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(54) **MOTION CAPTURE USING SYNCHRONIZED AND ALIGNED DEVICES**

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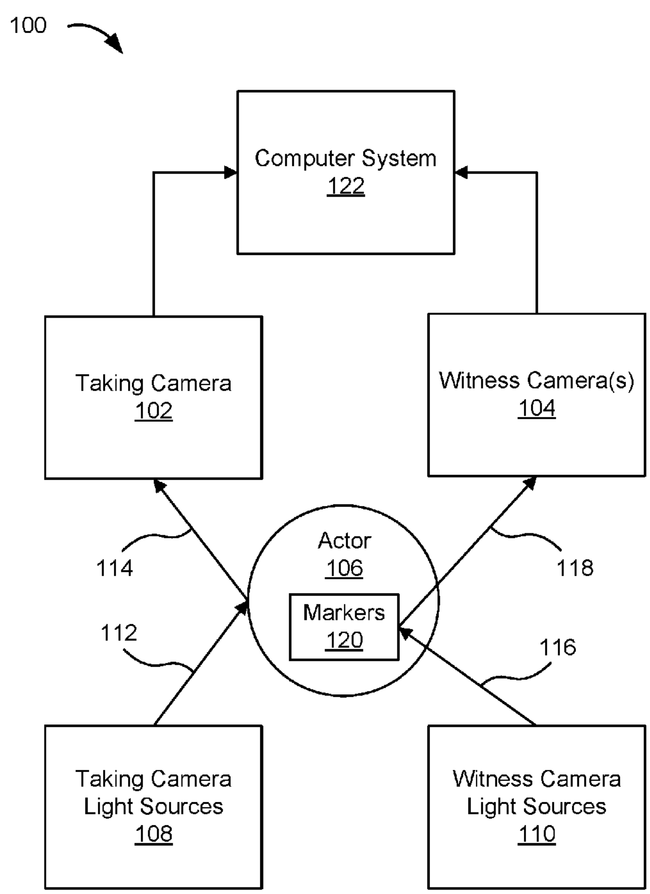
(57) **ABSTRACT**

A motion capture system comprising: a master clock configured to repeatedly generate and output, at a frame rate, a primary clock signal that conveys when a video frame starts; a first camera configured to capture light within a first set of wavelengths and operably coupled to receive the master clock signal and initiate an image capture sequence on a frame-by-frame basis in fixed phase relationship with the primary clock signal to generate a first set of images at the frame rate from light captured within the first set of wavelengths; a synchronization module operably coupled to receive the master clock signal from the master clock and configured to generate a synchronization signal offset in time from and in a fixed relationship with the primary clock signal; and a second camera configured to capture light within a second set of wavelengths, different than the first set of wavelengths, and operably coupled to receive the synchronization signal and initiate an image capture sequence on the frame-by-frame basis in a fixed phase relationship with the synchronization signal to generate a second set of images at the frame rate from light captured within the second set of wavelengths; wherein the amount of time the synchronization signal is offset from the master clock signal aligns, within each frame, the image capture sequence of the second camera with the image capture sequence of the first camera.



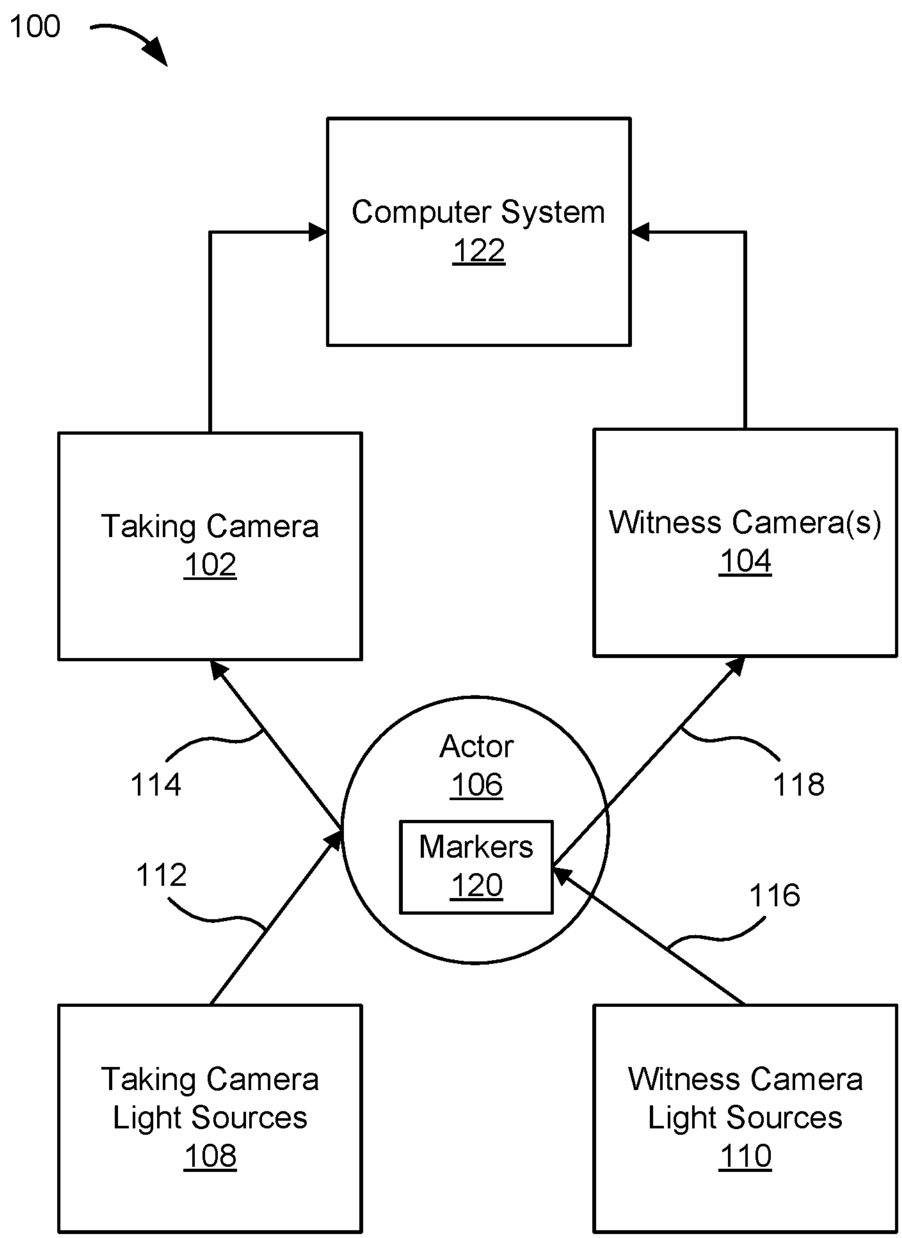

100
Computer System
122
Taking Camera
102
Witness Camera(s)
104
Actor
106
Markers
120
114
118
112
116
Taking Camera
Light Sources
108
Witness Camera
Light Sources
110

FIG. 1

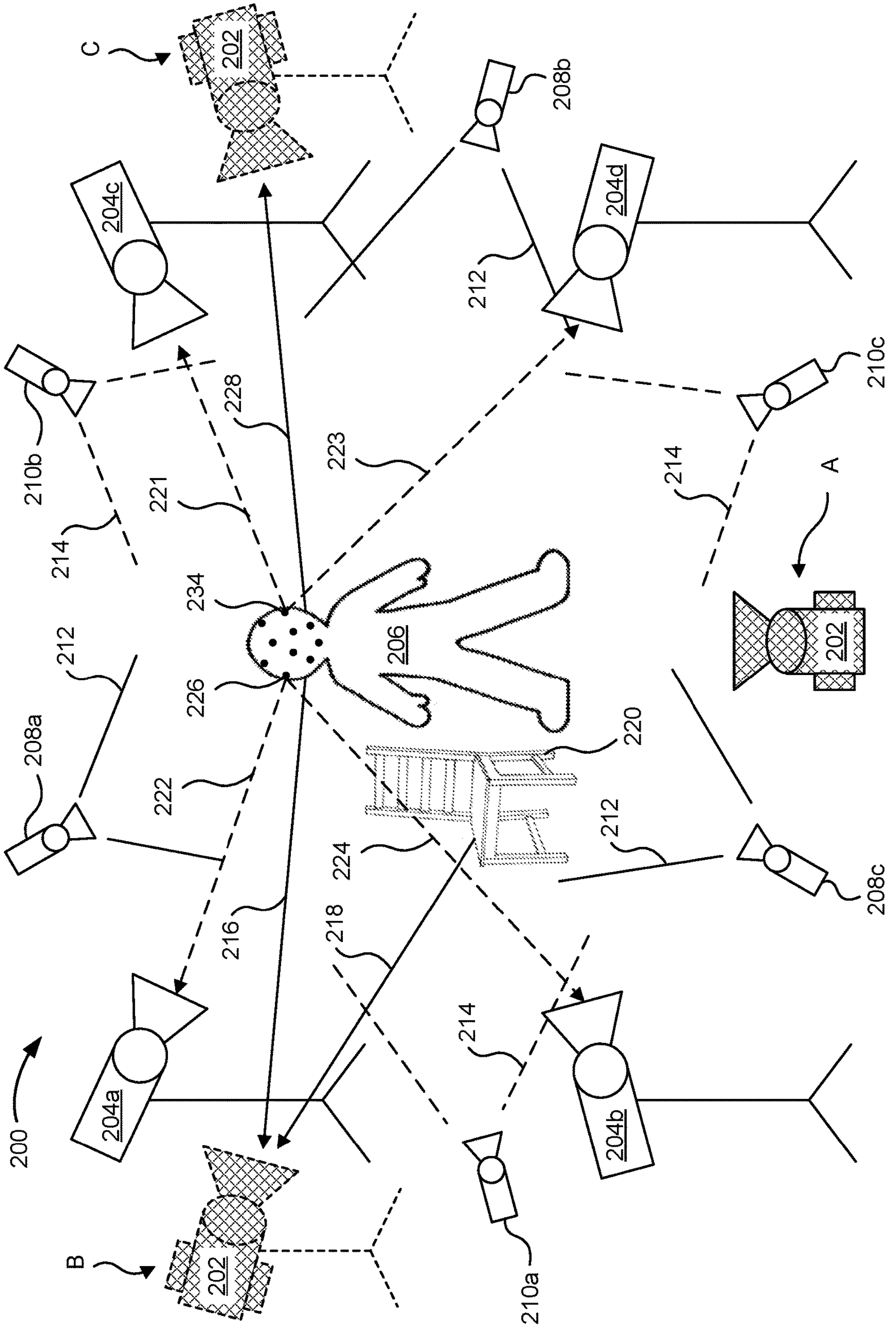

200
202
202
202
204a
204b
204c
204d
206
208a
208b
208c
210a
210b
210c
212
212
212
212
214
214
214
214
216
218
220
221
222
223
224
226
228
234
A
B
C

FIG. 2

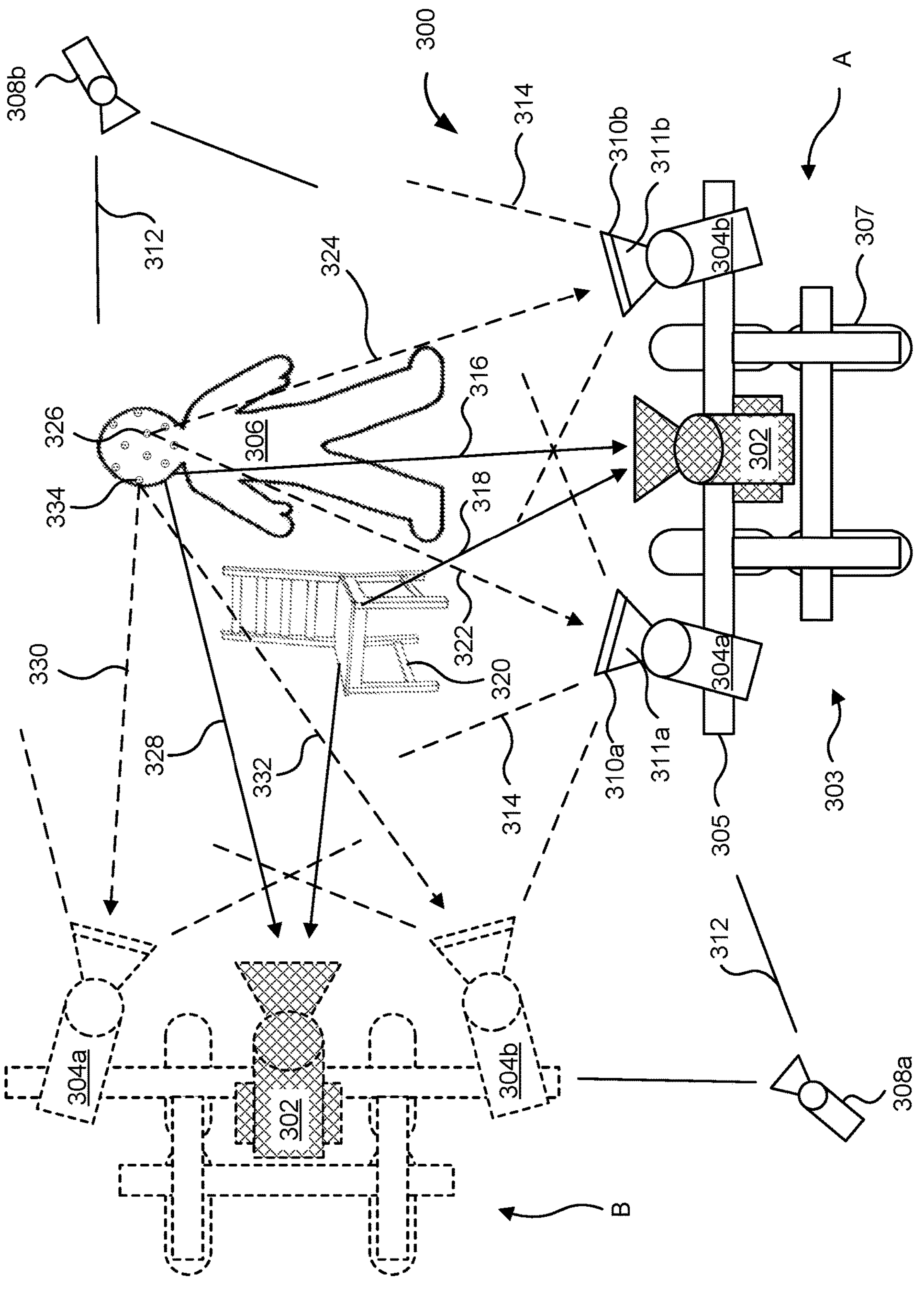

300
308b
312
314
310b
311b
304b
A
307
324
316
326
306
302
318
334
322
320
304a
310a
311a
305
303
330
328
332
314
312
308a
304a
302
304b
B

FIG. 3

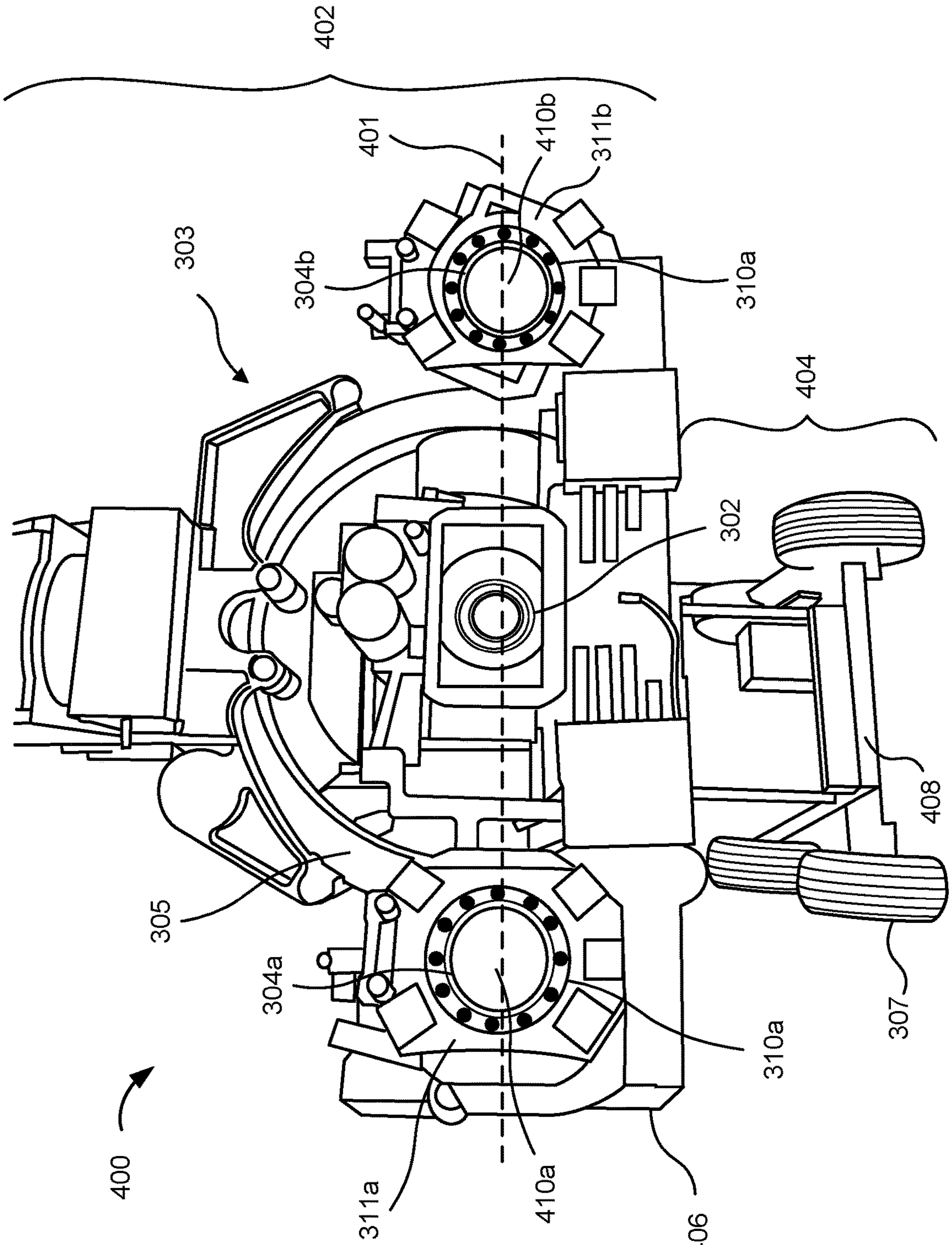

402
401
410b
311b
303
304b
310a
404
302
305
304a
310a
408
307
400
311a
410a
406

FIG. 4

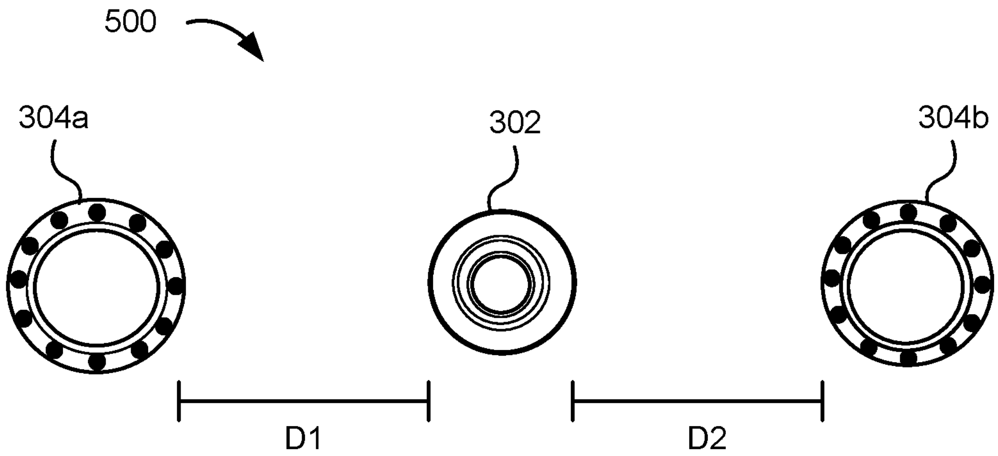


FIG. 5A

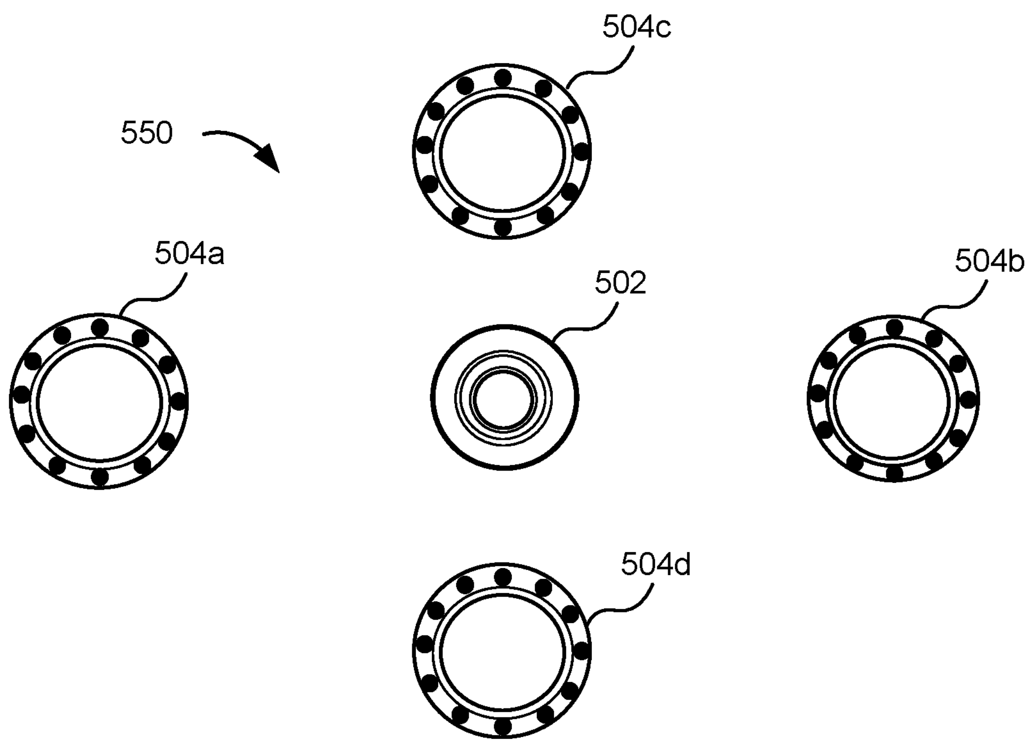


FIG. 5B

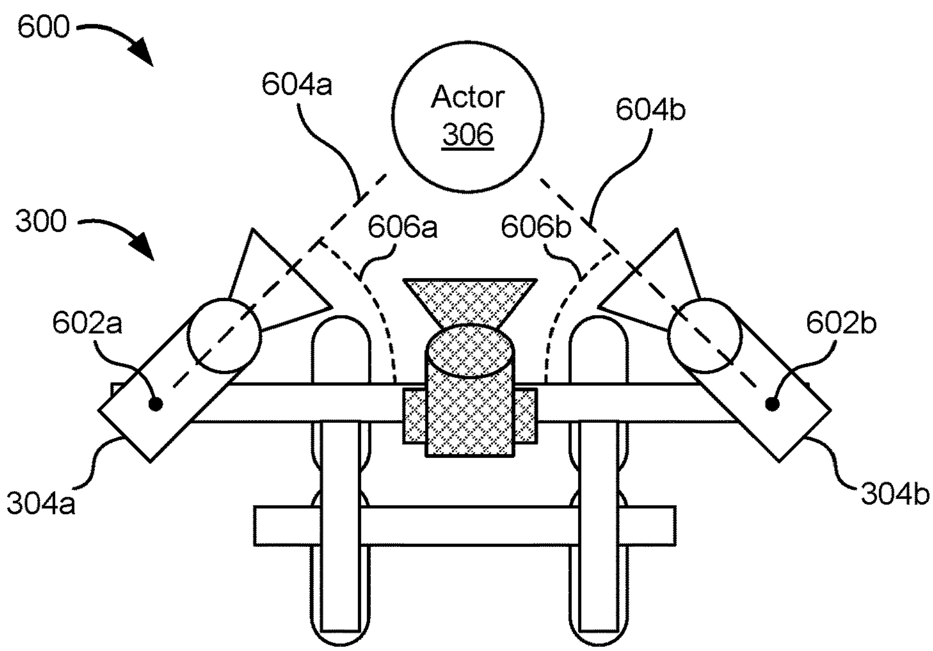

600
Actor
306
604a
604b
300
606a
606b
602a
602b
304a
304b

FIG. 6A

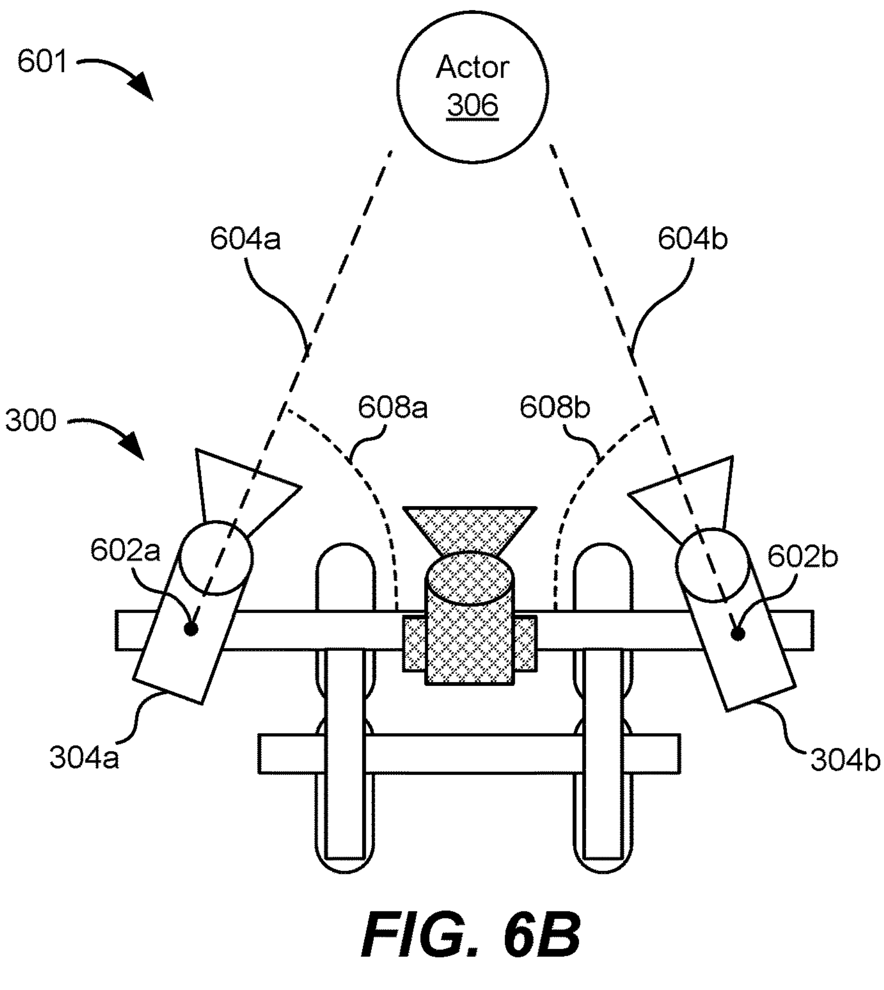

601
Actor
306
604a
604b
300
608a
608b
602a
602b
304a
304b

FIG. 6B

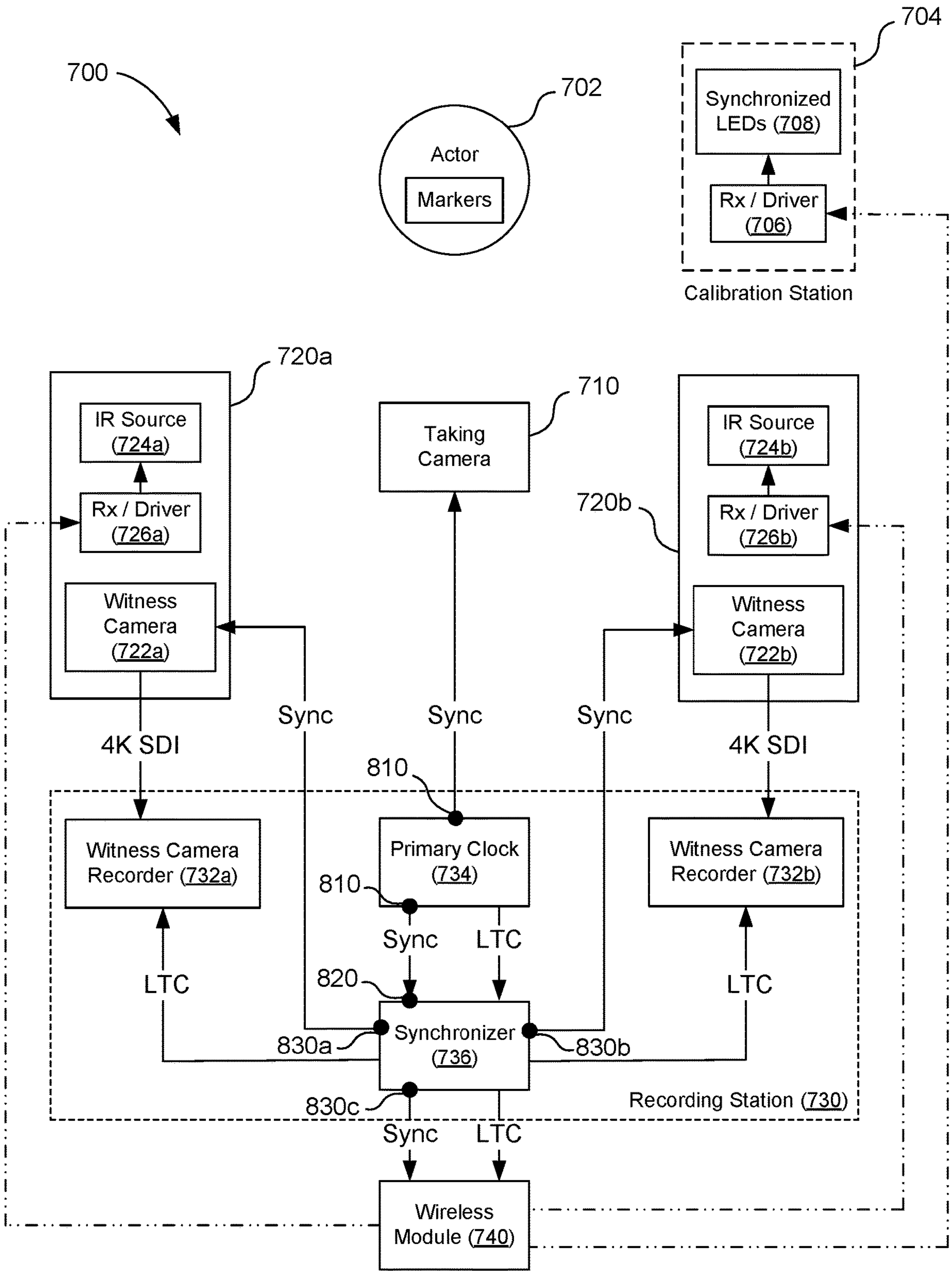

700
702
Actor
Markers
704
Synchronized LEDs (708)
Rx / Driver (706)
Calibration Station
720a
IR Source (724a)
Rx / Driver (726a)
Witness Camera (722a)
710
Taking Camera
720b
IR Source (724b)
Rx / Driver (726b)
Witness Camera (722b)
4K SDI
Sync
Sync
Sync
4K SDI
810
Witness Camera Recorder (732a)
Primary Clock (734)
Witness Camera Recorder (732b)
810
Sync
LTC
LTC
820
LTC
Synchronizer (736)
830a
830b
830c
Recording Station (730)
Sync
LTC
Wireless Module (740)

FIG. 7

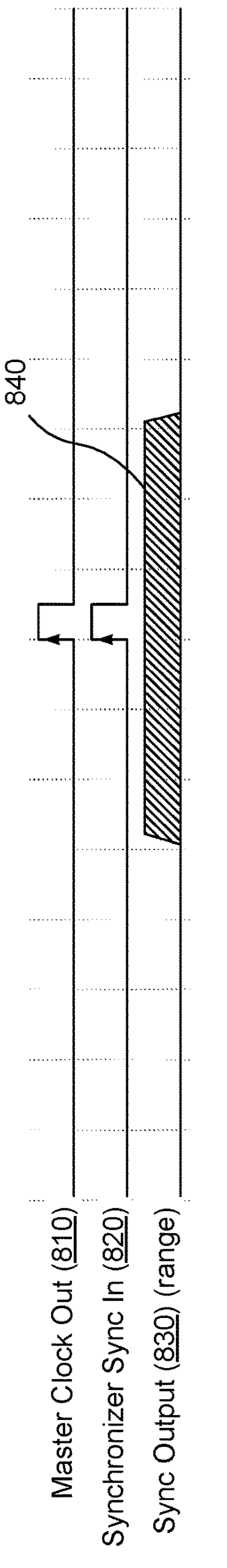


FIG. 8A

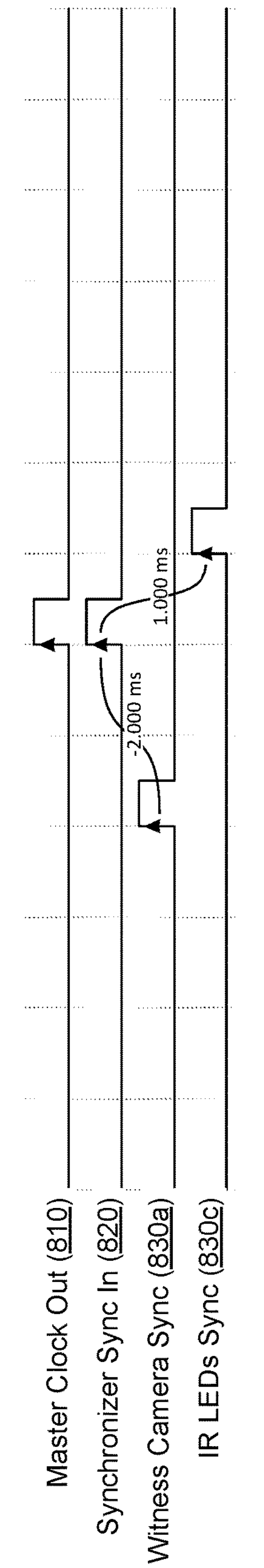


FIG. 8B

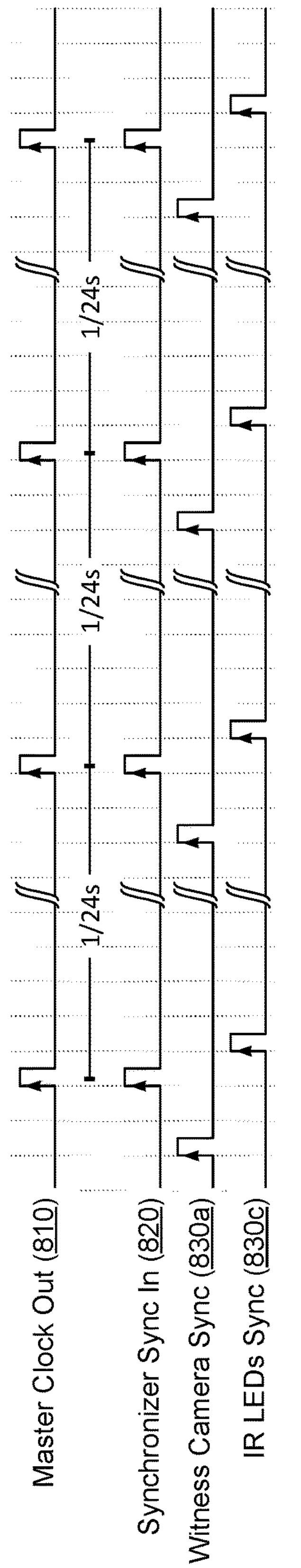


FIG. 8C

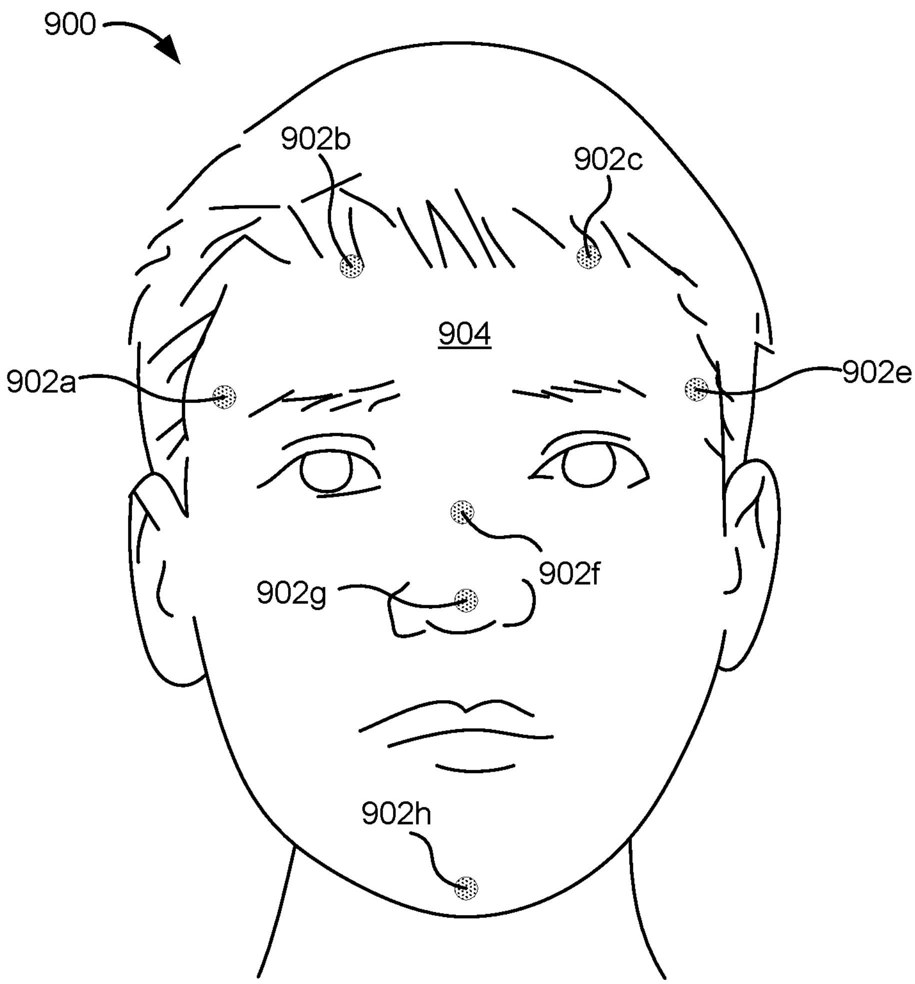


FIG. 9

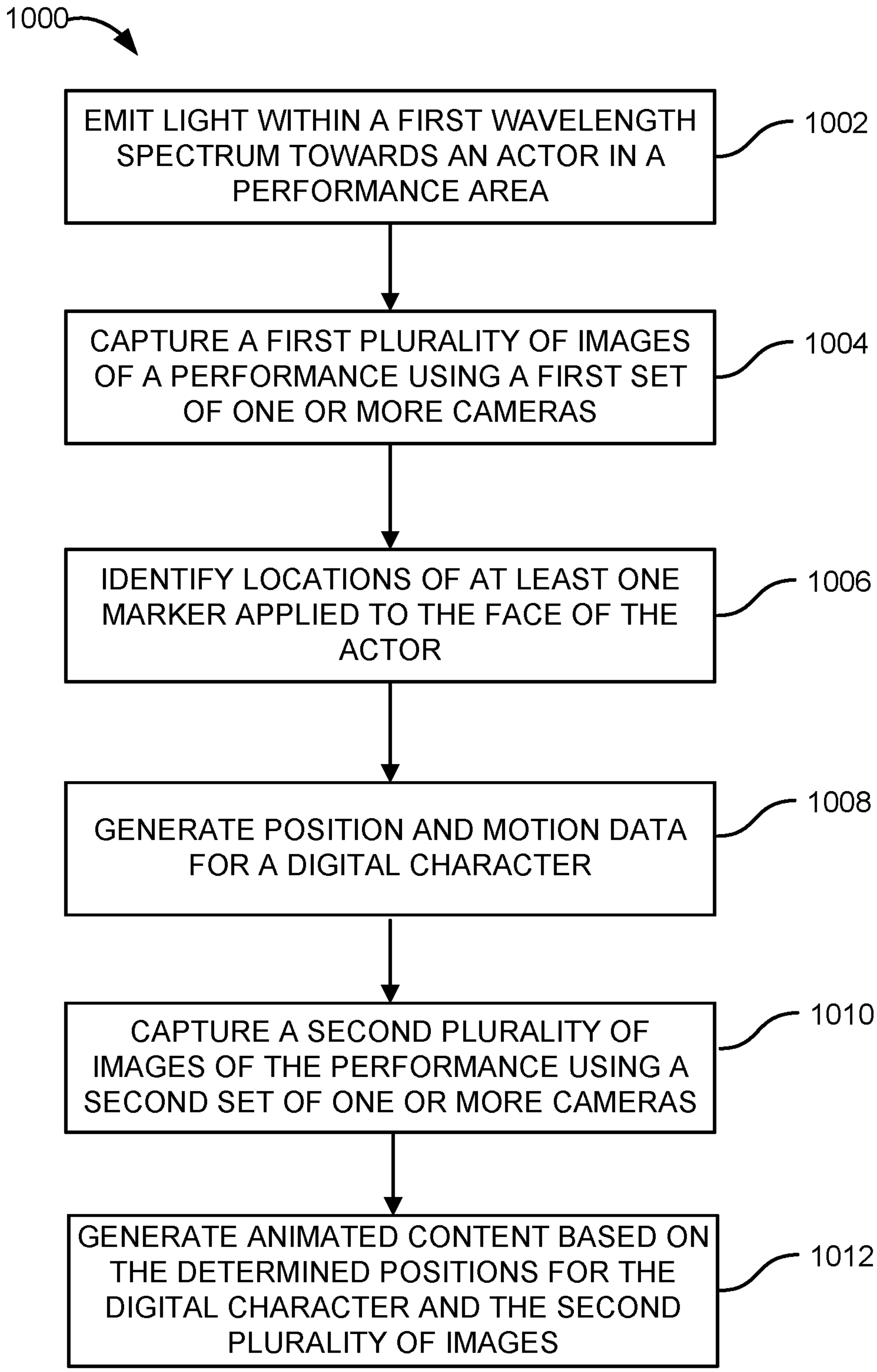

1000
EMIT LIGHT WITHIN A FIRST WAVELENGTH SPECTRUM TOWARDS AN ACTOR IN A PERFORMANCE AREA
1002
CAPTURE A FIRST PLURALITY OF IMAGES OF A PERFORMANCE USING A FIRST SET OF ONE OR MORE CAMERAS
1004
IDENTIFY LOCATIONS OF AT LEAST ONE MARKER APPLIED TO THE FACE OF THE ACTOR
1006
GENERATE POSITION AND MOTION DATA FOR A DIGITAL CHARACTER
1008
CAPTURE A SECOND PLURALITY OF IMAGES OF THE PERFORMANCE USING A SECOND SET OF ONE OR MORE CAMERAS
1010
GENERATE ANIMATED CONTENT BASED ON THE DETERMINED POSITIONS FOR THE DIGITAL CHARACTER AND THE SECOND PLURALITY OF IMAGES
1012

FIG. 10

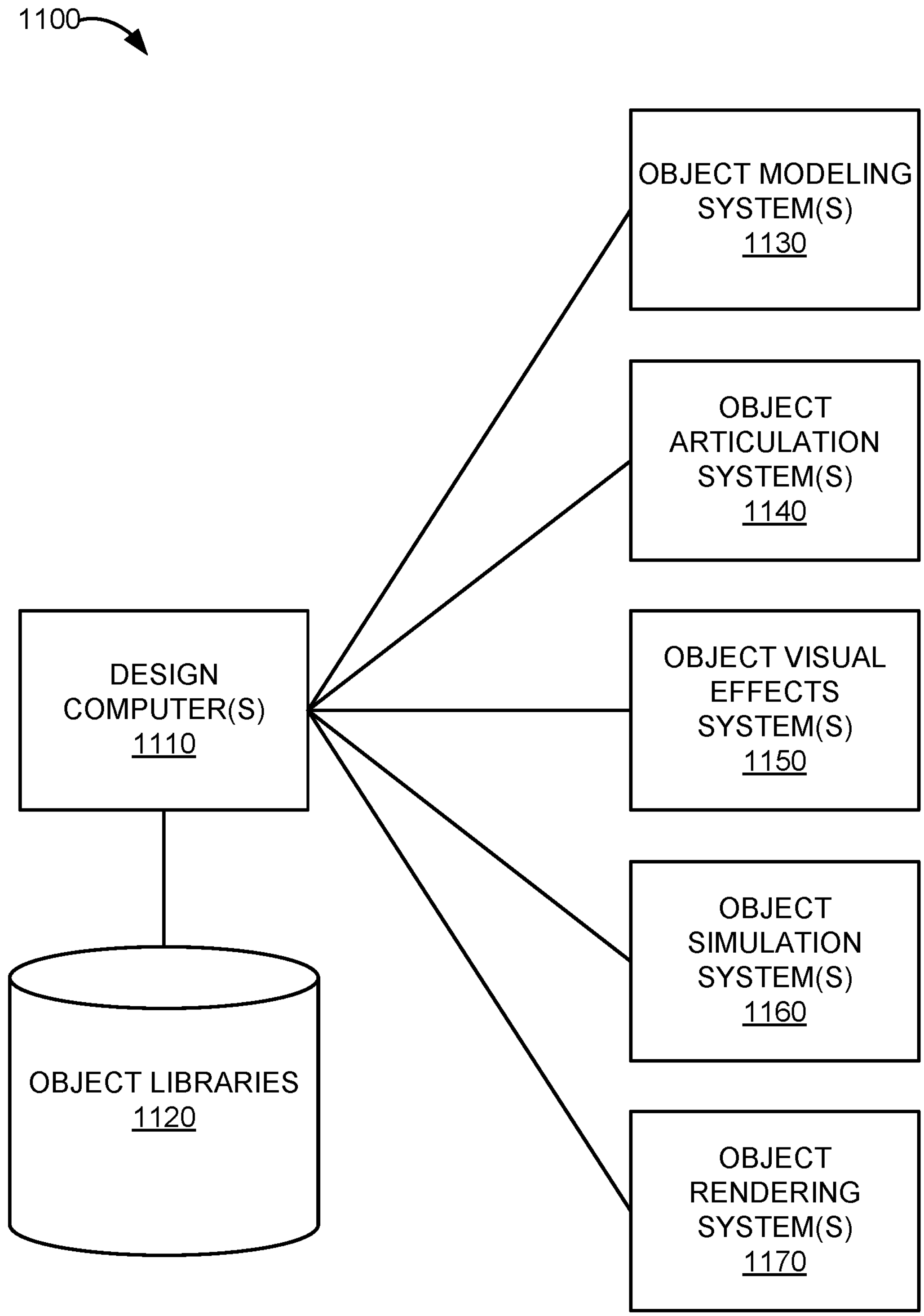

1100
OBJECT MODELING SYSTEM(S) 1130
OBJECT ARTICULATION SYSTEM(S) 1140
DESIGN COMPUTER(S) 1110
OBJECT VISUAL EFFECTS SYSTEM(S) 1150
OBJECT SIMULATION SYSTEM(S) 1160
OBJECT LIBRARIES 1120
OBJECT RENDERING SYSTEM(S) 1170

FIG. 11

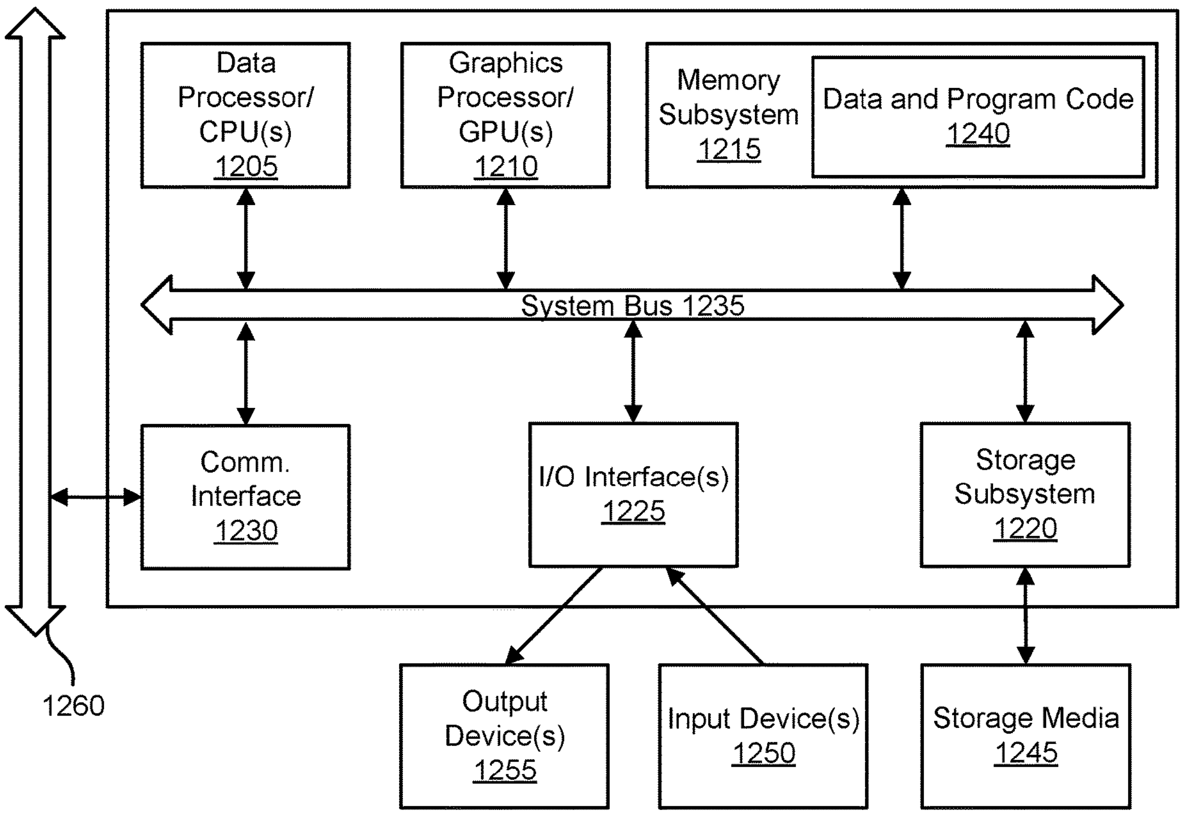

Data Processor/ CPU(s) 1205
Graphics Processor/ GPU(s) 1210
Memory Subsystem 1215
Data and Program Code 1240
System Bus 1235
Comm. Interface 1230
I/O Interface(s) 1225
Storage Subsystem 1220
Output Device(s) 1255
Input Device(s) 1250
Storage Media 1245
1260

FIG. 12

MOTION CAPTURE USING SYNCHRONIZED AND ALIGNED DEVICES

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 63/330,492, filed on Apr. 13, 2022, the disclosure of which is hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

[0002] Computer animation is the process of generating animated images of objects in a computer environment. In the film industry, computer animation is often used to animate the natural movement of humans for creating realistic characters in a film that have humanoid features and mannerisms. This type of animation is known in the film industry as motion-capture or performance capture. To capture the natural movements of a human, an actor is equipped with a number of markers, and a number of cameras track the positions of the markers in space as the actor moves. This technique allows the actor's movements and expressions to be captured, and the captured movements and expressions can then be manipulated in a digital environment to produce content, e.g., footage for a motion picture.

[0003] Such motion capture systems however have shortcomings. For instance, in order to accurately capture an actor's facial expressions some such systems may include head-mounted cameras and visible markers that interfere with the performance of the actor. Some motion capture systems have been developed that can capture facial expressions without head-mounted cameras and are thus an improvement over older systems. While some of such systems have been effective, improved systems and methods for motion capture are still desired.

SUMMARY

[0004] Embodiments provide systems and methods for motion capture to generate content (e.g., motion pictures, television programming, videos, etc.) using synchronized devices that can be precisely aligned with each other. For example, embodiments can synchronize and align multiple cameras within a motion capture system such that each camera initiates its image capture sequence (e.g., opening the shutters of each camera), within each frame, at the same time within microsecond precision.

[0005] Embodiments can also accurately capture an actor's facial expression without using head-mounted cameras. In some embodiments, an actor or other performing being can have multiple markers on his or her face that are essentially invisible to the human eye, but that can be clearly captured by camera systems of the present disclosure. Embodiments of the disclosure can capture the performance using two different camera systems, neither of which need be mounted on the actor and each of which can observe the same performance but capture different images of that performance. For instance, a first camera system can capture the performance within a first light wavelength spectrum (e.g., visible light spectrum), and a second camera system can simultaneously capture the performance in a second light wavelength spectrum different from the first spectrum (e.g., invisible light spectrum such as the IR light spectrum). The images captured by the first and second camera systems can be combined to generate content, such as animated content. Because the markers are invisible to the first camera system but clearly visible to the second camera system, images captured by the first camera system may not need to be significantly edited to remove any markers on the actor's face and can be used for various content production activities, such as generating movement of a digital or animated character. And, images captured by the second camera system can be used to position the head of an actor within a set or stage. Thus, the images can be used directly for generating content without needing to capture two separate performances.

[0006] In some embodiments, the first and second camera systems can be standalone cameras or mounted on a movable rig. Thus, these systems eliminate the need for head-mounted cameras for the motion capture of an actor's face. Eliminating the need for head-mounted cameras minimizes actor discomfort and improves actor performance and satisfaction.

[0007] In some embodiments, a motion capture system is provided that includes: a master clock, first and second cameras and a synchronization module. The master clock can be configured to repeatedly generate and output, at a frame rate, a primary clock signal that conveys when a video frame starts. The first camera can be configured to capture light within a first set of wavelengths and operably coupled to receive the master clock signal and initiate an image capture sequence on a frame-by-frame basis in fixed phase relationship with the primary clock signal to generate a first set of images at the frame rate from light captured within the first set of wavelengths. The synchronization module can be operably coupled to receive the master clock signal from the master clock and configured to generate a synchronization signal offset in time from and in a fixed relationship with the primary clock signal. And, the second camera can be configured to capture light within a second set of wavelengths, different than the first set of wavelengths, and operably coupled to receive the synchronization signal and initiate an image capture sequence on the frame-by-frame basis in a fixed phase relationship with the synchronization signal to generate a second set of images at the frame rate from light captured within the second set of wavelengths. Additionally, the amount of time the synchronization signal is offset from the master clock signal can align, within each frame, the image capture sequence of the second camera with the image capture sequence of the first camera.

[0008] According to some embodiments, a motion capture system is provided that includes: a primary clock configured to repeatedly generate and output, at a frame rate, a primary clock signal that conveys when video frames start; a first camera configured to capture light within a first set of wavelengths comprising the visible light spectrum and generate images from the captured light, wherein the first camera includes a first shutter and is operably coupled to receive the primary clock signal and activate the first shutter in a fixed phase relationship with the primary clock signal to capture a first set of images at the frame rate; a synchronization module operably coupled to receive the primary clock signal from the primary clock and configured to generate and output a synchronization signal offset from and in a fixed relationship with the primary clock signal; a second camera configured to capture light within a second set of wavelengths comprising infrared light and generate images from the captured light, wherein the second camera includes a second shutter and is operably coupled to receive the synchronization signal and activate the second shutter in fixed phase relationship with the synchronization signal to align the second camera with the first camera and capture a second sets of images at the frame rate; and a third camera configured to capture light within the second set of wavelengths and generate images from the captured light, wherein the third camera includes a third shutter and is operably coupled to receive the synchronization signal and activate the third shutter in fixed phase relationship with the synchronization signal to align the third camera with the first camera and capture a third set of images at the frame rate.

[0009] In some embodiments, a computer-implemented method of capturing motion with a motion capture system is provided. The method can include: generating and outputting, at a frame rate, a primary clock signal that conveys when a video frame starts; controlling a first camera with the primary clock signal to capture a first plurality of images of an actor in a performance area, wherein the first camera is operable to capture light at wavelengths in a first spectrum comprising visible light; emitting infrared light from an infrared light source at towards the actor in the performance area; generating a synchronization signal offset from and in a fixed relationship with the primary clock signal; and controlling a second camera with the synchronization signal to align the second camera with the first camera and capture a second plurality of images of the actor concurrent with capturing the first plurality of images of the actor, wherein the second camera is operable to capture light at infrared wavelengths.

[0010] In various implementations, the motion capture system and disclosed method can include one or more of the following features. The synchronization module can be configured to generate the synchronization signal by moving the output from master or primary clock, advancing or delaying the output, with microsecond precision in order to adjust for different timing characteristics of downstream devices. The synchronization module can be configured to generate and output a plurality of different synchronization signals offset from and in a fixed relationship with the master or primary clock signal, where a first synchronization signal in the plurality of synchronization signals is offset from the clock signal by X microseconds and a second synchronization signal in the plurality of synchronization signals is offset from the clock signal by Y microseconds where X is different than Y. The synchronization signal received by the second camera can be the first synchronization signal, and the driver can be operatively coupled to the synchronization module to receive the second synchronization signal and activate the light source in fixed phase relationship with the second synchronization signal to align the pulses of light generated by the light source with the image capture sequence of the second camera. The first synchronization signal can be offset from the master or primary clock by a negative amount and the second synchronization signal is offset from the master or primary clock by a positive amount. The first, second and third cameras can be mounted on a single support frame of a movable rig. The second and third cameras can be mounted on the moveable rig on opposing sides of the first camera. The first camera can be a taking camera and the second camera can be a witness camera. The first set of wavelengths can include (or be limited to) visible light while the second set of wavelengths can include (or be limited to) infrared light, and in some embodiments, the first and second sets of wavelengths do not include any overlapping wavelengths. The frame rate can be between 24 to 60 frames per second.

[0011] In additional implementations, the motion capture system can further include one or more of the following features. The motion capture system can further include a light source and a driver operatively coupled to the light source. The driver can be configured to generate, with the light source, pulses of light, synchronized with the frame rate, at a wavelength within the second set of wavelengths. The motion capture system can further include a third camera configured to capture light within the second set of wavelengths and operably coupled to receive the synchronization signal and initiate an image capture sequence on the frame-by-frame basis in a fixed phase relationship with the synchronization signal to generate a third set of images at the frame rate from light captured within the second set of wavelengths. The motion capture system can further include a wireless module coupled to receive the synchronization signal at an input and wirelessly transmit the synchronization signal to one or more downstream devices.

[0012] A better understanding of the nature and advantages of embodiments of the present disclosure may be gained with reference to the following detailed description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a block diagram of an exemplary motion capture system, according to some embodiments of the present disclosure.

[0014] FIG. **2** is a simplified diagram of an exemplary motion capture system configured with a taking camera and stationary witness cameras, according to some embodiments of the present disclosure.

[0015] FIG. **3** is a simplified diagram of an exemplary motion capture system configured with a taking camera and two witness cameras, all of which are mounted on a movable rig, according to some embodiments of the present disclosure.

[0016] FIG. **4** is a detailed, front-facing, perspective view of a motion capture system configured as a movable rig, according to some embodiments of the present disclosure.

[0017] FIGS. **5**A-**5**B are simplified illustrations of only the front ends of a taking camera and witness cameras in different camera arrangements, according to some embodiments of the present disclosure.

[0018] FIG. **6**A is a simplified diagram of an exemplary configuration of a motion capture system where an actor is positioned close to the system, according to some embodiments of the present disclosure.

[0019] FIG. **6**B is a simplified diagram of an exemplary configuration of a motion capture system where an actor is positioned far away from the system, according to some embodiments of the present disclosure.

[0020] FIG. **7** is a simplified block diagram of an exemplary motion capture system according to some embodiments of the present disclosure.

[0021] FIGS. **8**A-**8**C are simplified timing diagrams of different devices that can be part of a motion capture system according to some embodiments.

[0022] FIG. **9** is a simplified illustration of exemplary positions for gel-based markers that enable motion capture of the skull of an actor during a performance, according to some embodiments of the present disclosure.

[0023] FIG. **10** is a flow diagram of a method for performing motion capture with a motion capture system, according to some embodiments of the present disclosure.

[0024] FIG. **11** is a simplified block diagram of system for creating computer graphics imagery (CGI) and computer-aided animation that may implement or incorporate various embodiments in accordance with the disclosure.

[0025] FIG. **12** is a block diagram of an exemplary computer system, according to some embodiments of the present disclosure.

[0026] The present invention will now be described in detail with reference to certain embodiments thereof as illustrated in the above-referenced drawings. In the following description, 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 or all of these specific details. In other instances, well known details have not been described in detail in order not to unnecessarily obscure the present invention.

DETAILED DESCRIPTION

[0027] Embodiments of the present disclosure describe a motion capture system that includes two types of cameras for generating content. The first type of camera can be a taking camera configured to capture images of an actor in the visible light wavelength spectrum. The second type of camera can be a witness camera configured to capture images of markers on the actor in an invisible light wavelength spectrum, e.g., infrared (IR) light wavelength spectrum. In some embodiments, the markers on the actor are designed to reflect light only in the IR light wavelength spectrum. Thus, the markers may not be visible to the taking camera, but clearly visible to the witness camera(s). It is to be appreciated that the words "visible" and "invisible" used herein are to be interpreted in relation to what is detectable by the naked eye. By being configured to capture light in different spectrums, the taking camera and the one or more witness cameras can simultaneously capture different aspects of a scene based on their respective light wavelengths, thereby eliminating the need to capture two separate performances of the same scene to generate content.

[0028] In some embodiments, the witness camera(s) are standalone cameras that are stationary and positioned to capture markers on an actor from one point of view. Each witness camera can be positioned in different locations around a set so that the markers on the actor can be captured from different angles. The taking camera, on the other hand, can be a standalone camera like the witness cameras, but it might not be stationary. For instance, the taking camera can move around the set while the witness camera(s) are stationary. In some additional embodiments, the motion capturing system can be mounted on the same chassis of a single, movable rig. As an example, a motion capturing system can include a taking camera and two witness cameras laterally positioned on opposite sides of the taking camera. All three cameras can be pointing in the same general direction such that all three cameras can capture the same scene but at different angles. By separating taking and witness cameras from an actor's head, the actor can be less distracted during takes and be more comfortable throughout the shoot. Furthermore, mounting the motion capturing system on the same rig allows the entire system to be easily moved around a set.

[0029] Embodiments described herein allow the taking and witness cameras to be precisely synchronized and aligned with each other even if the cameras have different timing characteristics as is often the case with cameras from different manufacturers or of models.

[0030] Details of such motion capture systems will be discussed in detail further herein.

I. Motion Capture System

[0031] FIG. **1** is a simplified schematic diagram of an exemplary motion capture system **100**, according to some embodiments of the present disclosure. Motion capture system **100** includes a taking camera **102** and one or more witness cameras **104**. Each of taking camera **102** and witness camera(s) **104** can be any suitable image capturing device that can measure light and generate an image based on the measured light. In some embodiments, taking camera **102** is a first type of camera that can measure light in the visible light wavelength spectrum, and witness camera(s) **104** is a second type of camera that can measure light in the invisible light wavelength spectrum, where the visible and invisible light spectrums do not overlap. For example, taking camera **102** can be an RGB camera that can generate images by measuring light at wavelengths between approximately 390 to 700 nm, and witness camera(s) **104** can be two IR cameras that can generate images by measuring light at wavelengths between approximately 701 nm to 1 mm. In some embodiments, the visible and invisible light spectrums do not overlap so that taking camera **102** and witness camera(s) **104** capture different images even though they may be focused on substantially the same object in the area of a set.

[0032] In some embodiments, motion capture system **100** includes taking camera light sources **108** and witness camera light sources **110**. Each light source can be designed to emit light between a wavelength spectrum that matches the wavelength spectrum of a corresponding camera so that at least some light emitted from the light sources can be captured by respective cameras in system **100** after being reflected off of surfaces of actor **106**. For example, taking camera light sources **108** can emit visible light **112** to illuminate actor **106**. At least a portion **114** of visible light **112** can reflect off of actor **106** and be captured by taking camera **102**. Likewise, witness camera light sources **110** can emit invisible light **116** to illuminate actor **106**, and at least a portion **118** of invisible light **116** can reflect off of actor **106** and be captured by taking camera **102**. In some embodiments, portion **114** of visible light **112** is reflected off of the face, hair, head, neck, shoulders, or any other body part of actor **106**, while portion **118** of invisible light **116** is reflected off of markers **120** on a face of actor **106**. In certain embodiments such markers **120** can reflect invisible light but not visible light so that markers **120** are substantially undetectable by taking camera **102**. In other embodiments, such markers **120** can be relatively more reflective of invisible light than visible light such that markers **120** are substantially undetectable by taking camera **102**.

[0033] Operation of motion capture system **100** can be better understood from an exemplary use case scenario. For example, during filming of a motion picture, taking camera **102** can be used to capture the entire composition of a set, e.g. actor **106** looking around at his surroundings in front of a busy street in New York City. Taking camera light sources **108** are flood lights shining white, visible light that illuminates the scene with visible light so that taking camera **102**

can capture footage of actor **106** as he or she looks around, as well as any extras walking around the busy street, any building facades around actor **106**, and any cars that may pass by actor **106**. Meanwhile, witness camera light sources **110** are flood lights shining invisible, IR light that illuminates the scene with IR light so that witness cameras **104** can simultaneously capture footage of markers **120** on the face of actor **106**. Markers **120** can be configured as a retro-reflectors that can substantially reflect IR light, as will be discussed further herein. Accordingly, markers **120** may appear as bright dots in the images captured by witness cameras **104**.

[0034] Because taking camera **102** are unable to detect IR light, the images captured taking camera **102** will not include portions **118** of reflected IR light from markers **120**. As a result, the images captured by taking camera **102** can be used directly in an item of content and/or used to drive a digital replica of actor **106** based on a markerless motion solving system. In some embodiments, markers **120** can be detectable in both visible and invisible light spectrums. For instance, markers **120** can be black dots that are detectable in both visible light and IR light. In such instances, taking camera **102** and witness cameras **104** can both capture the positions of markers **120**, thereby enabling a more robust triangulation of the face of actor **106** during the performance.

[0035] By having two types of cameras **102** and **104** and two respective light sources **108** and **110**, motion capture system **100** can effectively and efficiently capture two different motion picture compositions with one shoot, i.e., one act of filming. Thus, motion capture system **100** enables the generation of content using a minimal number of performances by actor **106**. More specifically, actor **106** only needs to perform a single performance in order (1) to generate images directly usable for an item of content and/or driving a digital character in a virtual environment and (2) for accurately determining the location and facial expressions of a digital character mapped to the head of actor **106** in a virtual environment.

[0036] Based on the images captured from taking camera **102** and witness cameras **104**, motion capture system **100** can determine the locations of various parts of the head of actor **106** during a performance. In some embodiments, the captured images from taking camera **102** and witness cameras **104** can be provided to a computer system **122**, which can be located at a remote location, such as in an editing studio, or it can be positioned within the near vicinity of cameras **102** and **104**. Computer system **122** can be a special-purpose computer system, such as a content generation system, that utilizes the captured images from taking camera **102** and the locations of markers **120** of actor **106** captured by witness cameras **104** to position a digital or virtual head corresponding to the actor's head in a virtual environment or set. The content generation system can then generate content (e.g., a film, TV programming, content for a video game, etc.) based on the positioning. For example, continuing from the use case scenario above, computer system **122** can position a digital or virtual face on the actor's head to make the actor look different while the actor is looking around at his surroundings in front of the busy street in New York City. The images captured by taking camera **102** can be the actor's head, body, and his surroundings, while the images captured by witness cameras **104** can be the positions of markers **120** relative to the actor's head, body, and his surroundings. Thus, the positions of markers **120** can be used to accurately and realistically position the digital or virtual face on the actor's head during the performance. Details of computer system **122** is discussed in further detail herein with respect to FIGS. **9** and **10**.

[0037] In some embodiments, taking camera **102** and witness cameras **104** in motion capture system **100** can be configured in various different ways. For instance, taking camera **102** and witness cameras **104** can each be standalone cameras where witness cameras **104** are stationary. In another example, motion capture system **100** can be configured so that taking camera **102** and witness cameras **104** are all mounted on a same rig so that the cameras form a single image capturing device. Each of these embodiments will be discussed in detail further herein with respect to FIGS. **2**-**6**B.

[0038] A. Stationary Witness Cameras

[0039] As mentioned above, a motion capture system can include tracking and witness cameras where the tracking and witness cameras are standalone cameras, and where the witness cameras are also stationary. An exemplary motion capture system with such a configuration is shown in FIG. **2**.

[0040] FIG. **2** is a simplified diagram of an exemplary motion capture system **200** configured with a taking camera **202** and stationary witness cameras **204***a*-*d* where stationary witness cameras **204***a*-*d* are stationary, standalone cameras, according to some embodiments of the present disclosure. Each witness camera **204***a*-*d* can be stationary in that they are not easily movable once they are positioned in place and are not intended to be moved during a performance by actor **206**. For example, each witness camera **204***a*-*d* can rest on stands that fix witness cameras **204***a*-*d* in place throughout an entire performance by actor **206**. Although system **200** includes four witness cameras **204***a*-*d*, it is to be appreciated that embodiments are not limited to such configurations and that other embodiments can have more or less witness cameras.

[0041] Taking camera **202**, on the other hand, does not have to be stationary and can move around while actor **206** is performing. As an example, taking camera **202** can be mounted on a rail and move between two locations to capture a moving shot of actor **206** during his or her performance. In another example, taking camera **202** can move from point A to point B and then to point C throughout a performance by actor **206**. Taking camera **202** is shown with dashed lines in positions B and C is to illustrate that there is one taking camera (instead of three) and that it can move to different positions around actor **206**.

[0042] According to some embodiments of the present disclosure, taking camera **202** operates to capture light in a first wavelength spectrum, and witness cameras **204***a*-*d* operate to capture light in a second wavelength spectrum different from the first wavelength spectrum such that the two spectrums do not overlap. As an example, taking camera **202** can operate to capture visible light (i.e., light at wavelengths between approximately 390 to 700 nm) and witness cameras **204***a*-*d* can operate to capture invisible light (i.e., IR light at wavelengths between approximately 701 nm to 1 mm). To prevent overlap in the operable wavelengths of taking camera **202** and witness cameras **204***a*-*d*, one or more modifications can be implemented for each respective camera. As an example, IR filters can be implemented in front of the taking lenses for witness cameras **204***a*-*d* to only allow

IR light to pass through. Additionally, witness cameras **204***a-d* can be implemented with an IR image sensor that can detect IR light only, or witness cameras **204***a-d* can be implemented with an image sensor that does not have a coating that filters IR light so that IR light is allowed to be detected by the image sensor. It is to be appreciated that any other modification to separate the operating wavelength spectrums of taking camera **202** and witness cameras **204***a-d* without departing from the spirit and scope of the present disclosure can be envisioned in embodiments herein.

[0043] In certain embodiments, a plurality of light sources can project light against actor **206** to enable and/or improve the quality of images captured by taking camera **202** and witness cameras **204***a-d*. For instance, motion capture system **200** can include taking camera light sources **208***a-c* and witness camera light sources **210***a-c*. In some embodiments, taking camera light sources **208***a-c* and witness camera light sources **210***a-c* can emit light in different wavelength spectrums that correspond to the operating wavelengths of respective cameras for which they are configured to provide illumination. As an example, taking camera light sources **208***a-c* can emit visible light **212** and witness camera light sources **210***a-c* can emit IR light **214**. It is to be appreciated that for outdoor sets during the day, there may be enough ambient visible and IR light from the sun such that taking camera light sources **208***a-c* and/or witness camera light sources **210***a-c* may not be needed for taking camera **202** and witness cameras **204***a-d* to capture images of actor **206**. Thus, taking camera light sources **208***a-c* may be optional in motion capture system **200**.

[0044] During filming while actor **206** is performing, portions of light **212** and **214** emitted from light sources **208***a-c* and **210***a-c* (or from ambient visible and IR light) can reflect back to cameras **202** and **204***a-d*, which can then simultaneously capture images of actor **206** and/or the actor's surroundings. As an example, a portion **216** of visible light emitted from one or both taking camera light sources **208***a* and **208***c* can be reflected off of a face, or the entire body, of actor **206** and be captured by taking camera **202** in position B. In addition to portion **216**, a portion **218** of visible light can be reflected off of objects in the set around actor **206**, such as a chair **220** (or, from the use case scenario above, building facades, passing cars, or any other type of object found on a busy street in New York City), and also be captured by taking camera **202** in position B. According to some embodiments of the present disclosure, portions **222** and **224** of invisible light emitted from witness camera light source **210***a* can be reflected off a marker **226** on the face of actor **206** and be captured, simultaneously with the capturing of visible light by taking camera **202**, by respective witness cameras **204***a* and **204***b*. As can be seen from FIG. **2**, witness cameras **204***a* and **204***b* can be positioned in different locations around the set and actor **206**; thus, witness cameras **204***a* and **204***b* can view marker **226** from different angles and distances. The captured images of marker **226** can be utilized by a computer system, e.g., computer system **122** in FIG. **1**, to triangulate the position of marker **226** in a three-dimensional environment. The triangulated position of marker **226** can be combined with the footage captured by taking camera **202** to generate accurate digital performances of actor **206** in the set or digital performances of a digital character in a virtual environment. The same can be said for portions **221** and **223** of reflected IR light from marker **234**, and portion **228** of reflected visible light from the face of actor **206**, when taking camera **202** is at position C, or any other position around actor **206**, e.g., position A.

[0045] It can be appreciated that implementing more witness cameras in different positions around actor **206** can more reliably capture the movement of actor **206**. This is because when actor **206** is performing, some markers may be visible to some witness cameras but appear blocked to other witness cameras. For instance, as shown in FIG. **2**, marker **226** may be visible to witness cameras **204***a* and **204***b*, but appear blocked to witness cameras **204***c* and **204***d*. In other instances, some objects (e.g., a boom mic, filming personnel, and the like) around the set may unintentionally occlude the view of one or more witness cameras. By having more witness cameras around actor **206**, there is a greater chance that there will be at least one or more witness cameras that can capture the movement of marker **226** even though one or more witness cameras are occluded. Furthermore, using a greater number of witness cameras can minimize the occurrence where a marker is not visible to any witness camera. In such situations, calculation of the position of marker **226** may not be possible, or the calculation may be based on the captured images from taking camera **202**, which may result in an inaccurate determination of the marker's position because of a lack of depth perception. In such embodiments, marker **226**, and other markers visible on the face of actor **206**, can be visible to taking camera **202** and witness cameras **204***a-d*. For instance, marker **226** can be a black marker that absorbs visible light and reflects IR light. That way, from the perspective of taking camera **202**, marker **226** appears as a block dot; and from the perspective of witness cameras **204***a* and **204***b*, marker **226** appears as a bright dot. In some other embodiments, however, marker **226** can be visible to witness cameras **204***a-d* but invisible to taking camera **202**, as will be discussed further herein with respect to FIG. **7**.

[0046] By implementing two types of cameras, e.g., taking camera **202** and witness cameras **204***a-d*, that operate to capture light at non-overlapping wavelength spectrums, motion capturing system **200** can effectively and efficiently capture two different video footages with one shoot. Thus, motion capture system **200** enables the generation of content using a minimal number of performances by actor **206**. More specifically, actor **206** only needs to perform a single performance in order (1) to generate images directly usable for an item of content and/or driving a digital character in a virtual environment and (2) for accurately determining the location of a digital character mapped to the head of actor **206** in a virtual environment.

[0047] B. Non-Stationary Witness Cameras

[0048] As can be appreciated by the illustration of FIG. **2**, motion capture system **200** includes several standalone components, e.g., taking camera **202** and four witness cameras **204***a-d*. If the director shooting actor **206** in a set wants to change scenes and set locations, each of the standalone components may need to be moved individually. To simplify this process and enable motion capture system **200** to be more mobile and versatile, the taking camera and witness cameras can be mounted on a single, movable structure so that witness cameras **204***a-d* are non-stationary, as discussed herein with respect to FIG. **3**.

[0049] FIG. **3** is a simplified diagram of an exemplary motion capture system **300** configured with a taking camera **302** and two witness cameras **304***a-b* where taking camera

302 and stationary witness cameras 304*a-b* are mounted on a movable rig 303, according to some embodiments of the present disclosure. Rig 303 with taking and witness cameras 302 and 304*a-b* is shown from the top-down perspective. Taking camera 302 and witness cameras 304*a-b* can be configured to be substantially similar to taking camera 202 and witness cameras 204*a-d* in FIG. 2. Accordingly, details of taking camera 302 and 304*a-b* can be referenced in the disclosure of FIG. 2 and are not discussed herein for brevity.

[0050] As shown in FIG. 3, taking camera 302 and witness cameras 304*a-b* can be rigidly mounted on a single structure 305, according to some embodiments of the present disclosure. Structure 305 can be a stiff frame that is part of rig 303 and strong enough to support the weight of cameras 302 and 304*a-b*, such as a steel frame with bolting points for securing cameras 302 and 304*a-b*. Additionally, rig 303 can include a set of wheels 307 that enable rig 303, along with taking camera 302 and witness cameras 304, to roll between different positions around actor 306, such as between position A and position B. By being mounted on movable rig 303, witness cameras 304*a-b* are non-stationary, thereby significantly simplifying the moving process of motion capture system 300, whether it be for moving to different shot angles within a set, or for moving to a completely new set at a different location.

[0051] In certain embodiments, motion capture system 300 can include a plurality of light sources for projecting light against actor 306. For instance, motion capture system 300 can include taking camera light sources 308*a-b* positioned to illuminate actor 306 from different angles. Like taking camera light sources 208*a-c* in motion capture system 200 of FIG. 2, taking camera light sources 308*a-b* can be optional standalone light sources. However, unlike witness camera light sources 210*a-c* in motion capture system 200, witness camera light sources 310*a-b* can each be a part of a respective witness camera 304*a-b*. Thus, witness cameras 304*a-b* cannot only capture invisible (IR) light, but they can also illuminate actor 306 with invisible light, thereby reducing the number of standalone components for a motion capture system.

[0052] As an example, witness camera light source 310*a* can be formed as part of, or attached to, a lens hood 311*a* of witness camera 304*a*. In some embodiments, witness camera light source 310*a* is constructed as a ring of light emitters (e.g., light emitting diodes (LEDs)) positioned around a circumference of the front end of lens hood 311*a*. When constructed as a ring of light emitting diodes, witness camera light source 310*a* can project invisible (IR) light 314 at actor 306 from the exact angle at which witness camera 304*a* perceives actor 306. Thus, invisible light 314 cast upon actor 306 may not create any shadows when viewed from the position of witness camera 304*a*, thereby maximizing illumination efficiency of actor 306 and the brightness of reflected light detected by witness camera 304*a*. It is to be appreciated that taking camera light sources 308*a-b* and witness camera light sources 310*a-b* can be substantially similar in function to taking camera light sources 208*a-c* and witness camera light sources 210*a-b* of motion capture system 200 in FIG. 2, and thus have the same function and purpose. i.e., provide visible and invisible light to improve the quality of images captured by taking camera 302 and witness cameras 304*a-b*. A better understanding of the structure and construction of such a motion capture system can be achieved with reference to FIG. 4

[0053] FIG. 4 is a detailed, front-facing, perspective view of a motion capture system 400 configured as a movable rig, such as motion capture system 300 in FIG. 3, according to some embodiments of the present disclosure. For ease of discussion, components of motion capture system 400 that correspond with components of motion capture system 300 are labeled with the reference number used in FIG. 3.

[0054] As shown in FIG. 4, taking camera 302 and witness cameras 304*a-b* are mounted on movable rig 303. In some embodiments, rig 303 can include a head portion 402 coupled to a body portion 404. Head portion 402 can extend forward and be closer to a filming subject (e.g., an actor in a set) than body portion 404 and include a head frame 406 (of which support structure 305 is a part) along with various electrical wires and other ancillary components for enabling the operation of cameras 302 and 304*a-b*. Body portion 404 can include a body frame 408 to which a plurality of wheels 307 can be mounted to enable movement of motion capture system 400. In some embodiments, head frame 406 is coupled to body frame 408 via nuts and bolts or by welding joints. In certain embodiments, head frame 406 and body frame 408 are part of a same monolithic structure. Head frame 406 and body frame 408 together can form a chassis on which cameras 302 and 304*a-b* are mounted.

[0055] According to some embodiments of the present disclosure, taking camera 302 and witness cameras 304*a-b* can be mounted on support structure 305 so that taking camera 302, witness cameras 304*a-b*, and support structure 305 together form a rigid composition of components that can tilt and turn together as a whole. In some embodiments, structure 305 is a support plate that has sufficient tensile strength to hold cameras 302 and 304*a-b* in a stable position above ground. Structure 305 can bend around taking camera 302 to provide clearance space for taking camera 302 while providing additional structural strength. In some embodiments, witness cameras 304*a-b* can be mounted on laterally opposite sides of taking camera 302 so that witness cameras 304*a-b* and taking camera 302 are substantially aligned to the same horizontal axis 401. It is to be appreciated, however, that embodiments are not limited to such configurations, as will be discussed further herein with respect to FIG. 6B.

[0056] As mentioned herein, witness cameras 304*a-b* can be configured to capture light only in the invisible (IR) wavelength spectrum. Thus, one or more optical filters 410*a-b* can be positioned in front of the respective lenses of witness cameras 304*a-b*. That way, only IR light can pass through to witness cameras 304*a-b*.

[0057] With reference back to FIG. 3, during image capture while actor 306 is performing, portions of light 312 and 314 emitted from light sources 308*a-b* and 310*a-b* can reflect back to cameras 302 and 304*a-d*, respectively, which can then simultaneously capture images of actor 306 and/or the actor's surroundings. As an example, a portion 316 of ambient light or visible light emitted from taking camera light source 308*a* can be reflected off of a face, or the entire body, of actor 306 and be captured by taking camera 302 in position A. In addition to portion 316, a portion 318 of visible light can be reflected off of objects in the set around actor 306, such as a chair 320 (or, from the use case scenario above, building facades, passing cars, or any other type of object found on a busy street in New York City), and also be captured by taking camera 302 in position A. According to some embodiments of the present disclosure, portions 223 and **324** of invisible light emitted from witness camera light sources **310***a* and **310***b*, respectively, can be reflected off a marker **326** on the face of actor **306** and be captured, simultaneously with the capturing of visible light by taking camera **302**, by respective witness cameras **304***a* and **304***b*.

[0058] As can be seen from FIG. **3**, witness cameras **304***a* and **304***b* can be positioned at laterally opposite sides of taking camera **302**; thus, witness cameras **304***a* and **304***b* can view marker **326** from different angles and distances. This information can be utilized by a computer system, e.g., computer system **122** in FIG. **1**, to triangulate the position of marker **326** in a three-dimensional environment. The triangulated position of marker **326** can be combined with the footage captured by taking camera **302** to generate accurate digital performances corresponding to actor **306**. The same can be said for portions **330** and **332** of reflected IR light from marker **234**, and portion **328** of reflected visible light from the face of actor **306**, when taking camera **302** is at position B, as shown in FIG. **3**, or any other position around actor **306**. By being mounted on laterally opposite sides of taking camera **302**, witness cameras **304***a-b* can be better positioned to track the movements of markers on the face of actor **306** because of the natural symmetry of a human's face across a vertical axis. For instance, witness camera **304***a* can better capture markers on the left side of actor's **306** face while witness camera **304***b* can better capture markers on the right side of actor's **306** face. And, when both cameras **304***a-b* are utilized together, the accuracy of determining the position of markers on actor **306** by triangulation can be increased.

[0059] It is to be noted that unlike motion capture system **200** in FIG. **2** where witness camera light sources **210***a-c* are positioned around actor **206** to illuminate actor **206** from all angles, witness camera light sources **310***a-b* only illuminate actor **306** from the angles at which witness cameras **304***a-b* are positioned. In this case, it may not be necessary to illuminate actor **306** with invisible light from any other light source at a different position because such invisible light will not be utilized, or will have negligible utilization, by witness cameras **304***a-b*. To further increase the amount of reflected invisible light **314** emitted by witness camera light sources **310***a-b*, markers on the face of actor **306**, including markers **326** and **334**, can be configured as retroreflective gel-based markers that reflect light back to its source with minimal scattering, as will be discussed further herein with respect to FIG. **7**. Furthermore, to further differentiate the captured images by taking camera **302** and witness cameras **304***a-b*, the markers can be invisible to taking camera **302** but visible to witness cameras **304***a-b*. That way, taking camera **302** may not capture markers **326** and **334** on actor **306** during the performance so that the captured footage may not need to be edited to remove the presence of markers **326** and **334**, which may often be the case where such markers are visible to taking camera **302**. This can save time and cost associated with post processing of the captured images.

[0060] 1. Camera Configurations

[0061] As mentioned herein with respect to FIGS. **3** and **4**, witness cameras **304***a-b* can be mounted on laterally opposite sides of taking camera **302**. In some embodiments, witness cameras **304***a-b* can be positioned at various distances away from taking camera **302** as discussed herein with respect to FIG. **5**A. FIG. **5**A is a simplified illustration **500** of only the front ends of taking camera **302** and witness cameras **304** to better illustrate their positioning with respect to one another, according to some embodiments of the present disclosure. Additionally, the reference numerals used in FIG. **3** are used in FIG. **5**A for ease of understanding.

[0062] As shown in FIG. **5**A, witness camera **304***a* is positioned a distance D1 away from a left side of taking camera **302** and witness camera **304***b* is positioned a distance D2 away from a right side of taking camera **302**. In some embodiments, D1 and D2 are the same distances such that witness camera **304***a* is positioned the same distance away from taking camera **302** as witness camera **304***b*. In other embodiments, D1 and D2 can be different. D1 and D2 can be increased and decreased depending on distance to the actor and desired accuracy for triangulation. For instance, when the actor is positioned farther away, D1 and D2 may need to be increased to get more distinct captured images. If the distances D1 and D2 were small and the actor was positioned far away, witness cameras **304***a-b* will essentially be capturing the same images given their close proximity to one another relative to their distance away from the actor, thereby decreasing the accuracy of triangulation. In some embodiments, distances D1 and D2 are each between six inches and two feet.

[0063] Although embodiments herein have discussed motion capture systems with movable rigs as having two witness cameras positioned on laterally opposite sides of a taking camera, embodiments are not limited to such configurations, and that any configuration with more or less than two cameras positioned in any location around the taking camera are envisioned herein. FIG. **5**B is a simplified illustration of an exemplary camera arrangement **550**, according to some embodiments of the present disclosure. Camera arrangement **550** can include taking camera **502** surrounded by witness cameras **504***a-d*. Witness cameras **504***a-b* can be positioned on laterally opposite sides of taking camera **502**, while witness cameras **504***c-d* can be positioned on vertically opposite ends of taking camera **502**, as shown in FIG. **5**B. By having witness cameras **502***c-d* in addition to witness cameras **504***a-b*, an additional pair of witness cameras can provide positioning information to increase the accuracy of position determination of markers on an actor. Although FIG. **5**B illustrates camera arrangement **550** as having witness cameras **504***a-d* positioned laterally and vertically with respect to taking camera **502**, embodiments are not limited to such configurations and that configurations with any number of witness cameras positioned in any location around taking camera **502** are envisioned herein.

[0064] 2. Angle of Orientation of Witness Cameras

[0065] In addition to being able to modify the distance between the taking camera and each witness camera, motion capture systems with movable rigs can also modify the rotational orientation of each witness camera. For instance, witness cameras can be oriented in different angles for filming subjects positioned at different distances away from the motion capturing system. FIGS. **6**A and **6**B illustrate exemplary configurations for a motion capturing system where a filming subject is positioned at different distances away from the motion capturing system, according to some embodiments of the present disclosure. Specifically, FIG. **6**A is a simplified diagram of an exemplary configuration **600** of motion capture system **300** of FIG. **3** where actor **306** is positioned close to system **300**, and FIG. **6**B is a simplified diagram of an exemplary configuration **601** of motion capture system **300** where actor **306** is positioned far away from system **300**.

[0066] In some embodiments, witness cameras **304***a-b* can be rotated around respective pivot points **602***a-b* so that witness cameras **304***a-b* can be positioned at different angles with respect to support structure **305**. For instance, as shown in FIG. **6**A, when actor **306** is positioned close to system **300**, witness cameras **304***a-b* can each be pivoted around respective pivot points **602***a-b* and be oriented along respective central axes **604***a-b* so that cameras **304***a-b* are pointed at actor **306**. In such instances, central axes **604***a-b* can be oriented at respective angles **606***a-b*. On the other hand, when actor **306** is positioned far away from system **300**, as shown in FIG. **6**B, witness cameras **304***a-b* can be pivoted around their respective pivot points **602***a-b* so that their central axis **604***a-b* are oriented at respective angles **606**A-b, which are greater than angles **606***a-b*. Angles **606***a-b* and **606**A-b may not exceed 90 degrees to ensure that witness cameras **304***a-b* can focus on actor **306**. By enabling witness cameras **304***a-b* to rotate around a pivot point, motion capture system **300** can be better suited to capture motion when actor **306** is positioned at various distances away from the motion capture system as the actor may perform at different locations in a set.

[0067] In some embodiments, witness cameras **304***a-b* can be fixed in each angular position for the duration of a performance by actor **306**, or witness cameras **304***a-b* can dynamically adjust its angular position during the performance so that central axes **604***a-b* of witness cameras **304***a-b* are continuously aligned with actor **306** as actor **306** moves around a set during the performance. In the latter case, one or more sensors and motors can be implemented to track the position of actor **306** and mechanically rotate cameras **304***a-b* in real time to align their central axes **604***a-b* with actor **306**.

[0068] C. Camera Synchronization

[0069] FIG. **7** is a simplified schematic diagram of a motion capture system **700** according to some embodiments. Motion capture system **700** can be representative of motion capture system **100** discussed above and include a taking camera **710** along with left and right witness camera systems **720***a*, **720***b* that are used to capture the performance of an actor **702**. Each witness camera system can include a camera, such as an infrared camera, along with a matching light source (e.g., an infrared light source) and a receiver/driver circuit that drives the light source. Thus, as shown in the depicted embodiment, witness camera system **720***a* can include a witness camera **722***a*, an light source **724***a* and a receiver/driver **726***a*. Similarly, witness camera system **720***b* can include a witness camera **722***b*, a light source **724***b* and a receiver/driver **726***b*. Taking camera **710** can be representative of any of taking cameras **102**, **202** or **302**. Each witness camera **720***a*, **720***b* can be representative of any of witness cameras **104**, **204***a*/**204***b* or **304***a*/**304***b*. Thus, as an example, taking camera **710** can be an RGB camera and witness cameras **720***a*, **720***b* can be infrared cameras where the set of wavelengths that each of the two types of cameras capture do not overlap.

[0070] As is known to those of skill in the art, cameras **710**, **722***a* and **722***b* can capture sequences of video at various frame rates. For example, in some embodiments, cameras **710**, **722***a*, **722***b* are operated at a frame rate of 24 frames per second (fps) as is commonly done when filming cinematic films high end motion pictures. Embodiments are not limited to a particular frame rate, however, and in other embodiments cameras **710**, **722***a*, **722***b* can be operated at other frame rates including, as non-limiting examples, 25 fps and 30 fps. When filming a performance, motion capture system **700** activates each of the cameras according to the same frame rate. Thus, at a frame rate of 24 fps, system **700** activates each of cameras **710**, **722***a*, **722***b* at even intervals, twenty four times every second—or every 41.67 milliseconds. Each of the twenty four 41.67 millisecond intervals can be referred to as a frame, and during each frame, each camera activates (opens and closes) its shutter once to capture an image. Embodiments described herein synchronize cameras **710**, **722***a*, **722***b* to each at the system frame rate and, within each individual frame, align the timing of the cameras such that shutters of witness cameras **722***a*, **722***b* are opening at the same time as the shutter of taking camera **710** as described in more detail below.

[0071] Receiver/drivers **726***a*, **726***b* can be operatively coupled to their respective infrared light sources **724***a*, **724***b* and configured to flash the light sources at the frame rate of their respective infrared witness camera **722***a*, **722***b* such that the lights sources are outputting a pulse of light each frame. In some embodiments, each infrared light source can be an array of infrared LEDs, and in some embodiments, the array of LEDs can be arranged in a circular ring as described above with respect to FIG. **4**. Additionally, in some embodiments, taking camera **710** and left and right witness camera systems **720***a*, **720***b* can mounted together as part of a moveable rig similar to motion capture system **400** discussed in conjunction with FIG. **4**.

[0072] Motion capture system **700** can also include a recording station **730** that includes first and second camera recorders **732***a*, **732***b* for recording video from the witness cameras **722***a* and **722***b*, respectively. As shown, the camera recorders **732***a*, **732***b* can receive a video output signal (e.g., a 4K SDI or other video out signal) from witness cameras **722***a*, **722***b*, respectively, to record video from the cameras. In some embodiments, recording station **730** can be mounted with the taking and witness camera systems on a moveable rig while in other embodiments, recording station **730** can be located at a location separate from the witness and taking cameras.

[0073] Motion capture system can also include a primary clock **734** that generates temporal reference signals and distributes (outputs) the signals to other devices within system **700** so that the various devices can synchronize themselves. In some embodiments, the temporal reference signals include a tri-level sync signal (Sync) and a linear timecode (LTC) signal. As is known to those of skill in the art, the LTC signal conveys the frame number to downstream devices and the tri-level sync signal is a standard HD analog video signal generated at the system frame rate that conveys when the video frame starts (and thus conveys when to start taking a frame to the downstream devices). In some video setups, the taking camera and witness cameras can be accurately synchronized and aligned with each other based solely on these signals. For example, if the taking and witness cameras are all the same make and model cameras, the cameras will typically have the same timing characteristics and can thus be accurately synchronized and aligned with the tri-level synchronization signal generated by clock **734**.

[0074] In some embodiments, however, the taking and witness cameras can have different timing characteristics such that synchronizing the cameras directly with the tri-level sync signal output from primary clock **734** can result in timing mismatches (misalignment) within a given frame. One non-limiting example of a scenario in which the taking and witness cameras can have different timing characteristics is when the taking camera and witness cameras are either different model cameras and/or made by different manufacturers. For example, in some embodiments taking camera **710** can be a very high end, relatively large and expensive camera while the witness cameras can be smaller, less expensive cameras made by a different manufacturer. The different timing characteristics can be a result of some cameras operating off the rising edge of the synchronization signal while other cameras operate off the falling edge of the signal, can be the result of different latency delays in the time from receiving a sync signal until the shutter opens, or can be due to other operational characteristics of the cameras. While a human eye might not notice such sub-frame differences initially, when implementing algorithms that solve the location of various facial features (i.e., facial expression motion capture algorithms), controlling timing differences to within a 10th of a millisecond can generate improved results.

[0075] Embodiments disclosed herein can include a synchronization module **736** that enables motion capture system **700** to have complete control over camera synchronization and alignment allowing precise sub-frame synchronization (alignment) between the taking and witness cameras even if the different cameras have different timing characteristics. As an example, synchronization module **736** can receive synchronization signals from master clock **734**, including a tri-level sync signal and a linear time code signal and generate output signals that enable the tri-level sync signal to be offset in microseconds, both prior to and after the timing of the received tri-level sync signal, to adjust for different timing characteristics of different cameras. As used herein, “synchronizing” two cameras or devices to each other refers to operating the cameras or devices at the same frame rate, while “aligning” two cameras to each other refers to controlling the two cameras (or other devices) so that they initiate an image capture sequence (or other operation), within each frame (i.e., at the sub-frame level). In some embodiments, such alignment can be done within single digit microsecond precision.

[0076] Synchronization module **736** can precisely synchronize and align the timing of other downstream devices as well. For example, synchronization module can send timing signals to receiver/drivers **726***a*, **726***b* that activate light sources **724***a*, **724** at the same frame rate as the cameras in order to synchronize the light sources with their respective cameras **722***a*, **722***b*. The timing signals can also align the pulses of light generated by each driver/light source pair such that the pulse of light is timed to precisely match the opening of each cameras **722***a*, **722***b* shutter. Thus, synchronization module **736** is able to very precisely move the output from master clock **734**, advancing or delaying the output, in order to adjust for different timing characteristics of any downstream device including both witness **722***a* or **722***b* and LED drivers **726***a*, **726***b*, thereby precisely synchronizing and aligning the witness cameras and IR light sources with taking camera **710**.

[0077] Specific offset values for each individual downstream device (camera or other device) can be determined and set on a camera-by-camera (or downstream device-by-downstream device) basis. In some instances, precise offsets for a camera or other downstream device can be determined based on manufacturer specifications and/or known data about the device. In order to set more precise synchronization between devices, however, some embodiments can calculate or otherwise determine specific offsets through a pre-shoot calibration process in which visible and infrared light is projected by a device (referred to herein as an “active marker”) for a very brief time period (e.g., one quarter of a millisecond) that can be used to judge the time alignment between the light pulse of the active marker and the line scanning of the rolling shutter.

[0078] Once the precise timing of the taking camera rolling shutter is known, offsets for the witness cameras and other downstream devices can be determined in order to align those devices to the taking camera shutter using the same active marker. The calculated offsets can then be stored in synchronization module **736** and used with the particular set up of cameras and downstream devices as long as the setup remains unchanged. If one or more cameras or other downstream devices are changed in motion capture system **700**, a new pre-shoot calibration process can be performed to calculate new or updated offsets based on the updated motion capture system configuration.

[0079] Further details on an embodiment of synchronization module **736** as well as an example of how synchronization module **736** can be used to control the timing characteristics of downstream devices to more precisely synchronizes and align the devices to the taking camera are discussed below with respect to FIGS. **8**A-**8**C. Prior to such a discussion, however, further details of various embodiments of motion capture system **700** are provided.

[0080] In some embodiments, motion capture system **700** can also include a wireless module **740** coupled to an output of synchronizer **736**. Wireless module **740** can receive Sync and LTC signals output from synchronization module **736** and wirelessly transmit those signals to downstream devices, such as receiver/drivers **724***a*, **724***b* using any appropriate wireless protocol. In the embodiment depicted in FIG. **7**, wireless module **740** is shown as a separate device that is physically distinct from synchronizer **736** and is positioned outside of recording station **730**. It is to be understood that FIG. **7** is just one example of a schematic diagram of motion capture system **700** according to embodiments disclosed herein. In other embodiments, wireless module **740** and synchronization module **736** can be part of the same device. In still other embodiments, wireless module **740** is optional and all downstream devices controlled by synchronization module **736** can have a wired input to the synchronization module. In still other embodiments, all downstream devices, including the witness cameras can be controlled wirelessly via signals output from wireless module **740**.

[0081] In some embodiments, motion capture system **700** can also include a calibration device **704** that includes a receiver/driver **706** and a light source **708**. The receiver/driver **706** can wirelessly receive a Sync signal **830***c* from wireless module **740** and activate a light source **708** that generates light within the same wavelength range captured by the witness cameras. In some embodiments, light source **708** can have similar or identical characteristics to light sources **724***a*, **724***b* and output infrared light. Light source

708 can then be activated (flashed) in synchronization and aligned with the witness camera shutters and, in use, placed in view of the witness cameras. In this manner, when the witness camera shutters are open the light can be seen via the witness cameras in order to visually confirm that the cameras are in sync with the sync signal. As used herein, a camera "shutter" includes both mechanical and electronic shutters and other mechanisms that can be controlled to repeatedly start and stop image capture periods in a video camera within each frame.

[0082] Reference is now made to FIG. **8**A, which is a timing diagram depicting the relationship between an output **810** of master clock, an input **820** of synchronization module **736** (which, from a timing perspective, is essentially the same as the output **810** of the master clock) and an output **830** of synchronization module **736** according to some embodiments. As shown in FIG. **7**, synchronization module **736** is able to advance or delay output **830** within a predetermined range **840** of the output **830** of the master clock. In some embodiments, predetermined range can be any time value within the range of a given video frame. For example, at a frame rate of 24 frames per second, synchronization module **736** can advance or delay output signal **830** within a range of approximately ±41.7 milliseconds (±1.001/24=41.708333 ms). In other embodiments, the predetermined range can be plus/minus one half a frame, plus/minus 20 ms, plus/minus 10 ms or plus/minus 5 ms. Notably, synchronization module **736** is able to provide multiple outputs **830**, each of which can be delayed or advanced as shown in accordance with FIG. **8**A with range **840**. For convenience, the input and output signals **810**, **820** and **830** are shown as nodes **810**, **820** and **830** (i.e., nodes **830***a*, **830***b* and **830***c*), respectively in FIG. **7**. Specifically, output **810** is shown in FIG. **7** as being coupled to taking camera **710** and to synchronization module **736** at input **820**, and output **830** is shown as being coupled to witness cameras **720***a*, **720***b* and wireless module **740** as outputs **830***a*, **830***b* and **830***c*.

[0083] Reference is now made to FIGS. **8**B and **8**C, which are timing diagram depicting a specific example use case in which synchronization module **736** is synchronizing and aligning a witness camera and IR lights to the main taking camera. In the specific use case example depicted, the main taking camera has a latency of 1 millisecond (ms) from sync until the shutter opens; the witness camera has a latency of 3 ms from sync until the shutter opens; and the IR illumination happens immediately upon trigger. Since the main camera opens its shutter 1 ms after the master clock sync (sync **810**) and the witness camera opens its shutter 2 ms after the master clock (sync **810**), as shown in FIG. **8**B, synchronization module **736** configures the Sync output signal **830***a* for the witness camera to lead master sync **810** by 2 ms. This has the effect of both cameras opening their shutters precisely 1 ms after master sync.

[0084] Similarly, the IR illumination needs to be delayed to align with the witness camera opening its shutter. Since the IR lights are activated immediately upon trigger, synchronization module **736** configures the Sync output signal **830***c* to have a lag of 1 ms with respect to the master clock. This aligns it with the witness camera (and the main camera) shutter within each frame.

[0085] As shown in FIG. **8**C, which depicts a sequence of four continuous frames, the synchronization signals **810**, **820**, **830***a*, **830***c* are received/sent at a base frame rate (24 frames per second in the example). For each frame, the signals' lead/lag is static with respect to the master clock, according to the user's configuration.

II. Gel-Based Markers

[0086] As briefly mentioned above with respect to FIGS. **2** and **3**, a plurality of markers can be positioned on an actor's face to capture the motion of an actor's head by reflecting invisible light but not visible light. According to some embodiments of the present disclosure, the markers can be retroreflective gel-based markers that can be applied to an actor's face as if it were makeup. As a retroreflective substance, each marker, when applied to an actor's face, can act as a surface that reflects light back to its source with a minimum of scattering along a vector that is parallel but opposite in direction from the light's source. By being retroreflective, each marker can effectively negate any noise from ambient light. For instance, under normal lighting conditions indoors (i.e., absent lights directly beaming at the markers), the markers may not be visible or have negligible visibility. For instances where a set is positioned outside, the sun can emit vast amounts of IR light. However, because the markers are retroreflective, the IR light emitted from the sun may not reflect back to the witness cameras. Instead, only the IR light emitted from the witness camera light sources (e.g., ring of IR LEDs around the witness cameras' lenses) will get reflected back to the witness cameras.

[0087] To enable the retroreflectivity of the gel-based markers, the gel-based markers can be formed of a plurality of microspheres suspended within a gel. The plurality of microspheres can be formed of glass or some other mirror-like material that enables the retroreflective properties of the gel-based markers. In some embodiments, the plurality of microspheres are formed of a first set of microspheres having a first diameter, and a second set of microspheres having a second diameter different from the first. The first set of microspheres can have a larger diameter than the second set of microspheres so that the spaces between the first set of microspheres can be filled in by the second set of microspheres to achieve a fuller coverage of a surface upon which the gel-based marker is applied. In some embodiments, the gel in which the microspheres are suspended can be substantially transparent to IR light so that IR light can enter and exit the gel without being substantially attenuated. In some embodiments, the gel is not transparent to visible light, but transparent to IR light. In such cases, the gel can exhibit a pigment that matches the skin color of the actor so that the markers can be inconspicuous when worn by the actor. The gel may be any suitable type of gel, such as standard hand sanitizer or a glycerin-based gel.

[0088] In some embodiments, the gel-based markers can be positioned at various locations on an actor's face to enable motion capture of the actor's skull as he or she is performing. For example, the gel-based markers may be applied to two, three, six, eight, or more points on an actor's face. The markers can be positioned on substantially rigid parts of an actor's face to minimize distortion caused by facial movement during a performance. FIG. **9** is a simplified illustration **900** of exemplary positions for gel-based markers **902***a-g* that enable motion capture of the skull of an actor **904** during a performance, according to some embodiments of the present disclosure. As shown in FIG. **9**, markers **902***a* and **902***e* can be positioned at the temples of actor **904**, markers **902***b* and **902***c* can be positioned along the hairline of actor **904**, markers **902***f* and **902***g* can be positioned on the nose bridge and tip, respectively, and marker **902***h* can be positioned on the chin of actor **904**. These positions are selected because they may be substantially free of movement caused by facial expressions and talking. That way, the positions can closely track the movement of the skull of actor **904**. By tracking these positions, the witness cameras can more accurately capture the movement of the actor's head.

[0089] Each marker **902***a-h* can be any shape suitable for motion capture by witness cameras. For instance, each marker can be substantially circular, oval, triangular, square, rectangular, and the like. It is to be appreciated that any shape that does not depart from the spirit and scope of the present disclosure can be utilized in embodiments herein.

[0090] According to some embodiments of the present disclosure, and as mentioned several times herein, markers **902***a-h* can be unreflective and unabsorptive to visible light, but highly retroreflective to IR light. Thus, even though a taking camera and one or more witness cameras are filming an actor with markers **902***a-h*, only the witness cameras may capture markers **902***a-h*. By applying markers that are only visible to witness cameras and not a taking camera, embodiments enable the generation of content using a minimal number of performances by a performer. More specifically, a performer only needs to perform a single performance in order (1) to generate images directly usable for an item of content and/or driving a digital character in a virtual environment and (2) for accurately determining the location of a digital character mapped to the actor's head in a virtual environment.

III. Method for Motion Capture

[0091] FIG. **10** is a flow diagram of a method **1000** for performing motion capture with a motion capture system, according to some embodiments of the present disclosure. At block **1002**, light within a first wavelength spectrum can be emitted towards a performance area. For example, standalone witness camera light sources (e.g., sources **310***a-c*), or witness light sources (e.g., sources **310***a-b*) formed as part of respective witness cameras mounted on a movable rig can emit invisible light towards an actor (e.g., actor **306** or **306**) in a set, as discussed herein with respect to FIGS. **2** and **3**. The invisible light can be within the IR light wavelength spectrum, such as within a wavelength spectrum of between 701 nm and 1 mm.

[0092] At block **1004**, a first plurality of images of a performance can be captured by a first set of one or more cameras. As an example, images of a plurality of markers applied to substantially rigid portions an actor's face (e.g., forehead, nose, cheek bones, temple, chin, etc.) while the actor is performing can be captured by witness cameras, e.g., witness cameras **304***a-d* or witness cameras **304***a-b* in FIGS. **2** and **3** can capture markers applied to the faces of actors **306** and **306**, respectively.

[0093] In certain embodiments, instead of being continuously on, the ring of light emitters **310***a* can be controlled (e.g., by a driver circuit, such as one of receiver/drivers **726***a*, **726***b*) to pulsate in precise synchronization with the recording of the taking and witness cameras. More specifically, the ring of light emitters **310***a* can be controlled, in response to a timing signal such as the Sync signal generated by synchronizer module **736**, to only project light and/or be activated when the cameras are capturing images from an environment and/or have their shutters open. As an illustrative example, the cameras can be configured to capture images at a rate of 24 frames per second. The images can be captured at evenly spaced intervals of each second. The cameras can further be configured to take $1/500^{th}$ of a second to capture an image and/or have its shutters open. As such, there are periods of each second during which the cameras are not actively recording imagery from an environment. In particular, for each second, the camera takes an image, waits a short period, takes a second image, waits a short period, takes a third image, and so on.

[0094] In certain embodiments, the ring of light emitters **310***a* can be synchronized with the cameras such that the desired level of light for the images to be captured ("Activated Light Level") is projected only during the twenty four instances of each second when the cameras are capturing images/have their camera shutters open. The twenty four instances during which images are captured can, returning to the example above, amount in total to $48/1000$th of each second of an imagery shooting/capture session. In some embodiments, the ring of light emitters **310***a* can project light at a desired intensity level during the entirety of each of the twenty four instances. In other embodiments, the ring of light emitters **310***a* can only project light for a portion of each of the twenty four instances rather than the entirety. For example, the ring of light emitters can be configured to project light during half of each of the twenty four instances.

[0095] Taking the above example, the ring of light emitters can project light a total of $24/1000^{th}$ of each second of a shooting session. In this way, the strength of the light emitted can be reduced in the images captured by the cameras. This can be desirable when the system is being used in an outdoor setting with additional lighting coming from the sun. During the periods outside of the twenty four "recording" instances of each second, the ring of light emitters can emit a lower level of light ("Lower Light Level") or no light at all. Returning to the example, the ring of light emitters can be turned off or alternatively project a relatively low level of 30 Lux during the other $952/1000^{th}$ periods of each second. As a result of this configuration, the ring of light emitters can appear to "pulsate" several times each second. In some embodiments, the Activated Light Level and the Lower Light Level can be configured based on settings information received from a user of the system.

[0096] As a result of the above, energy can be conserved as the ring of light emitters are consuming relatively less amounts of energy over the duration of an imagery shooting session. In some embodiments, heatsinks or other heat exchange devices can be applied to the ring of light emitters. By reducing the amount of time the ring of lights are in full operation and including heatsinks, the system overall can generate less heat overall. In doing so, the system may experience fewer heat related issues. Additionally, the generation of less heat also removes the need for more extensive active cooling systems (e.g., fans). As such, the system can operate more quietly and with a smaller footprint. Further the costs associated with operating the system can be reduced because of the reduction in electricity usage due to the ring of light emitters not being continuously in operation and the removal of active cooling systems.

[0097] In some embodiments, the system can include a synchronization module, such as synchronization module **736** described above. The synchronization module can be configured to send control signals to the ring of light emitters and/or the witness cameras in order to synchronize and align their operation so that the ring of light emitters is activated (e.g., projecting light at a desired level for the captured images) when the witness cameras are recording during an imagery shooting session. The system can further be configured such that when the synchronization module stops sending control signals, the light emitters are turned off and/or the witness cameras stop recoding. Configuration of the module can be based on user input information, information obtained from the cameras, etc. For example, the module can request and receive settings information from the cameras regarding the cameras' configured frames per second recording rate, shutter speed, etc. Based on this information, the synchronization module can send control signals to the ring of light emitters that synchronize the operation of the emitters with the cameras. In some embodiments, the control signals can be provided to the ring of light emitters and/or the cameras at predetermined intervals during each second. In this way, the system can be synchronized to operate at 24, 30, 48, 60, 120 and/or any other desirable frames per second rate.

[0098] In some embodiments, the synchronization module can synchronize and align the ring of light emitters and cameras with other components of the system as described above with respect to synchronization module **736**. In certain embodiments, the ring of light emitters and cameras can be synchronized with the displays (e.g., LED displays) of an immersive or volumetric content production system. In some embodiments, the displays can be configured to interleave images of a 3D environment with chroma key images (e.g., green screen/blue screen images). The synchronization module can synchronize the ring of light emitters and cameras with the interleaving of the images of the 3D environment/chroma key images. As an illustrative example, the displays can present a 3D background such as a forest during certain periods of a second and a green screen during other periods of the same second. The synchronization module can synchronize and align various devices such that the ring of light emitters are projecting the Activated Light Level and the cameras are recording during the periods of each second that the green screen is being displayed. The ring of light emitters and/or cameras can be inactive when the 3D background is being displayed.

[0099] At block **1006**, locations of at least one marker applied to the actor's face can be identified. For instance, positions captured by witness cameras **304***a-b* can be triangulated to determine the locations of the markers in the performance area. This location can then be used to position a digital character, or one or more features thereof such as the face of a digital character, whose position accurately corresponds to the location of the markers applied to the actor's face so that the digital character can accurately represent the actor's face.

[0100] At block **1008**, position and motion data for a digital character in a virtual environment can be determined based on the identified locations of the markers applied to the actor's face. For instance, a computer system, e.g., computer system **122** in FIG. **1**, can receive the captured images of one or more witness cameras and utilize the captured images to determine the position of the markers on the actor via triangulation. Once the position of the markers are determined, then a digital character can be rendered and positioned at a location within the virtual environment that corresponds to the determined positions of the markers. In some embodiments, the position of the markers with respect to one another can be used to determine the orientation at which the digital character faces in the virtual environment. For instance, the position of the marker at the tip of the nose relative to the positions of the markers at the temple, hairline, and chin can be used to determine which way the actor's face is oriented. This information can then be used to determine the orientation of the digital character in the virtual environment.

[0101] At block **1010**, a second plurality of images of the performance can be captured by a second set of one or more cameras. For instance, a taking camera, e.g., taking camera **302** or **302** in FIGS. **2** and **3**, respectively, can capture images of an actor and his or her surroundings in a set during the actor's performance. In some embodiments, the second set of one or more cameras captures the images simultaneously with the first set of one or more cameras. That way, the captured images can be of the same performance but just from different perspectives. However, the second plurality of images may be based upon what is perceived from reflected visible light. For example, the way the actor's face and costume looks, the way the chair looks, and how the actor is positioned with respect to the chair can all be captured by the second set of one or more cameras.

[0102] Thereafter, at block **1012**, content can be generated based on the determined positions for the digital character and the second plurality of images. That is, content can be generated where the digital character is positioned within the set as perceived by the taking camera. In some instances, the digital character can be positioned where the actor is positioned when viewed from the taking camera. Thus, the digital character can be have a size and positioning that accurately corresponds to the size and movements of the actor as captured by the witness cameras when the witness cameras are capturing the images of the markers on the actor's face.

[0103] For example, 3D positioning of the markers can be determined via triangulation techniques to determine the position of one or more markers on the surfaces of the actor's face. This process may be performed at different times, to thereby determine where and how a marker on the face of an actor moves as he or she performs. The 3D positioning data may then be used to set a pose of the rigid portions of a computer generated object, e.g. face. The computer generated object can be positioned within a setting captured in the second plurality of images by the second set of cameras. The second plurality of images may be used by a suitable solver system to determine the movement of those features of the computer generated object that are substantially non-rigid (e.g., an actor's eyebrows, eyes, cheeks, etc). Since images of the markers and images of the actor during the performance were captured, the computer generated object can accurately be mapped to the actor's face in the resulting content.

IV. Example Computer System

[0104] FIG. **11** is a simplified block diagram of system **1100** for creating computer graphics imagery (CGI) and computer-aided visual effects that may implement or incorporate various embodiments in accordance with the disclosure. In this example, system **1100** can include one or more design computers **1110**, object library **1120**, one or more object modeler systems **1130**, one or more object articulation systems **1140**, one or more object visual effects systems **1150**, one or more object simulation systems **1160**, and one or more object rendering systems **1170**. Any of the systems **1130-1170** may be invoked by or used directly by a user of the one or more design computers **1110** and/or automatically invoked by or used by one or more processes associated with the one or more design computers **1110**. Any of the elements of system **1100** can include hardware and/or software elements configured for specific functions.

[0105] The one or more design computers **1110** can include hardware and software elements configured for designing CGI and assisting with computer-aided animation. Each of the one or more design computers **1110** may be embodied as a single computing device or a set of one or more computing devices. Some examples of computing devices are PCs, laptops, workstations, mainframes, cluster computing system, grid computing systems, cloud computing systems, embedded devices, computer graphics devices, gaming devices and consoles, consumer electronic devices having programmable processors, or the like. The one or more design computers **1110** may be used at various stages of a production process (e.g., pre-production, designing, creating, editing, simulating, animating, rendering, post-production, etc.) to produce images, image sequences, motion pictures, video, audio, or associated effects related to CGI and animation.

[0106] In one example, a user of the one or more design computers **1110** acting as a modeler may employ one or more systems or tools to design, create, or modify objects within a computer-generated scene. The modeler may use modeling software to sculpt and refine a 3D model to fit predefined aesthetic needs of one or more character designers. The modeler may design and maintain a modeling topology conducive to a storyboarded range of deformations. In another example, a user of the one or more design computers **1110** acting as an articulator may employ one or more systems or tools to design, create, or modify controls or animation variables (avars) of models. In general, rigging is a process of giving an object, such as a character model, controls for movement, therein "articulating" its ranges of motion. The articulator may work closely with one or more animators in rig building to provide and refine an articulation of the full range of expressions and body movement needed to support a character's acting range in an animation. In a further example, a user of design computer **1110** acting as an animator may employ one or more systems or tools to specify motion and position of one or more objects over time to produce an animation.

[0107] Object library **1120** can include elements configured for storing and accessing information related to objects used by the one or more design computers **1110** during the various stages of a production process to produce CGI and animation. Some examples of object library **1120** can include a file, a database, or other storage devices and mechanisms. Object library **1120** may be locally accessible to the one or more design computers **1110** or hosted by one or more external computer systems.

[0108] Some examples of information stored in object library **1120** can include an object itself, metadata, object geometry, object topology, rigging, control data, animation data, animation cues, simulation data, texture data, lighting data, shader code, or the like. An object stored in object library **1120** can include any entity that has an n-dimensional (e.g., 2D or 3D) surface geometry. The shape of the object can include a set of points or locations in space (e.g., object space) that make up the object's surface. Topology of an object can include the connectivity of the surface of the object (e.g., the genus or number of holes in an object) or the vertex/edge/face connectivity of an object.

[0109] The one or more object modeling systems **1130** can include hardware and/or software elements configured for modeling one or more objects. Modeling can include the creating, sculpting, and editing of an object. In various embodiments, the one or more object modeling systems **1130** may be configured to generated a model to include a description of the shape of an object. The one or more object modeling systems **1130** can be configured to facilitate the creation and/or editing of features, such as non-uniform rational B-splines or NURBS, polygons and subdivision surfaces (or SubDivs), that may be used to describe the shape of an object. In general, polygons are a widely used model medium due to their relative stability and functionality. Polygons can also act as the bridge between NURBS and SubDivs. NURBS are used mainly for their ready-smooth appearance and generally respond well to deformations. SubDivs are a combination of both NURBS and polygons representing a smooth surface via the specification of a coarser piecewise linear polygon mesh. A single object may have several different models that describe its shape.

[0110] The one or more object modeling systems **1130** may further generate model data (e.g., 2D and 3D model data) for use by other elements of system **1100** or that can be stored in object library **1120**. The one or more object modeling systems **1130** may be configured to allow a user to associate additional information, metadata, color, lighting, rigging, controls, or the like, with all or a portion of the generated model data.

[0111] The one or more object articulation systems **1140** can include hardware and/or software elements configured to articulating one or more computer-generated objects. Articulation can include the building or creation of rigs, the rigging of an object, and the editing of rigging. In various embodiments, the one or more articulation systems **1140** can be configured to enable the specification of rigging for an object, such as for internal skeletal structures or eternal features, and to define how input motion deforms the object. One technique is called "skeletal animation," in which a character can be represented in at least two parts: a surface representation used to draw the character (called the skin) and a hierarchical set of bones used for animation (called the skeleton).

[0112] The one or more object articulation systems **1140** may further generate articulation data (e.g., data associated with controls or animations variables) for use by other elements of system **1100** or that can be stored in object library **1120**. The one or more object articulation systems **1140** may be configured to allow a user to associate additional information, metadata, color, lighting, rigging, controls, or the like, with all or a portion of the generated articulation data.

[0113] The one or more object visual effects systems **1150** can include hardware and/or software elements configured for animating one or more computer-generated objects. Animation can include the specification of motion and position of an object over time. The one or more object visual effects systems **1150** may be invoked by or used directly by a user of the one or more design computers **1110** and/or automatically invoked by or used by one or more processes associated with the one or more design computers **1110**.

[0114] In various embodiments, the one or more visual effects systems **1150** may be configured to enable users to manipulate controls or animation variables or utilized character rigging to specify one or more key frames of animation sequence. The one or more visual effects systems **1150** generate intermediary frames based on the one or more key frames. In some embodiments, the one or more visual effects systems **1150** may be configured to enable users to specify animation cues, paths, or the like according to one or more predefined sequences. The one or more visual effects systems **1150** generate frames of the animation based on the animation cues or paths. In further embodiments, the one or more visual effects systems **1150** may be configured to enable users to define animations using one or more animation languages, morphs, deformations, or the like. In various embodiments, the one or more visual effects systems **1150** may be configured to generate animated content utilizing captured images from taking and witness cameras of any of the motion capture systems discussed herein.

[0115] The one or more object visual effects systems **1150** may further generate animation data (e.g., inputs associated with controls or animations variables) for use by other elements of system **1100** or that can be stored in object library **1120**. The one or more object visual effects systems **1150** may be configured to allow a user to associate additional information, metadata, color, lighting, rigging, controls, or the like, with all or a portion of the generated animation data.

[0116] The one or more object simulation systems **1160** can include hardware and/or software elements configured for simulating one or more computer-generated objects. Simulation can include determining motion and position of an object over time in response to one or more simulated forces or conditions. The one or more object simulation systems **1160** may be invoked by or used directly by a user of the one or more design computers **1110** and/or automatically invoked by or used by one or more processes associated with the one or more design computers **1110**.

[0117] In various embodiments, the one or more object simulation systems **1160** may be configured to enables users to create, define, or edit simulation engines, such as a physics engine or physics processing unit (PPU/GPGPU) using one or more physically-based numerical techniques. In general, a physics engine can include a computer program that simulates one or more physics models (e.g., a Newtonian physics model), using variables such as mass, velocity, friction, wind resistance, or the like. The physics engine may simulate and predict effects under different conditions that would approximate what happens to an object according to the physics model. The one or more object simulation systems **1160** may be used to simulate the behavior of objects, such as hair, fur, and cloth, in response to a physics model and/or animation of one or more characters and objects within a computer-generated scene.

[0118] The one or more object simulation systems **1160** may further generate simulation data (e.g., motion and position of an object over time) for use by other elements of system **1100** or that can be stored in object library **1120**. The generated simulation data may be combined with or used in addition to animation data generated by the one or more object visual effects systems **1150**. The one or more object simulation systems **1160** may be configured to allow a user to associate additional information, metadata, color, lighting, rigging, controls, or the like, with all or a portion of the generated simulation data.

[0119] The one or more object rendering systems **1170** can include hardware and/or software element configured for "rendering" or generating one or more images of one or more computer-generated objects. "Rendering" can include generating an image from a model based on information such as geometry, viewpoint, texture, lighting, and shading information. The one or more object rendering systems **1170** may be invoked by or used directly by a user of the one or more design computers **1110** and/or automatically invoked by or used by one or more processes associated with the one or more design computers **1110**. One example of a software program embodied as the one or more object rendering systems **1170** can include PhotoRealistic RenderMan, or PRMan, produced by Pixar Animations Studios of Emeryville, California.

[0120] In various embodiments, the one or more object rendering systems **1170** can be configured to render one or more objects to produce one or more computer-generated images or a set of images over time that provide an animation. The one or more object rendering systems **1170** may generate digital images or raster graphics images.

[0121] In various embodiments, a rendered image can be understood in terms of a number of visible features. Some examples of visible features that may be considered by the one or more object rendering systems **1170** may include shading (e.g., techniques relating to how the color and brightness of a surface varies with lighting), texture-mapping (e.g., techniques relating to applying detail information to surfaces or objects using maps), bump-mapping (e.g., techniques relating to simulating small-scale bumpiness on surfaces), fogging/participating medium (e.g., techniques relating to how light dims when passing through non-clear atmosphere or air) shadows (e.g., techniques relating to effects of obstructing light), soft shadows (e.g., techniques relating to varying darkness caused by partially obscured light sources), reflection (e.g., techniques relating to mirror-like or highly glossy reflection), transparency or opacity (e.g., techniques relating to sharp transmissions of light through solid objects), translucency (e.g., techniques relating to highly scattered transmissions of light through solid objects), refraction (e.g., techniques relating to bending of light associated with transparency), diffraction (e.g., techniques relating to bending, spreading and interference of light passing by an object or aperture that disrupts the ray), indirect illumination (e.g., techniques relating to surfaces illuminated by light reflected off other surfaces, rather than directly from a light source, also known as global illumination), caustics (e.g., a form of indirect illumination with techniques relating to reflections of light off a shiny object, or focusing of light through a transparent object, to produce bright highlight rays on another object), depth of field (e.g., techniques relating to how objects appear blurry or out of focus when too far in front of or behind the object in focus), motion blur (e.g., techniques relating to how objects appear blurry due to high-speed motion, or the motion of the camera), non-photorealistic rendering (e.g., techniques relating to rendering of scenes in an artistic style, intended to look like a painting or drawing), or the like.

[0122] The one or more object rendering systems **1170** may further render images (e.g., motion and position of an object over time) for use by other elements of system **1100**

or that can be stored in object library **1120**. The one or more object rendering systems **1170** may be configured to allow a user to associate additional information or metadata with all or a portion of the rendered image.

[0123] FIG. **12** is a block diagram of computer system **1200**. FIG. **12** is merely illustrative. In some embodiments, a computer system includes a single computer apparatus, where the subsystems can be the components of the computer apparatus. In other embodiments, a computer system can include multiple computer apparatuses, each being a subsystem, with internal components. Computer system **1200** and any of its components or subsystems can include hardware and/or software elements configured for performing methods described herein.

[0124] Computer system **1200** may include familiar computer components, such as one or more one or more data processors or central processing units (CPUs) **1205**, one or more graphics processors or graphical processing units (GPUs) **1210**, memory subsystem **1215**, storage subsystem **1220**, one or more input/output (I/O) interfaces **1225**, communications interface **1230**, or the like. Computer system **1200** can include system bus **1235** interconnecting the above components and providing functionality, such connectivity and inter-device communication.

[0125] The one or more data processors or central processing units (CPUs) **1205** can execute logic or program code or for providing application-specific functionality. Some examples of CPU(s) **1205** can include one or more microprocessors (e.g., single core and multi-core) or micro-controllers, one or more field-gate programmable arrays (FPGAs), and application-specific integrated circuits (ASICs). As used herein, a processor includes a multi-core processor on a same integrated chip, or multiple processing units on a single circuit board or networked.

[0126] The one or more graphics processor or graphical processing units (GPUs) **1210** can execute logic or program code associated with graphics or for providing graphics-specific functionality. GPUs **1210** may include any conventional graphics processing unit, such as those provided by conventional video cards. In various embodiments, GPUs **1210** may include one or more vector or parallel processing units. These GPUs may be user programmable, and include hardware elements for encoding/decoding specific types of data (e.g., video data) or for accelerating 2D or 3D drawing operations, texturing operations, shading operations, or the like. The one or more graphics processors or graphical processing units (GPUs) **1210** may include any number of registers, logic units, arithmetic units, caches, memory interfaces, or the like.

[0127] Memory subsystem **1215** can store information, e.g., using machine-readable articles, information storage devices, or computer-readable storage media. Some examples can include random access memories (RAM), read-only-memories (ROMS), volatile memories, non-volatile memories, and other semiconductor memories. Memory subsystem **1215** can include data and program code **1240**.

[0128] Storage subsystem **1220** can also store information using machine-readable articles, information storage devices, or computer-readable storage media. Storage subsystem **1220** may store information using storage media **1245**. Some examples of storage media **1245** used by storage subsystem **1220** can include floppy disks, hard disks, optical storage media such as CD-ROMS, DVDs and bar codes, removable storage devices, networked storage devices, or the like. In some embodiments, all or part of data and program code **1240** may be stored using storage subsystem **1220**.

[0129] The one or more input/output (I/O) interfaces **1225** can perform I/O operations. One or more input devices **1250** and/or one or more output devices **1255** may be communicatively coupled to the one or more I/O interfaces **1225**. The one or more input devices **1250** can receive information from one or more sources for computer system **1200**. Some examples of the one or more input devices **1250** may include a computer mouse, a trackball, a track pad, a joystick, a wireless remote, a drawing tablet, a voice command system, an eye tracking system, external storage systems, a monitor appropriately configured as a touch screen, a communications interface appropriately configured as a transceiver, or the like. In various embodiments, the one or more input devices **1250** may allow a user of computer system **1200** to interact with one or more non-graphical or graphical user interfaces to enter a comment, select objects, icons, text, user interface widgets, or other user interface elements that appear on a monitor/display device via a command, a click of a button, or the like.

[0130] The one or more output devices **1255** can output information to one or more destinations for computer system **1200**. Some examples of the one or more output devices **1255** can include a printer, a fax, a feedback device for a mouse or joystick, external storage systems, a monitor or other display device, a communications interface appropriately configured as a transceiver, or the like. The one or more output devices **1255** may allow a user of computer system **1200** to view objects, icons, text, user interface widgets, or other user interface elements. A display device or monitor may be used with computer system **1200** and can include hardware and/or software elements configured for displaying information.

[0131] Communications interface **1230** can perform communications operations, including sending and receiving data. Some examples of communications interface **1230** may include a network communications interface (e.g. Ethernet, Wi-Fi, etc.). For example, communications interface **1230** may be coupled to communications network/external bus **1260**, such as a computer network, a USB hub, or the like. A computer system can include a plurality of the same components or subsystems, e.g., connected together by communications interface **1230** or by an internal interface. In some embodiments, computer systems, subsystem, or apparatuses can communicate over a network. In such instances, one computer can be considered a client and another computer a server, where each can be part of a same computer system. A client and a server can each include multiple systems, subsystems, or components.

[0132] Computer system **1200** may also include one or more applications (e.g., software components or functions) to be executed by a processor to execute, perform, or otherwise implement techniques disclosed herein. These applications may be embodied as data and program code **1240**. Additionally, computer programs, executable computer code, human-readable source code, shader code, rendering engines, or the like, and data, such as image files, models including geometrical descriptions of objects, ordered geometric descriptions of objects, procedural descriptions of models, scene descriptor files, or the like, may be stored in memory subsystem **1215** and/or storage subsystem **1220**.

[0133] Such programs may also be encoded and transmitted using carrier signals adapted for transmission via wired, optical, and/or wireless networks conforming to a variety of protocols, including the Internet. As such, a computer readable medium according to an embodiment of the present invention may be created using a data signal encoded with such programs. Computer readable media encoded with the program code may be packaged with a compatible device or provided separately from other devices (e.g., via Internet download). Any such computer readable medium may reside on or within a single computer product (e.g. a hard drive, a CD, or an entire computer system), and may be present on or within different computer products within a system or network. A computer system may include a monitor, printer, or other suitable display for providing any of the results mentioned herein to a user.

[0134] Any of the methods described herein may be totally or partially performed with a computer system including one or more processors, which can be configured to perform the steps. Thus, embodiments can be directed to computer systems configured to perform the steps of any of the methods described herein, potentially with different components performing a respective steps or a respective group of steps. Although presented as numbered steps, steps of methods herein can be performed at a same time or in a different order. Additionally, portions of these steps may be used with portions of other steps from other methods. Also, all or portions of a step may be optional. Additionally, any of the steps of any of the methods can be performed with modules, circuits, or other means for performing these steps.

V. Additional Embodiments

[0135] In the foregoing specification, aspects of the invention are described with reference to specific embodiments thereof, but those skilled in the art will recognize that the invention is not limited thereto. Various features and aspects of the above-described invention may be used individually or jointly. For example, while specific examples discussed above referred to a frame rate of 24 frames per second (fps), embodiments are not limited to any particular frame rate. Other embodiments can generate clock and synchronization signals at higher or lower frequency rate than 24 fps, and in some particular embodiments, the clock and synchronization signals can operate between 24 and 60 fps, including commonly used video capture frame rates of 24 fps, 25 fps, 30 fps or 60 fps. Further, embodiments can be utilized in any number of environments and applications beyond those described herein without departing from the broader spirit and scope of the specification. The specification and drawings are, accordingly, to be regarded as illustrative rather than restrictive.

[0136] Additionally, for the purposes of explanation, numerous specific details have been set forth in order to provide a thorough understanding of various embodiments of the present invention. It will be apparent, however, to one skilled in the art that embodiments of the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices may have been shown in block diagram form.

[0137] This description has provided exemplary embodiments only, and is not intended to limit the scope, applicability, or configuration of the disclosure. Rather, this description of the exemplary embodiments provides those skilled in the art with an enabling description for implementing an exemplary embodiment. It should be understood that various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the invention as set forth in the appended claims.

[0138] Specific details have been given in the description to provide a thorough understanding of the embodiments. However, it will be understood by one of ordinary skill in the art that the embodiments may be practiced without these specific details. For example, circuits, systems, networks, processes, and other components may be shown as components in block diagram form in order not to obscure the embodiments in unnecessary detail. In other instances, well-known circuits, processes, algorithms, structures, and techniques may be shown without unnecessary detail in order to avoid obscuring the embodiments.

[0139] Also, it is noted that individual embodiments may be described as a process which is depicted as a flowchart, a flow diagram, a data flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe the operations as a sequential process, many of the operations can be performed in parallel or concurrently. In addition, the order of the operations may be re-arranged. A process is terminated when its operations are completed, but could have additional steps not included in a figure. A process may correspond to a method, a function, a procedure, a subroutine, a subprogram, etc. When a process corresponds to a function, its termination can correspond to a return of the function to the calling function or the main function.

[0140] The term “non-transitory, computer-readable medium” includes, but is not limited to portable or fixed storage devices, optical storage devices, and various other mediums capable of storing instruction(s) and/or data. A code segment or machine-executable instructions may represent a procedure, a function, a subprogram, a program, a routine, a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements. A code segment may be coupled to another code segment or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, etc., may be passed, forwarded, or transmitted via any suitable means including memory sharing, message passing, token passing, network transmission, etc.

[0141] Furthermore, embodiments may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware or microcode, the program code or code segments to perform the necessary tasks may be stored in a machine readable medium. A processor(s) may perform the necessary tasks.

[0142] Additionally, for the purposes of illustration, methods may have been described in a particular order. It should be appreciated that in alternate embodiments, the methods may be performed in a different order than that described. It should also be appreciated that the methods described above may be performed by hardware components or may be embodied in sequences of machine-executable instructions, which may be used to cause a machine, such as a general-purpose or special-purpose processor or logic circuits programmed with the instructions to perform the methods. These machine-executable instructions may be stored on one or more machine readable mediums, such as CD-ROMs or other type of optical disks, floppy diskettes, ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, flash memory, or other types of machine-readable mediums suitable for storing electronic instructions. Alternatively, the methods may be performed by a combination of hardware and software.

[0143] Although the disclosure has been described with respect to specific embodiments, it will be appreciated that the disclosure is intended to cover all modifications and equivalents within the scope of the following claims.

What is claimed is:

1. A motion capture system comprising:

a master clock configured to repeatedly generate and output, at a frame rate, a primary clock signal that conveys when a video frame starts;

a first camera configured to capture light within a first set of wavelengths and operably coupled to receive the master clock signal and initiate an image capture sequence on a frame-by-frame basis in fixed phase relationship with the primary clock signal to generate a first set of images at the frame rate from light captured within the first set of wavelengths;

a synchronization module operably coupled to receive the master clock signal from the master clock and configured to generate a synchronization signal offset in time from and in a fixed relationship with the primary clock signal; and

a second camera configured to capture light within a second set of wavelengths, different than the first set of wavelengths, and operably coupled to receive the synchronization signal and initiate an image capture sequence on the frame-by-frame basis in a fixed phase relationship with the synchronization signal to generate a second set of images at the frame rate from light captured within the second set of wavelengths;

wherein the amount of time the synchronization signal is offset from the master clock signal aligns, within each frame, the image capture sequence of the second camera with the image capture sequence of the first camera.

2. The motion capture system set forth in claim **1** wherein the synchronization module is configured to generate the synchronization signal by moving the output from master clock, advancing or delaying the output, with microsecond precision in order to adjust for different timing characteristics of downstream devices.

3. The motion capture system set forth in claim **2** wherein the synchronization module is configured to generate and output a plurality of different synchronization signals offset from and in a fixed relationship with the master clock signal, wherein a first synchronization signal in the plurality of synchronization signals is offset from the master clock signal by X microseconds and a second synchronization signal in the plurality of synchronization signals is offset from the master clock signal by Y microseconds where X is different than Y.

4. The motion capture system set forth in claim **3** further comprising a light source and a driver operatively coupled to the light source and configured to generate, with the light source, pulses of light, synchronized with the frame rate, at a wavelength within the second set of wavelengths.

5. The motion capture system set forth in claim **4** wherein:

the synchronization signal received by the second camera is the first synchronization signal, and

the driver is operatively coupled to the synchronization module to receive the second synchronization signal and activate the light source in fixed phase relationship with the second synchronization signal to align the pulses of light generated by the light source with the image capture sequence of the second camera.

6. The motion capture system set forth in claim **3** wherein the first synchronization signal is offset from the master clock by a negative amount and the second synchronization signal is offset from the master clock by a positive amount.

7. The motion capture system set forth in claim **1** further comprising a third camera configured to capture light within the second set of wavelengths and operably coupled to receive the synchronization signal and initiate an image capture sequence on the frame-by-frame basis in a fixed phase relationship with the synchronization signal to generate a third set of images at the frame rate from light captured within the second set of wavelengths.

8. The motion capture system set forth in claim **7** wherein the first, second and third cameras are mounted on a single support frame of a movable rig with the second and third cameras on opposing sides of the first camera.

9. The motion capture system set forth in claim **1** further comprising a wireless module coupled to receive the synchronization signal at an input and wirelessly transmit the synchronization signal to one or more downstream devices.

10. The motion capture system set forth in claim **1** wherein the first camera is a taking camera and the second camera is a witness camera, the first set of wavelengths comprises visible light, the second set of wavelengths comprises infrared light and the first and second sets of wavelengths do not overlap.

11. The motion capture system set forth in in claim **1** wherein the frame rate is between 24 to 60 frames per second.

12. A motion capture system comprising:

a primary clock configured to repeatedly generate and output, at a frame rate, a primary clock signal that conveys when video frames start;

a first camera configured to capture light within a first set of wavelengths comprising the visible light spectrum and generate images from the captured light, wherein the first camera includes a first shutter and is operably coupled to receive the primary clock signal and activate the first shutter in a fixed phase relationship with the primary clock signal to capture a first set of images at the frame rate;

a synchronization module operably coupled to receive the primary clock signal from the primary clock and configured to generate and output a synchronization signal offset from and in a fixed relationship with the primary clock signal;

a second camera configured to capture light within a second set of wavelengths comprising infrared light and generate images from the captured light, wherein the second camera includes a second shutter and is operably coupled to receive the synchronization signal and activate the second shutter in fixed phase relationship with the synchronization signal to align the second camera with the first camera and capture a second sets of images at the frame rate; and

a third camera configured to capture light within the second set of wavelengths and generate images from the captured light, wherein the third camera includes a third shutter and is operably coupled to receive the synchronization signal and activate the third shutter in fixed phase relationship with the synchronization signal to align the third camera with the first camera and capture a third set of images at the frame rate.

13. The motion capture system set forth in claim **12** wherein the synchronization module is configured to generate and output a plurality of different synchronization signals offset from and in a fixed relationship with the primary clock signal, wherein a first synchronization signal in the plurality of synchronization signals is offset from the primary clock signal by X microseconds and a second synchronization signal in the plurality of synchronization signals is offset from the primary clock signal by Y microseconds where X is different than Y.

14. The motion capture system set forth in claim **13** further comprising a light source and a driver configured to generate pulses of light at a wavelength within the second set of wavelengths; wherein the synchronization signal received by the second and third cameras is the first synchronization signal, and wherein the driver is operatively coupled to the synchronization module to receive the second synchronization signal and activate the light source in fixed phase relationship with the second synchronization signal to align the light source with the second camera.

15. The motion capture system set forth in claim **12** further comprising a wireless module coupled to receive the synchronization signal at an input and wirelessly transmit the synchronization signal to one or more downstream devices.

16. The motion capture system set forth in claim **12** wherein the synchronization module is configured to precisely move the output from the primary clock, advancing or delaying the output within each frame, in order to adjust for different timing characteristics of any downstream device.

17. The motion capture system set forth in claim **12** wherein the first, second and cameras are mounted on a single support frame of a movable rig with the second and third cameras on opposing sides of the first camera.

18. A computer-implemented method of capturing motion with a motion capture system, the method comprising:

generating and outputting, at a frame rate, a primary clock signal that conveys when a video frame starts;

controlling a first camera with the primary clock signal to capture a first plurality of images of an actor in a performance area, wherein the first camera is operable to capture light at wavelengths in a first spectrum comprising visible light;

emitting infrared light from an infrared light source at towards the actor in the performance area;

generating a synchronization signal offset from and in a fixed relationship with the primary clock signal; and

controlling a second camera with the synchronization signal to align the second camera with the first camera and capture a second plurality of images of the actor concurrent with capturing the first plurality of images of the actor, wherein the second camera is operable to capture light at infrared wavelengths.

19. The computer-implemented method of claim **18** further comprising:

generating a second synchronization signal offset from and in a fixed relationship with the primary clock signal; and

controlling the infrared light source to emit pulses of infrared light into the performance area based on the second synchronization signal to synchronize the pulses of infrared light with a shutter of the second camera.

20. The computer-implemented method of claim **18** wherein:

the first plurality of images represents at least a portion of a body of the actor and a set surrounding the actor in the performance area;

the second plurality of images represents captured light emitted from the infrared light source that has been reflected off of at least one marker applied to the face of the actor; and wherein the method further comprises:

identifying locations of at least one marker applied to the face of the actor by analyzing at least some of the second plurality of images captured by the second camera; and

generating position and motion data for a digital character based on the identified locations of the at least one marker applied to the face of the actor.

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