITY COMPANY)
181 LYTTON AVENUE
PALO ALTO, CA 94301

Int. Cl.: 42

FOR: RENTAL OF COMPUTER HARDWARE AND SOFTWARE FOR USE IN THE FIELD OF ENTERTAINMENT, IN CLASS 42 (U.S. CLS. 100 AND 101).

SERVICE MARK

FIRST USE 9-1-2009; IN COMMERCE 9-1-2009.

PRINCIPAL REGISTER

THE MARK CONSISTS OF STANDARD CHARACTERS WITHOUT CLAIM TO ANY PARTICULAR FONT, STYLE, SIZE, OR COLOR.

THE FOREIGN WORDING IN THE MARK TRANSLATES INTO ENGLISH AS IT MOVES.

SN 78-599,227, FILED 3-31-2005.

LANA PHAM, EXAMINING ATTORNEY

UNITED STATES PATENT AND TRADEMARK OFFICE
DEPARTMENT OF COMMERCE

David J. Kappos

Director of the United States Patent and Trademark Office

Exhibit 8

Int. Cl.: 41

Prior U.S. Cls.: 100, 101, and 107

Reg. No. 3,628,974
Registered May 26, 2009

United States Patent and Trademark Office

SERVICE MARK
PRINCIPAL REGISTER

CONTOUR

MOVA, LLC (CALIFORNIA LIMITED LIABILITY COMPANY)
181 LYTTON STREET
PALO ALTO, CA 94301

FOR: VISUAL EFFECTS AND MOTION PICTURE PRODUCTION SERVICES, ALL IN THE FIELD OF ENTERTAINMENT; ENTERTAINMENT SERVICES, NAMELY, SPECIAL EFFECTS, VISUAL EFFECTS AND ANIMATION SERVICES FEATURING MOTION CAPTURE FOR TRANSLATING MOVEMENT OF A REAL SUBJECT AND MAPPING SUCH MOVEMENT ONTO A 3-DIMENSIONAL COMPUTER-GENERATED MODEL OR AS A COMPUTER-GENERATED SUBJECT, IN CLASS 41 (U.S. CLS. 100, 101 AND 107).

FIRST USE 8-1-2006; IN COMMERCE 7-25-2007.

THE MARK CONSISTS OF STANDARD CHARACTERS WITHOUT CLAIM TO ANY PARTICULAR FONT, STYLE, SIZE, OR COLOR.

SN 78-981,021, FILED 5-4-2006.

DANIEL CAPSHAW, EXAMINING ATTORNEY

CIVIL COVER SHEET

The JS-CAND 44 civil cover sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law, except as provided by local rules of court. This form, approved in its original form by the Judicial Conference of the United States in September 1974, is required for the Clerk of Court to initiate the civil docket sheet. *(SEE INSTRUCTIONS ON NEXT PAGE OF THIS FORM.)*

I. (a) PLAINTIFFS

REARDEN LLC and REARDEN MOVA LLC,

(b) County of Residence of First Listed Plaintiff San Francisco, CA
(EXCEPT IN U.S. PLAINTIFF CASES)

(c) Attorneys *(Firm Name, Address, and Telephone Number)*
HAGENS BERMAN SOBOL SHAPIRO LLP, 715 Hearst Ave., Ste. 202
Berkeley, CA 94710, Telephone: (510) 725-3000

DEFENDANTS

THE WALT DISNEY COMPANY, WALT DISNEY MOTION PICTURES GROUP, INC., BUENA VISTA HOME ENTERTAINMENT, INC., MARVEL STUDIOS, LLC, and MANDEVILLE FILMS, INC.,

County of Residence of First Listed Defendant
(IN U.S. PLAINTIFF CASES ONLY)

NOTE: IN LAND CONDEMNATION CASES, USE THE LOCATION OF THE TRACT OF LAND INVOLVED.

Attorneys *(If Known)*

II. BASIS OF JURISDICTION *(Place an "X" in One Box Only)*

- ☐ 1 U.S. Government Plaintiff
- ☒ 3 Federal Question *(U.S. Government Not a Party)*
- ☐ 2 U.S. Government Defendant
- ☐ 4 Diversity *(Indicate Citizenship of Parties in Item III)*

III. CITIZENSHIP OF PRINCIPAL PARTIES *(Place an "X" in One Box for Plaintiff and One Box for Defendant)*
(For Diversity Cases Only)

	PTF	DEF		PTF	DEF
Citizen of This State	☐ 1	☐ 1	Incorporated *or* Principal Place of Business In This State	☐ 4	☐ 4
Citizen of Another State	☐ 2	☐ 2	Incorporated *and* Principal Place of Business In Another State	☐ 5	☐ 5
Citizen or Subject of a Foreign Country	☐ 3	☐ 3	Foreign Nation	☐ 6	☐ 6

IV. NATURE OF SUIT *(Place an "X" in One Box Only)*

CONTRACT
- 110 Insurance
- 120 Marine
- 130 Miller Act
- 140 Negotiable Instrument
- 150 Recovery of Overpayment Of Veteran's Benefits
- 151 Medicare Act
- 152 Recovery of Defaulted Student Loans (Excludes Veterans)
- 153 Recovery of Overpayment of Veteran's Benefits
- 160 Stockholders' Suits
- 190 Other Contract
- 195 Contract Product Liability
- 196 Franchise

REAL PROPERTY
- 210 Land Condemnation
- 220 Foreclosure
- 230 Rent Lease & Ejectment
- 240 Torts to Land
- 245 Tort Product Liability
- 290 All Other Real Property

TORTS

PERSONAL INJURY
- 310 Airplane
- 315 Airplane Product Liability
- 320 Assault, Libel & Slander
- 330 Federal Employers' Liability
- 340 Marine
- 345 Marine Product Liability
- 350 Motor Vehicle
- 355 Motor Vehicle Product Liability
- 360 Other Personal Injury
- 362 Personal Injury -Medical Malpractice

PERSONAL INJURY
- 365 Personal Injury – Product Liability
- 367 Health Care/ Pharmaceutical Personal Injury Product Liability
- 368 Asbestos Personal Injury Product Liability

PERSONAL PROPERTY
- 370 Other Fraud
- 371 Truth in Lending
- 380 Other Personal Property Damage
- 385 Property Damage Product Liability

CIVIL RIGHTS
- 440 Other Civil Rights
- 441 Voting
- 442 Employment
- 443 Housing/ Accommodations
- 445 Amer. w/Disabilities–Employment
- 446 Amer. w/Disabilities–Other
- 448 Education

PRISONER PETITIONS

HABEAS CORPUS
- 463 Alien Detainee
- 510 Motions to Vacate Sentence
- 530 General
- 535 Death Penalty

OTHER
- 540 Mandamus & Other
- 550 Civil Rights
- 555 Prison Condition
- 560 Civil Detainee– Conditions of Confinement

FORFEITURE/PENALTY
- 625 Drug Related Seizure of Property 21 USC § 881
- 690 Other

LABOR
- 710 Fair Labor Standards Act
- 720 Labor/Management Relations
- 740 Railway Labor Act
- 751 Family and Medical Leave Act
- 790 Other Labor Litigation
- 791 Employee Retirement Income Security Act

IMMIGRATION
- 462 Naturalization Application
- 465 Other Immigration Actions

BANKRUPTCY
- 422 Appeal 28 USC § 158
- 423 Withdrawal 28 USC § 157

PROPERTY RIGHTS
- ☒ 820 Copyrights
- 830 Patent
- 835 Patent—Abbreviated New Drug Application
- 840 Trademark

SOCIAL SECURITY
- 861 HIA (1395ff)
- 862 Black Lung (923)
- 863 DIWC/DIWW (405(g))
- 864 SSID Title XVI
- 865 RSI (405(g))

FEDERAL TAX SUITS
- 870 Taxes (U.S. Plaintiff or Defendant)
- 871 IRS–Third Party 26 USC § 7609

OTHER STATUTES
- 375 False Claims Act
- 376 Qui Tam (31 USC § 3729(a))
- 400 State Reapportionment
- 410 Antitrust
- 430 Banks and Banking
- 450 Commerce
- 460 Deportation
- 470 Racketeer Influenced & Corrupt Organizations
- 480 Consumer Credit
- 490 Cable/Sat TV
- 850 Securities/Commodities/ Exchange
- 890 Other Statutory Actions
- 891 Agricultural Acts
- 893 Environmental Matters
- 895 Freedom of Information Act
- 896 Arbitration
- 899 Administrative Procedure Act/Review or Appeal of Agency Decision
- 950 Constitutionality of State Statutes

V. ORIGIN *(Place an "X" in One Box Only)*

- ☒ 1 Original Proceeding
- ☐ 2 Removed from State Court
- ☐ 3 Remanded from Appellate Court
- ☐ 4 Reinstated or Reopened
- ☐ 5 Transferred from Another District *(specify)*
- ☐ 6 Multidistrict Litigation–Transfer
- ☐ 8 Multidistrict Litigation–Direct File

VI. CAUSE OF ACTION

Cite the U.S. Civil Statute under which you are filing **(Do not cite jurisdictional statutes unless diversity)**:
28 U.S.C. § 1400(a) and 1391 (b), (c) and (d)

Brief description of cause:
Copyright infringement claims.

VII. REQUESTED IN COMPLAINT:

☐ CHECK IF THIS IS A **CLASS ACTION** UNDER RULE 23, Fed. R. Civ. P.

DEMAND $

CHECK YES only if demanded in complaint:
JURY DEMAND: ☒ Yes ☐ No

VIII. RELATED CASE(S), IF ANY *(See instructions)*:

JUDGE District Judge Jon S. Tigar DOCKET NUMBER Case No. 15-cv-00797

IX. DIVISIONAL ASSIGNMENT (Civil Local Rule 3-2)

(Place an "X" in One Box Only) ☒ **SAN FRANCISCO/OAKLAND** ☐ **SAN JOSE** ☐ **EUREKA-MCKINLEYVILLE**

DATE 07/17/2017 **SIGNATURE OF ATTORNEY OF RECORD** /s/ Rio S. Pierce