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**Linnell**

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(54) **SYSTEM AND METHOD FOR 3D PROJECTION MAPPING WITH ROBOTICALLY CONTROLLED OBJECTS**

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**G06T 15/20** (2011.01)  
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CPC ..... **H04N 5/2224** (2013.01); **B25J 9/1633** (2013.01); **B25J 11/00** (2013.01);  
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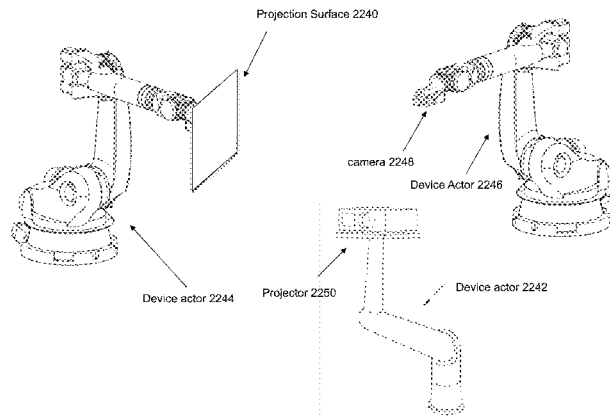
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(57) **ABSTRACT**

A system for motion control is presented. In one embodiment, a motion control 3D projection system includes a projector; and a projection surface coupled to a robotic arm, where the robotic arm moves the projection surface through a set of spatial coordinates, and a 3D projection from the projector is projected onto a set of coordinates of the projection surface and matches the 3D projection to the set of coordinates of the projection surface as the projection surface moves through the set of spatial coordinates. In additional embodiments, a master control system may integrate additional robotic arms and other devices to create a motion control scene with a master timeline.

**20 Claims, 28 Drawing Sheets**



**Related U.S. Application Data**

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(52) **U.S. Cl.**  
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 USPC ..... 348/51, 61  
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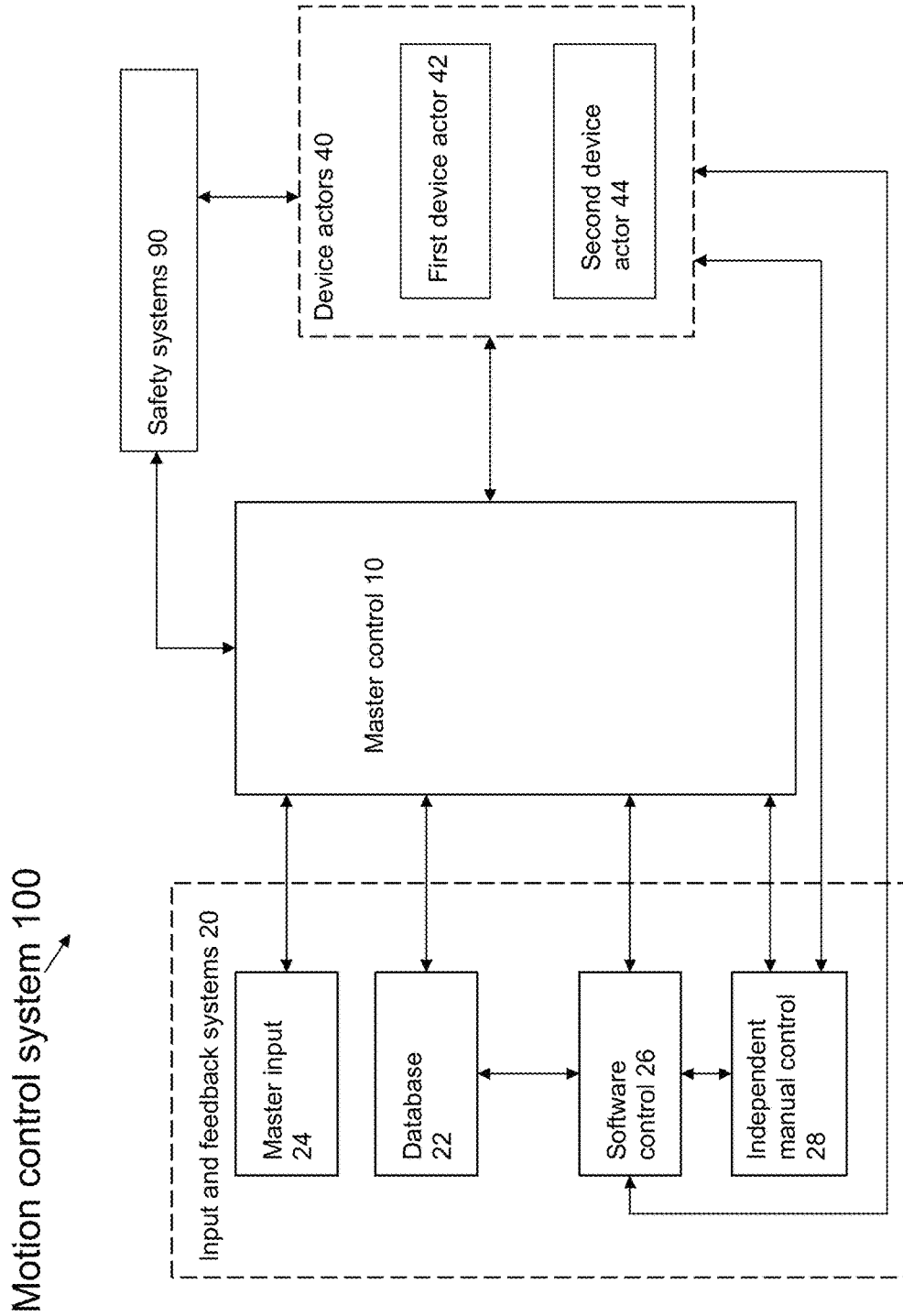


Figure 1

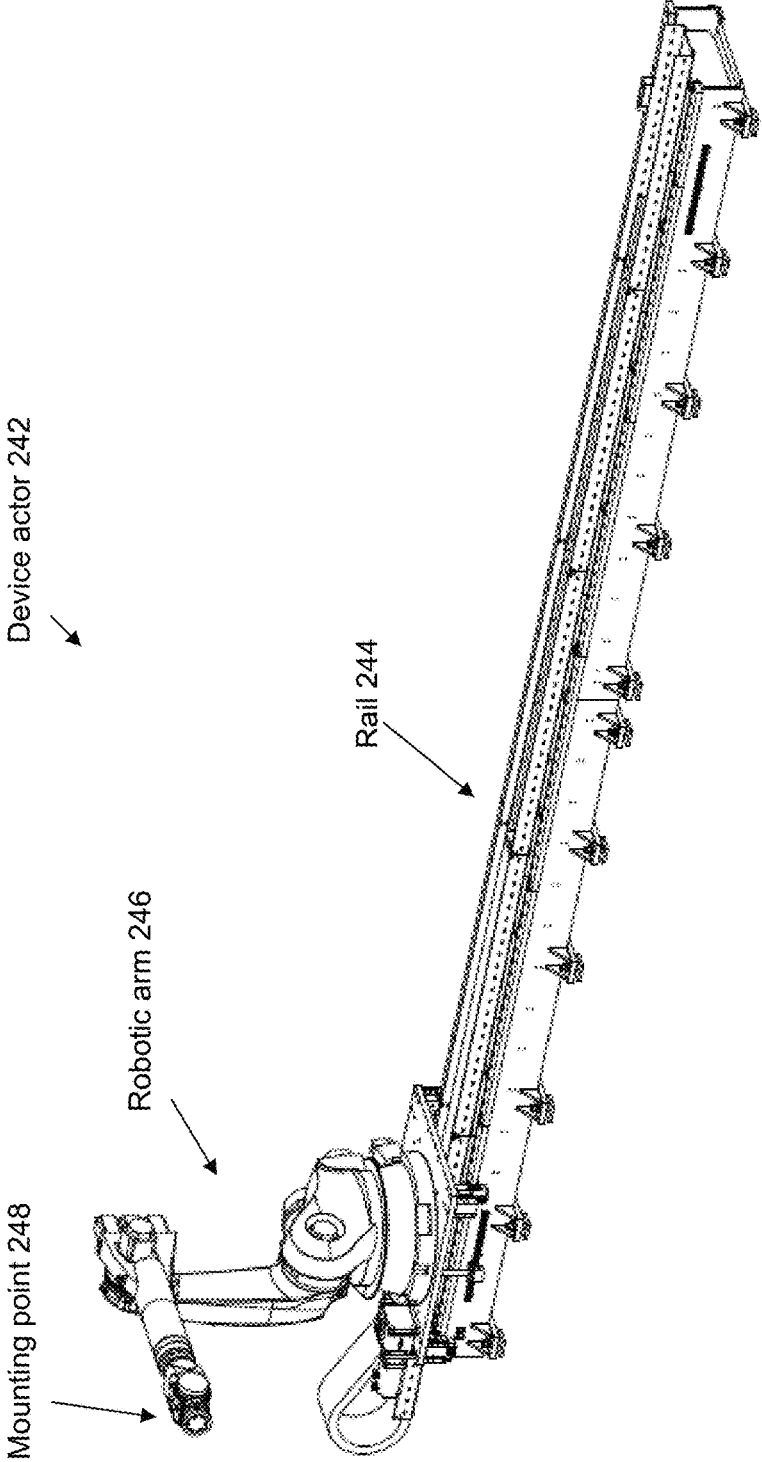


Figure 2

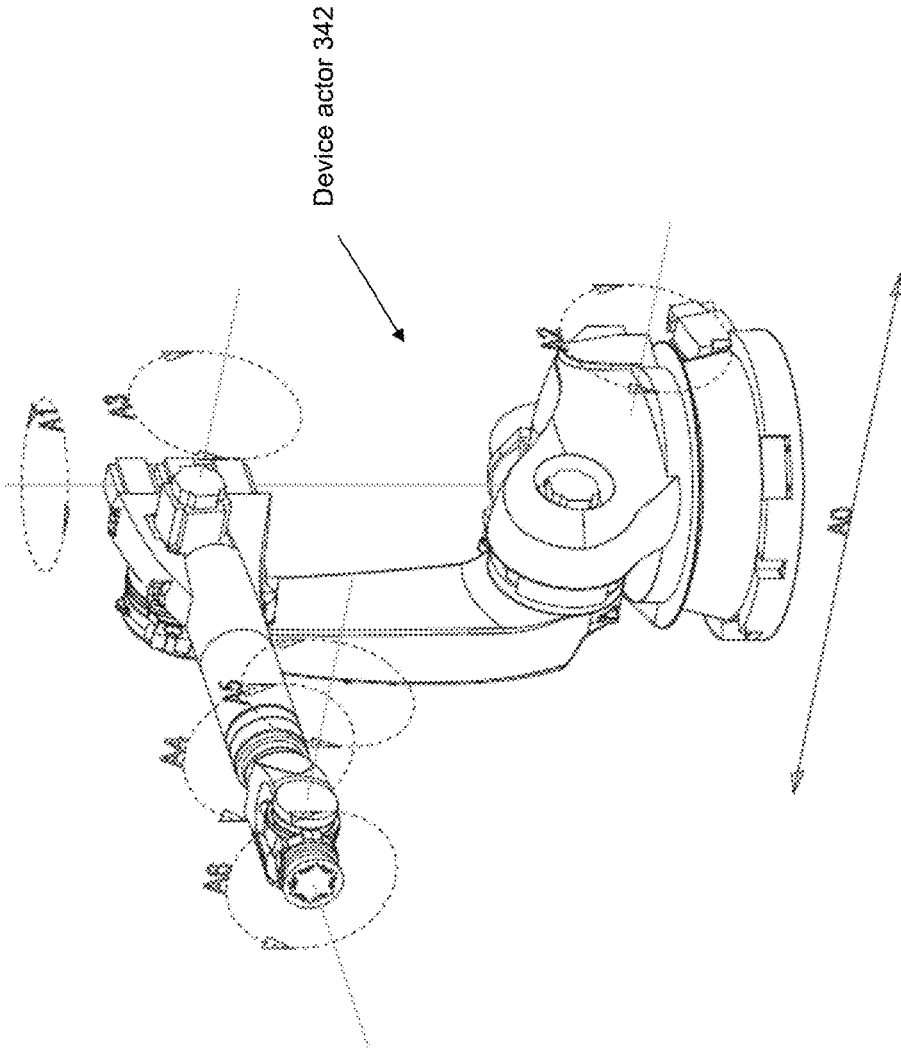


Figure 3a

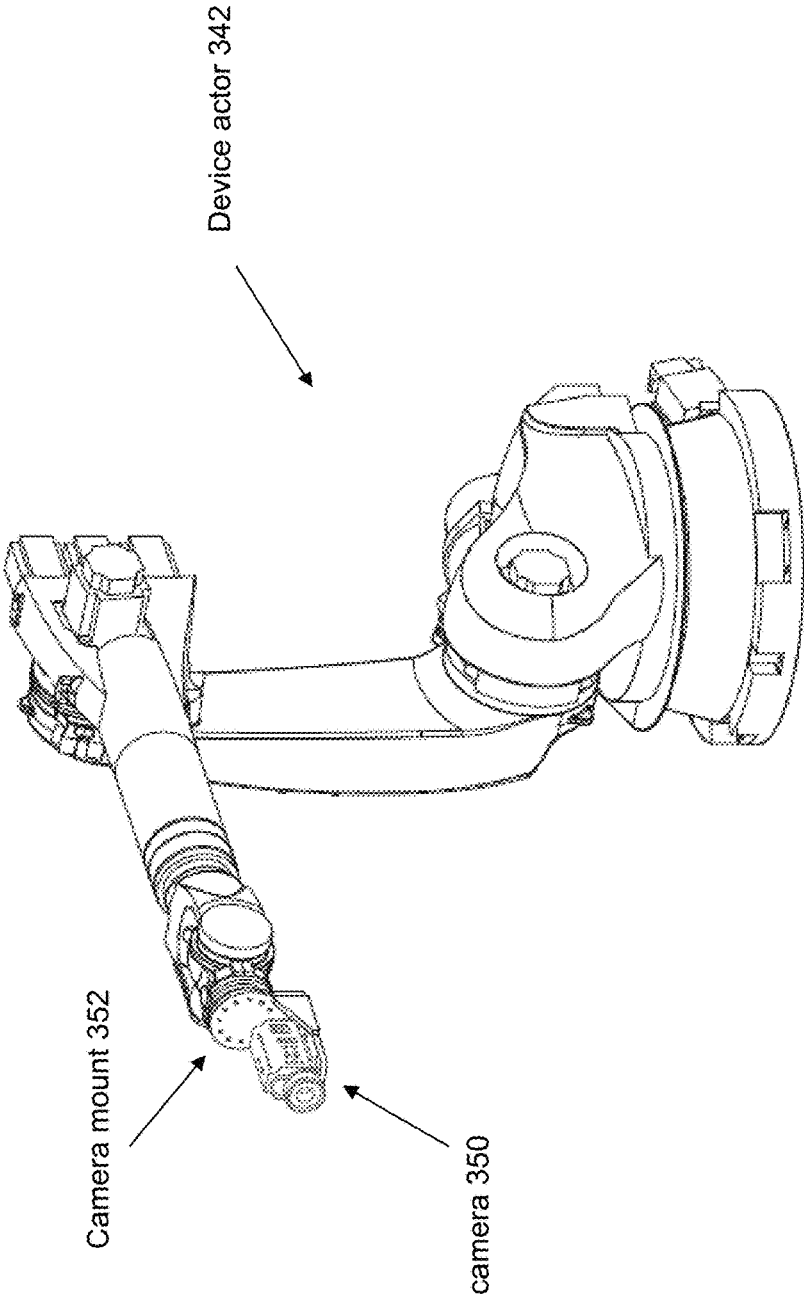


Figure 3b

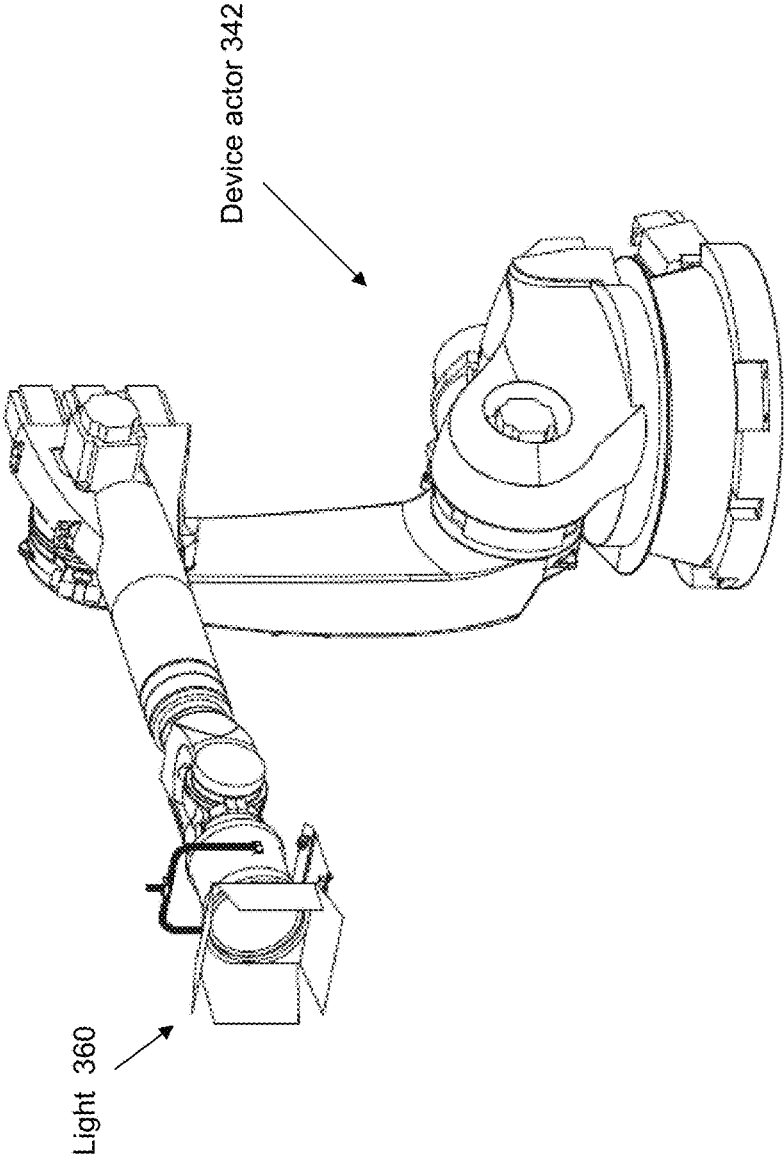


Figure 3c

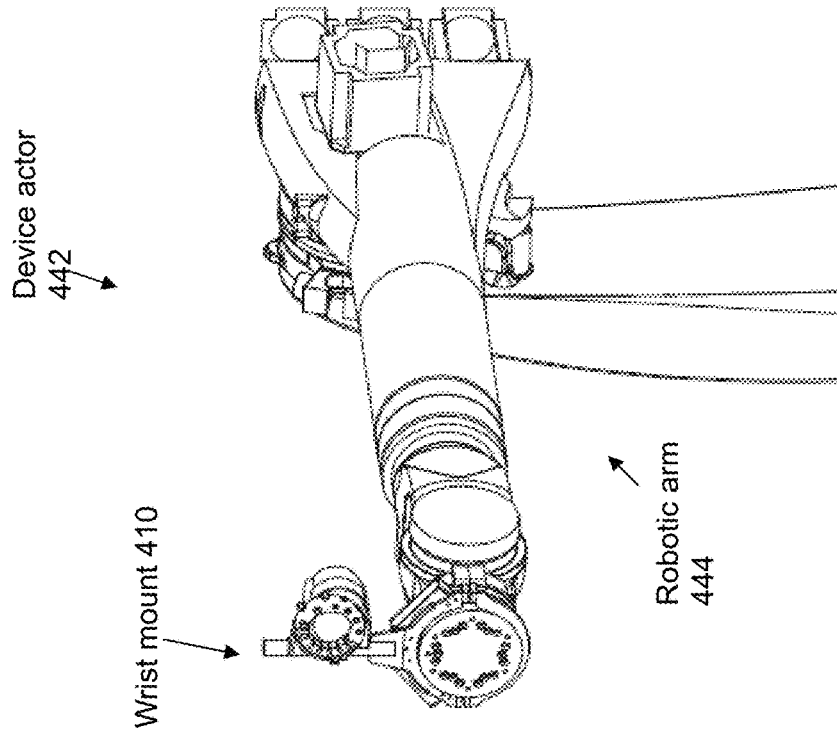


Figure 4b

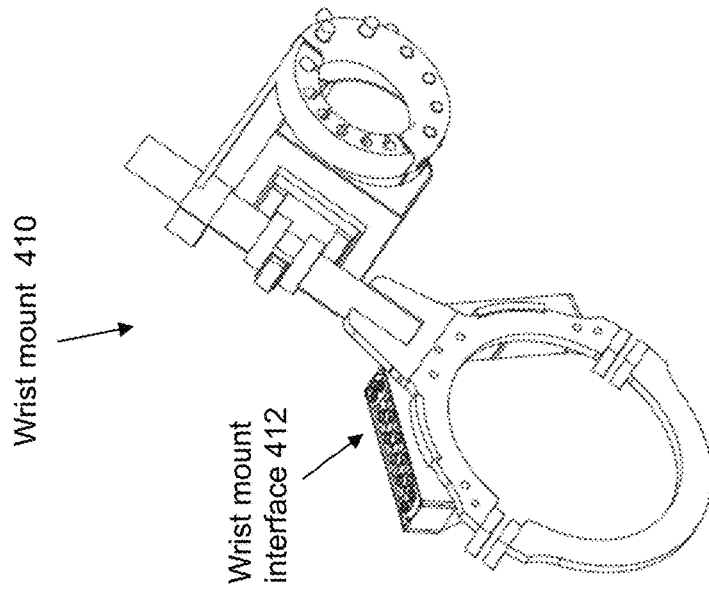


Figure 4a



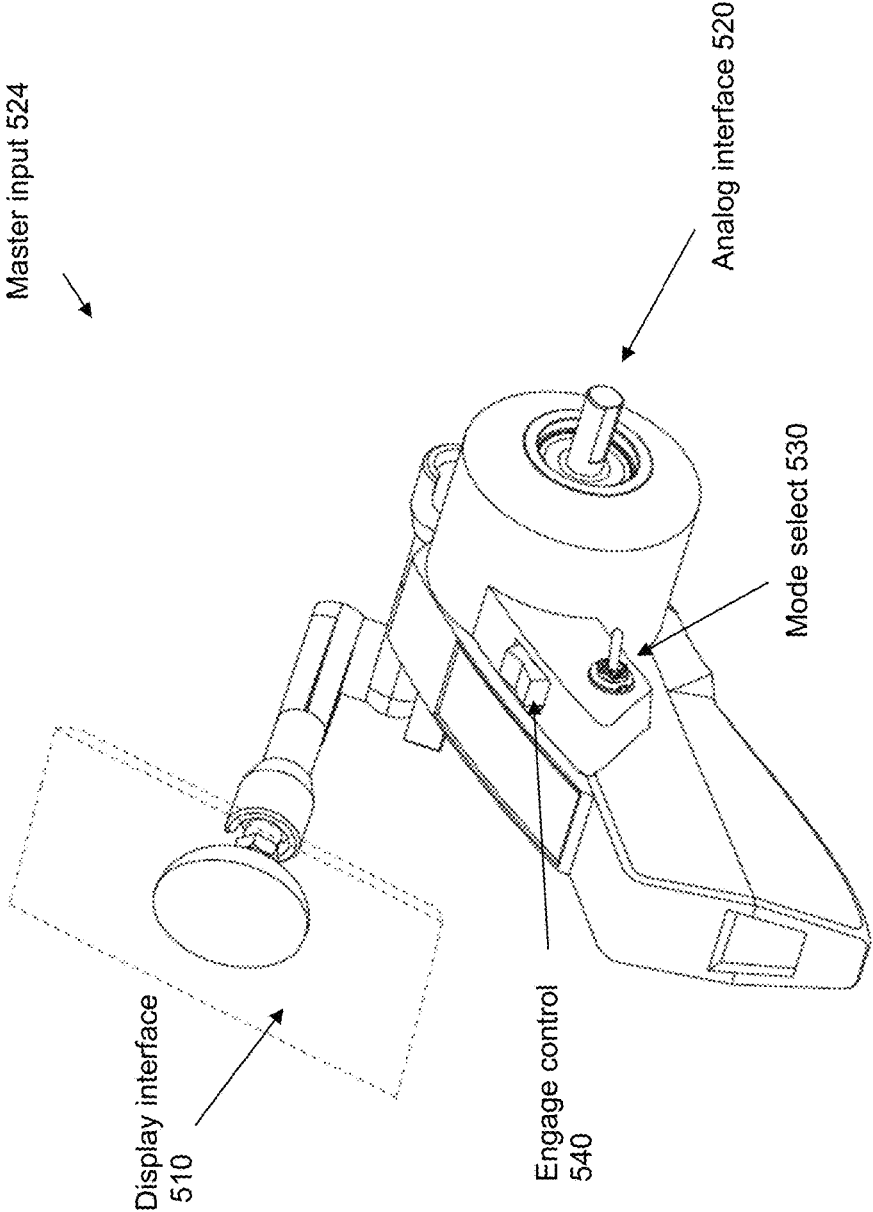


Figure 5a

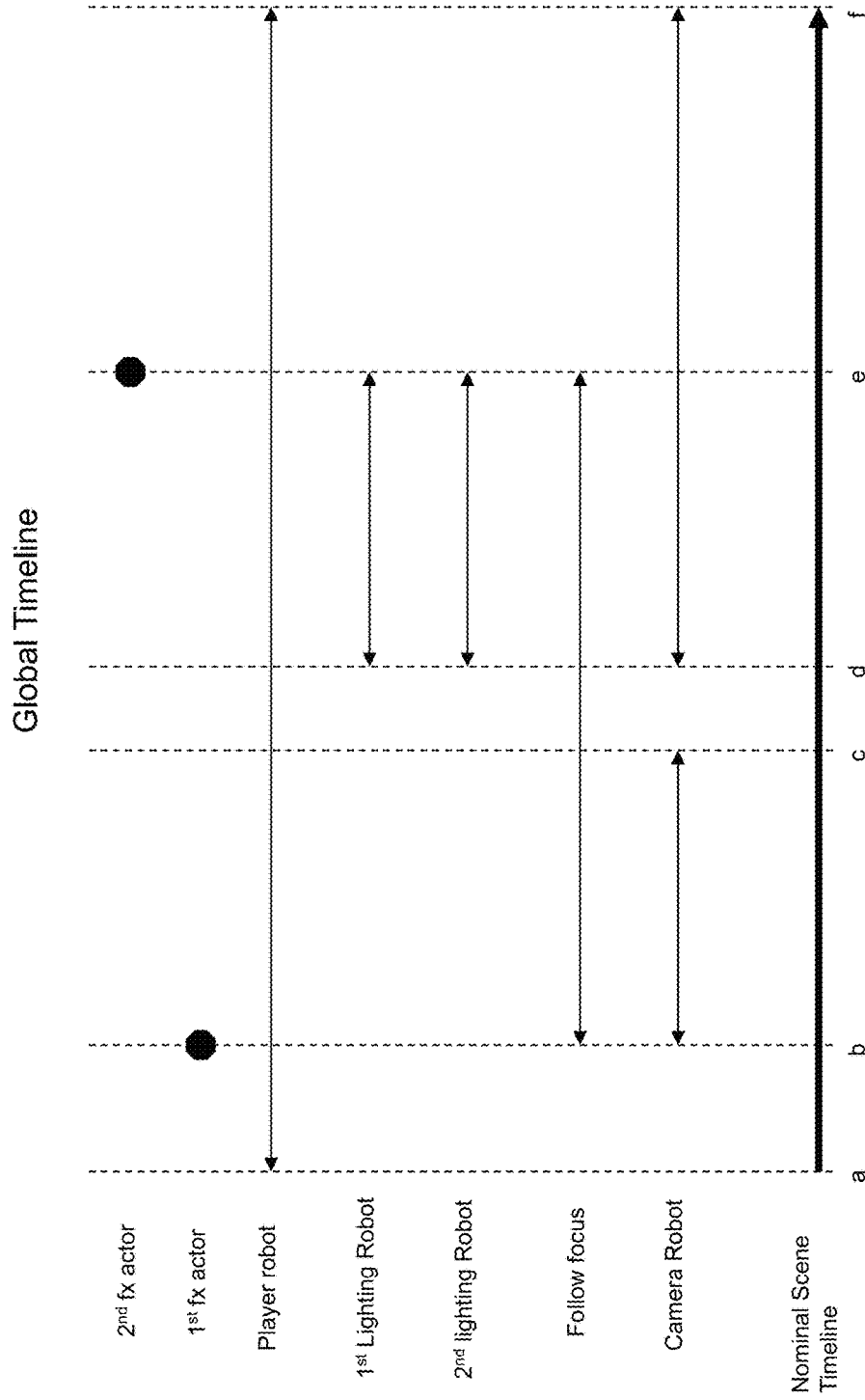


Figure 5b

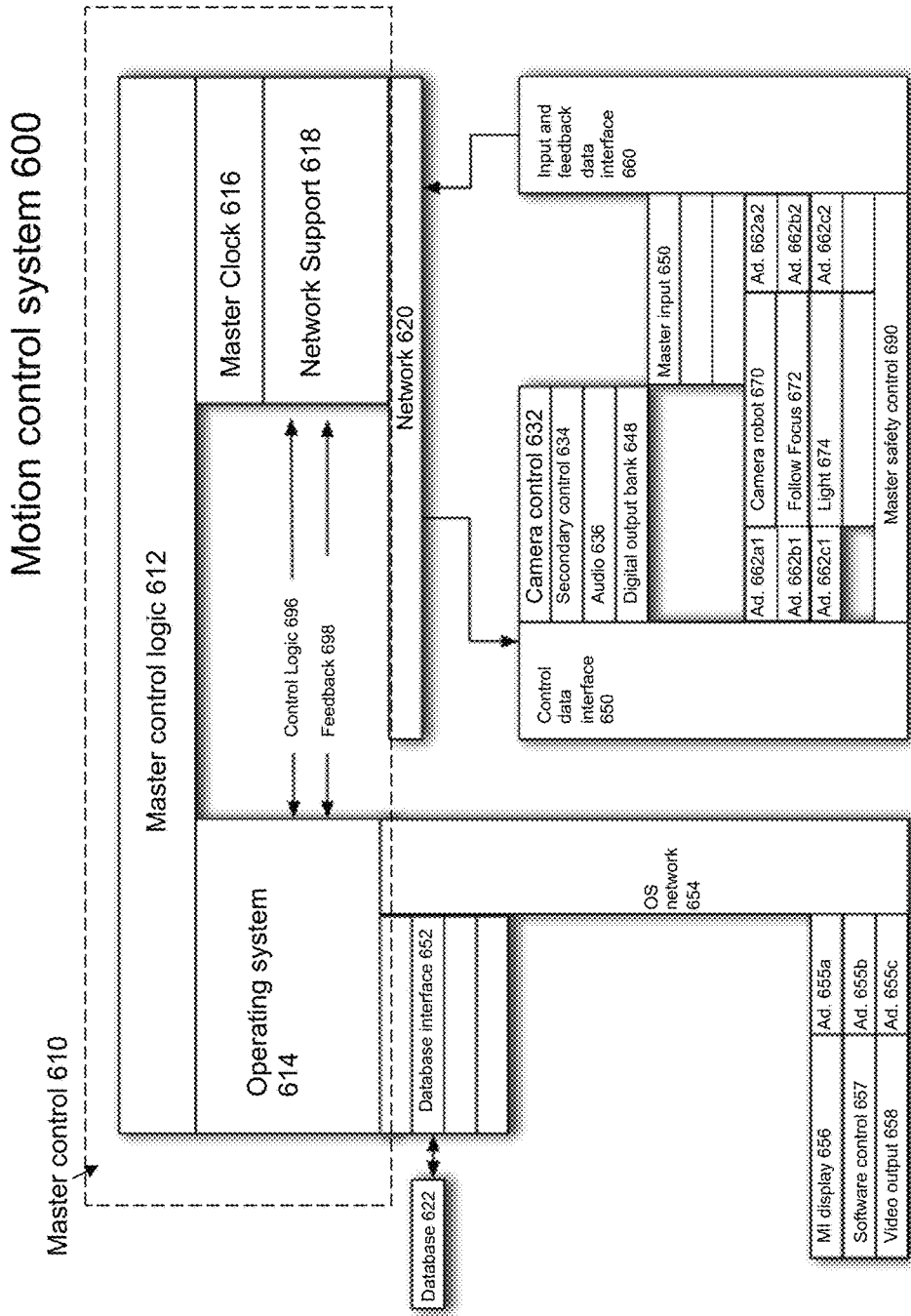


Figure 6a

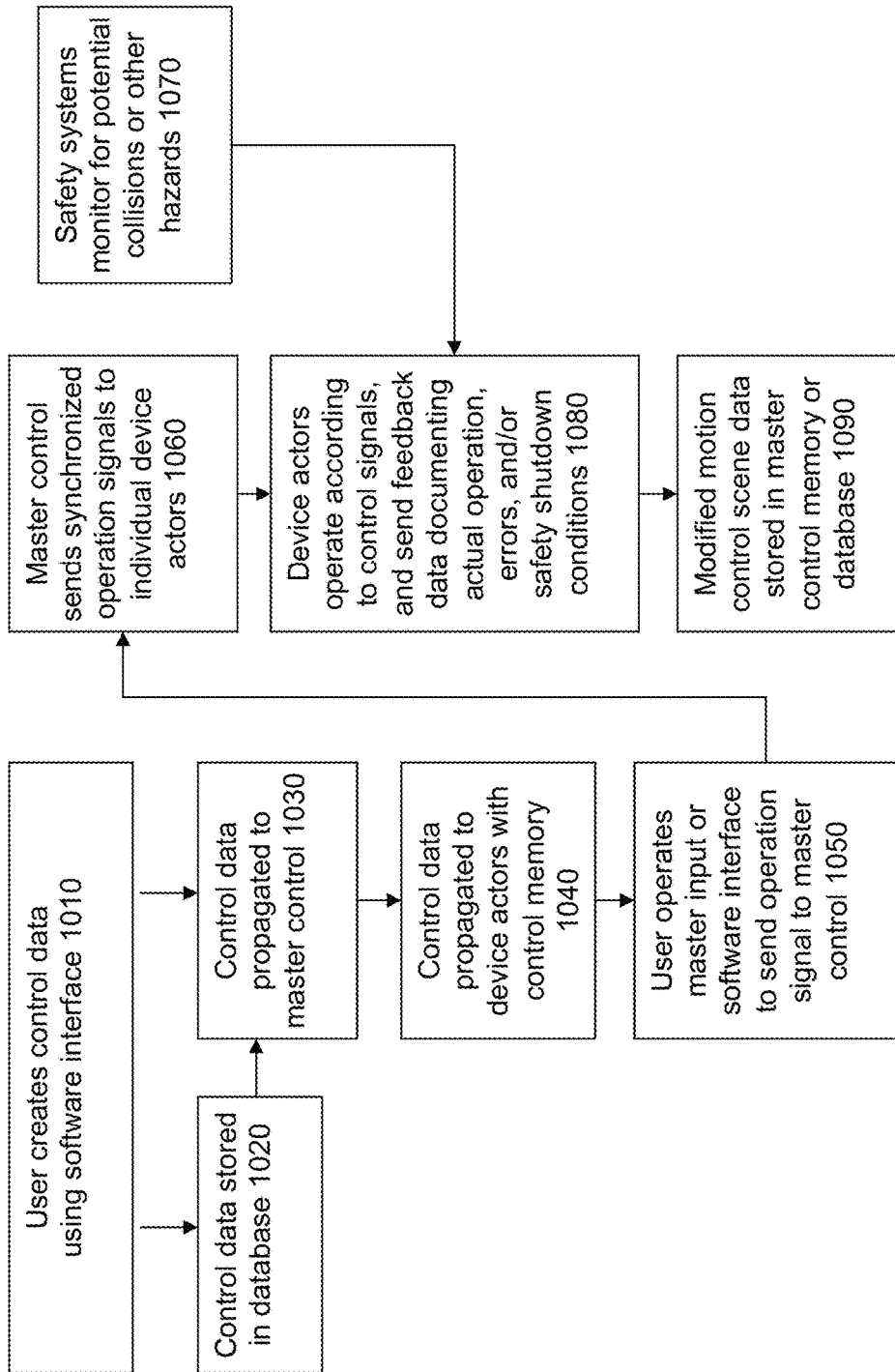


Figure 6b

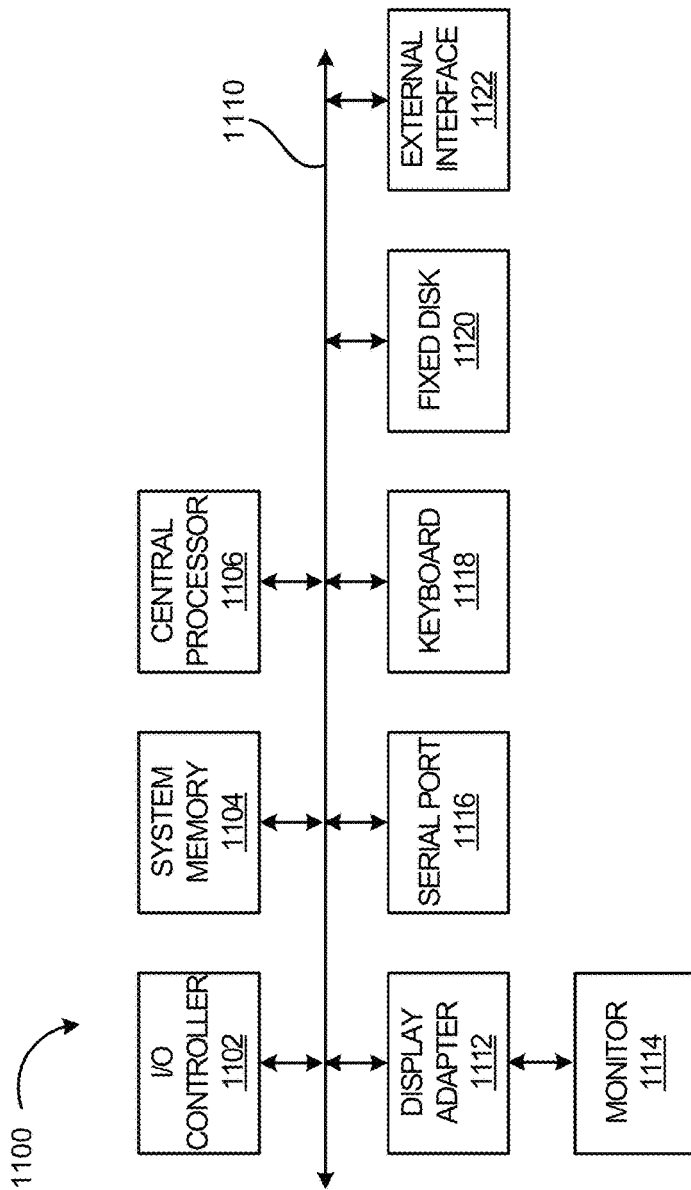
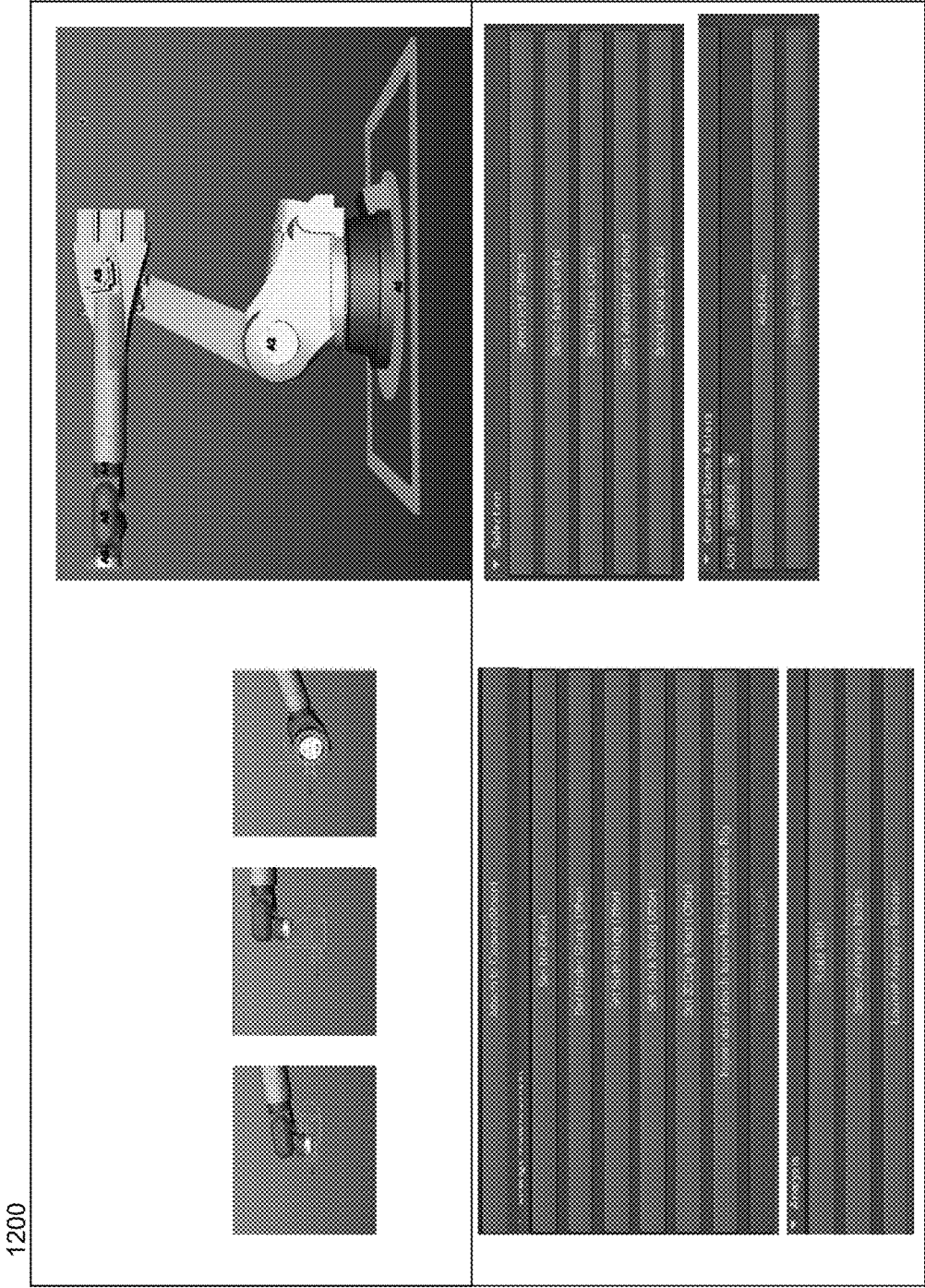


Figure 7



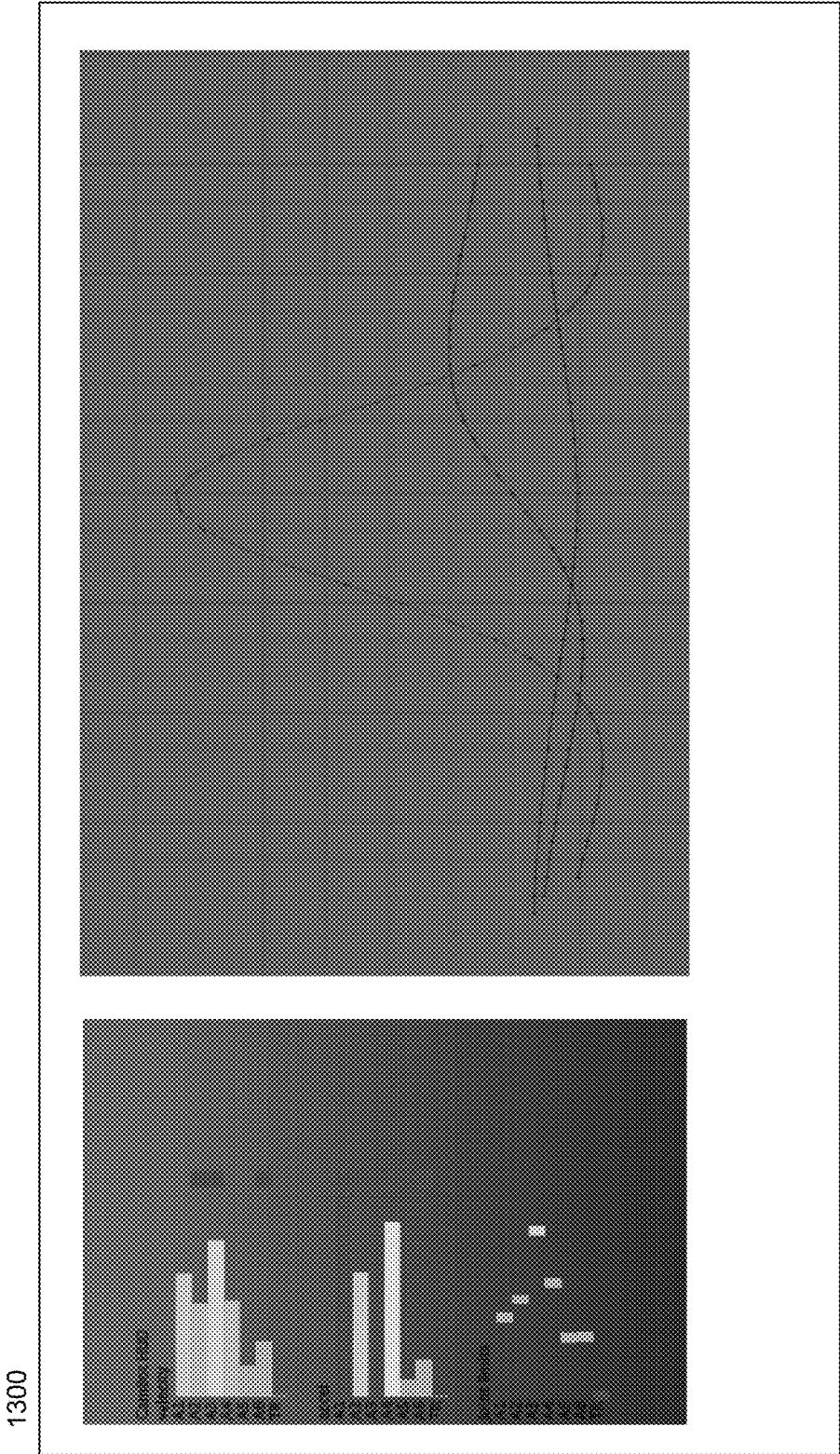


Figure 9

1300

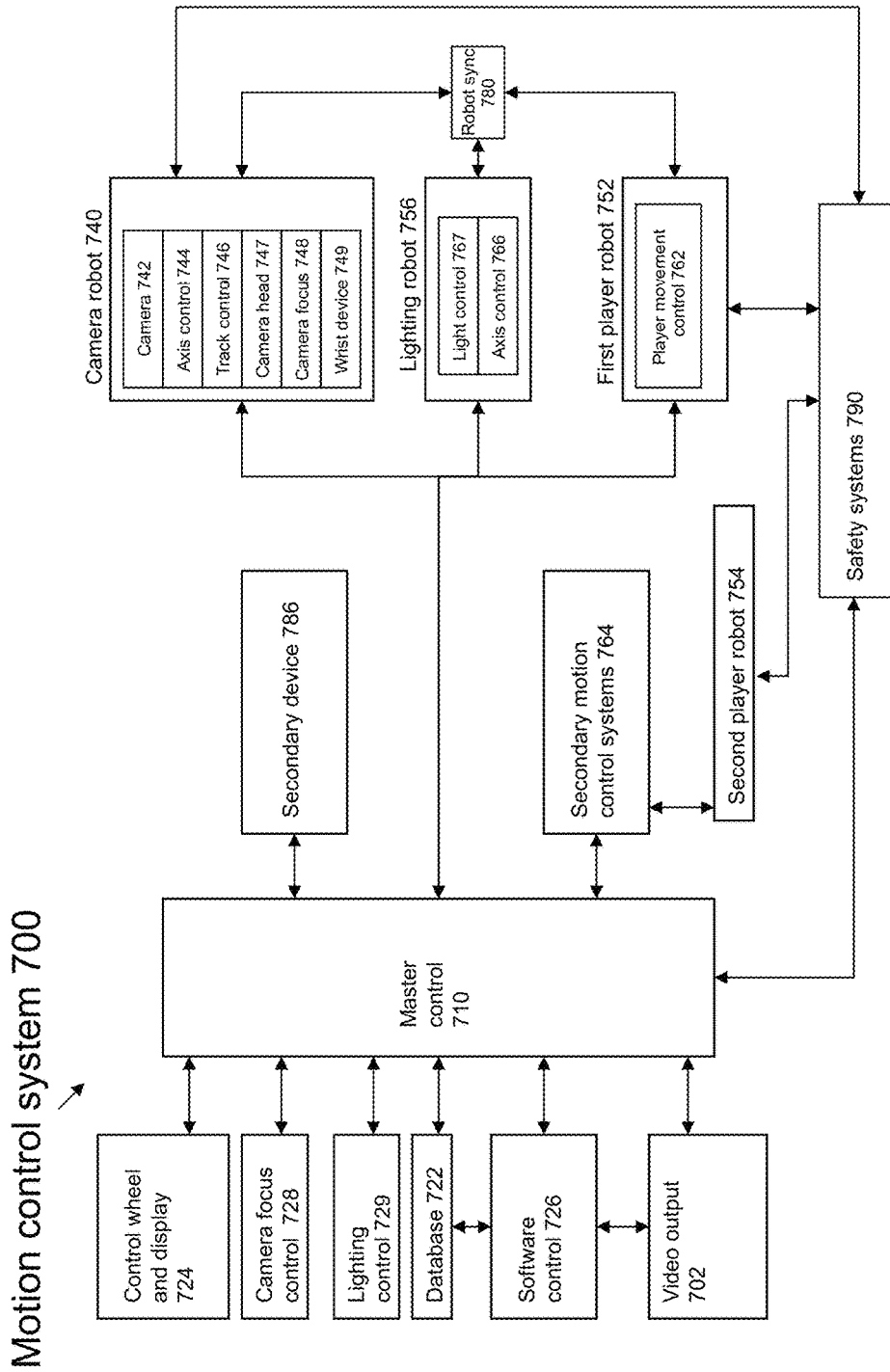


Figure 10



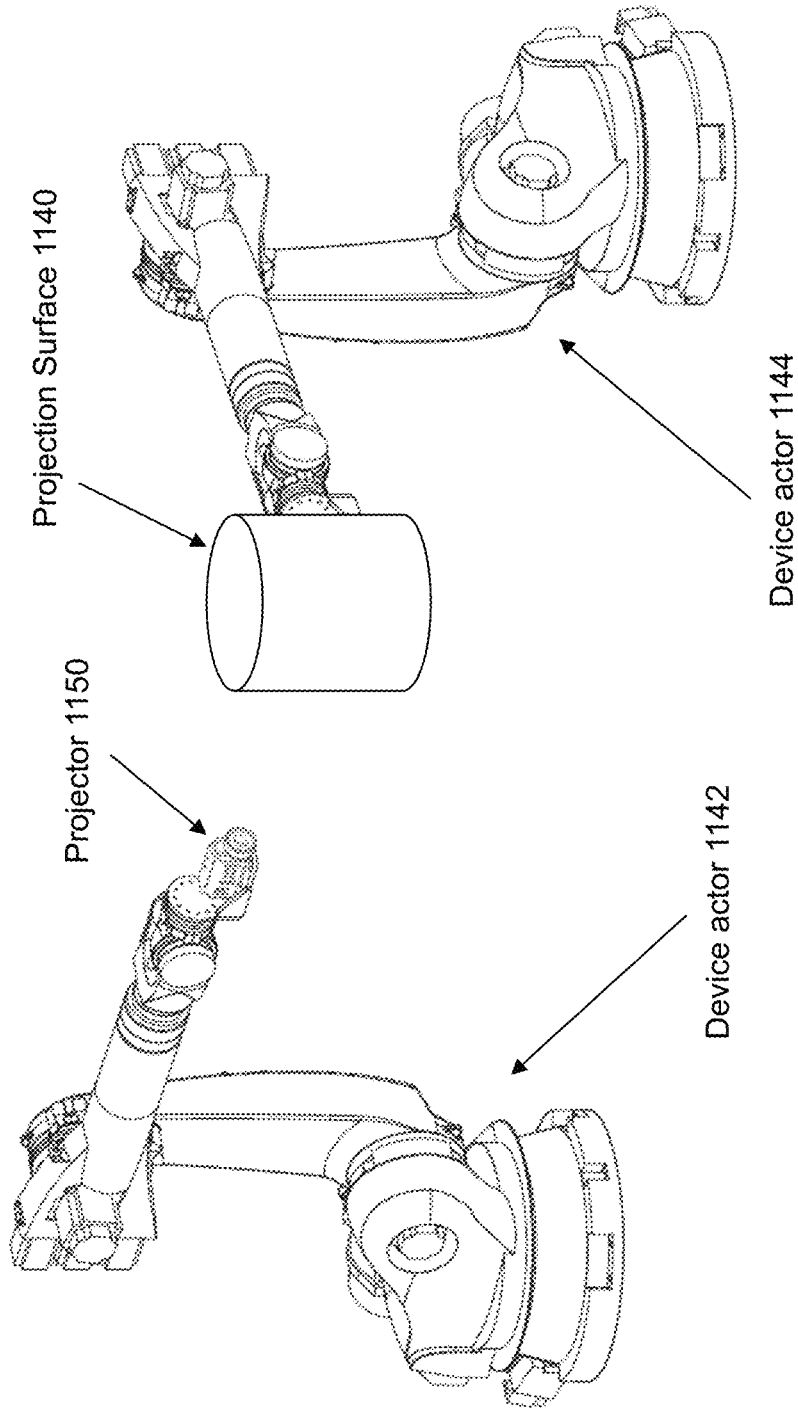
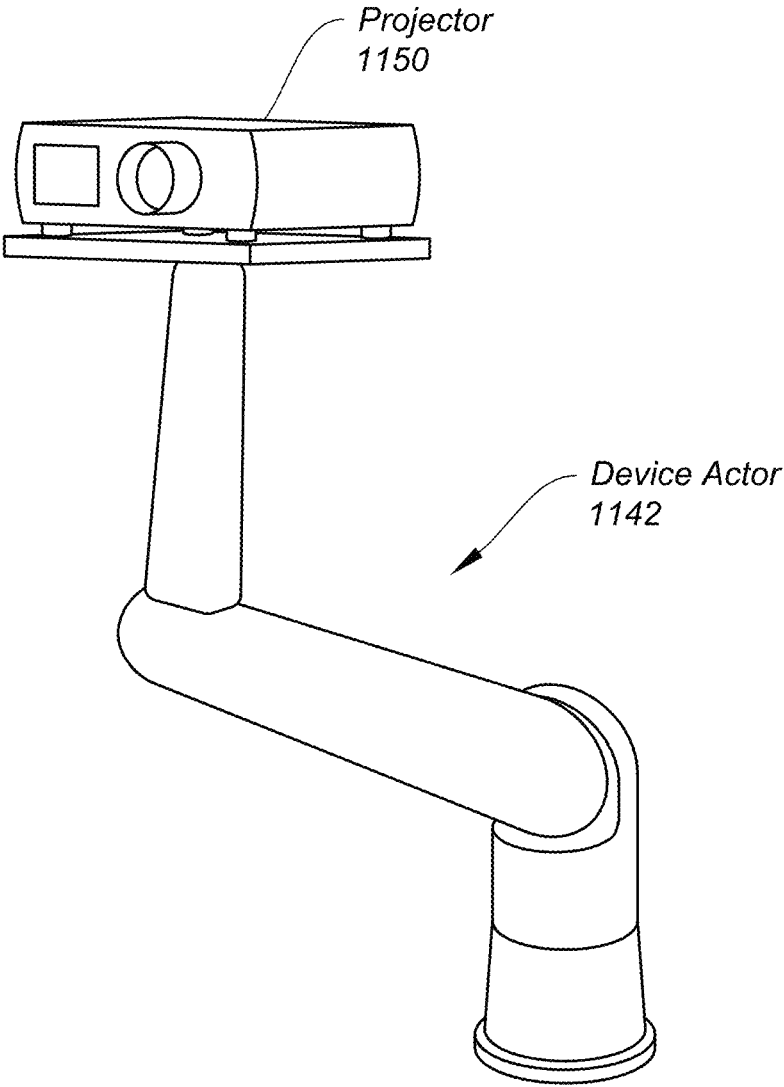
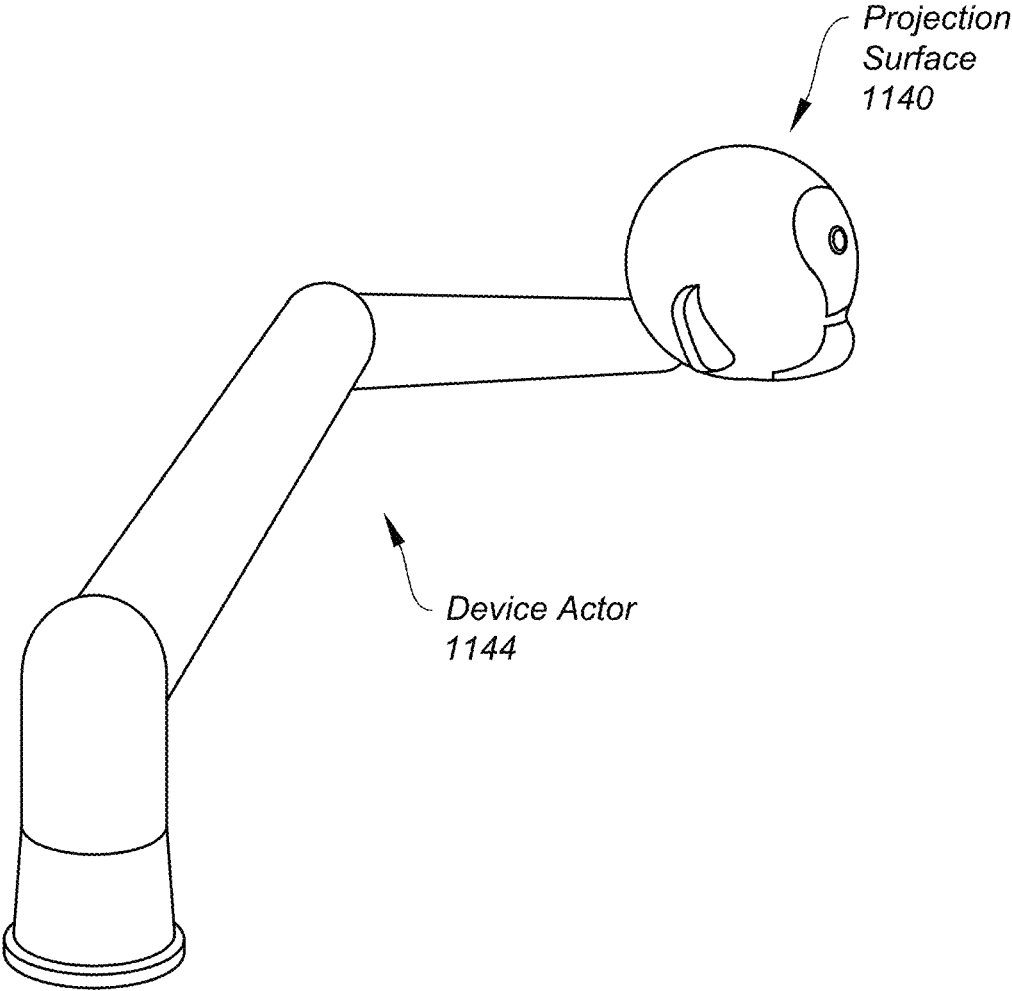


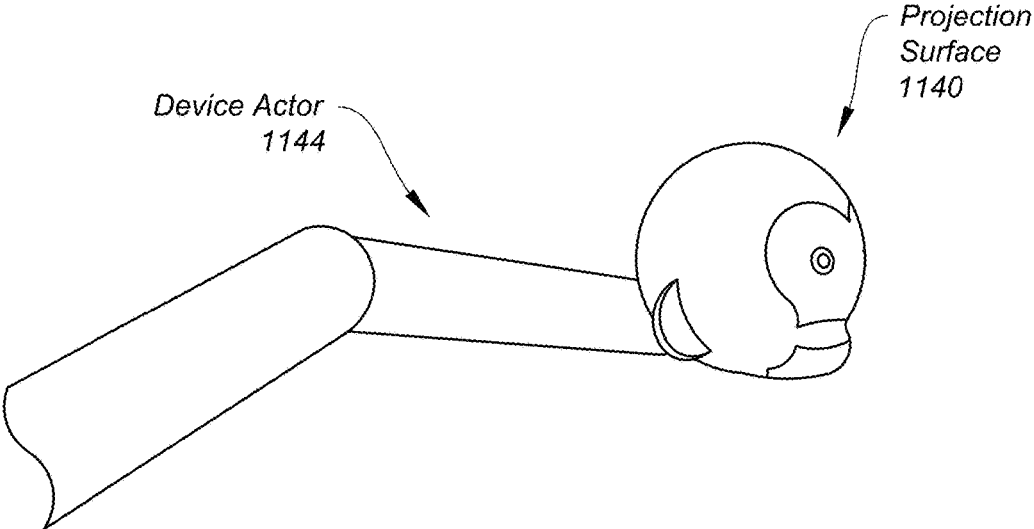
Figure 11



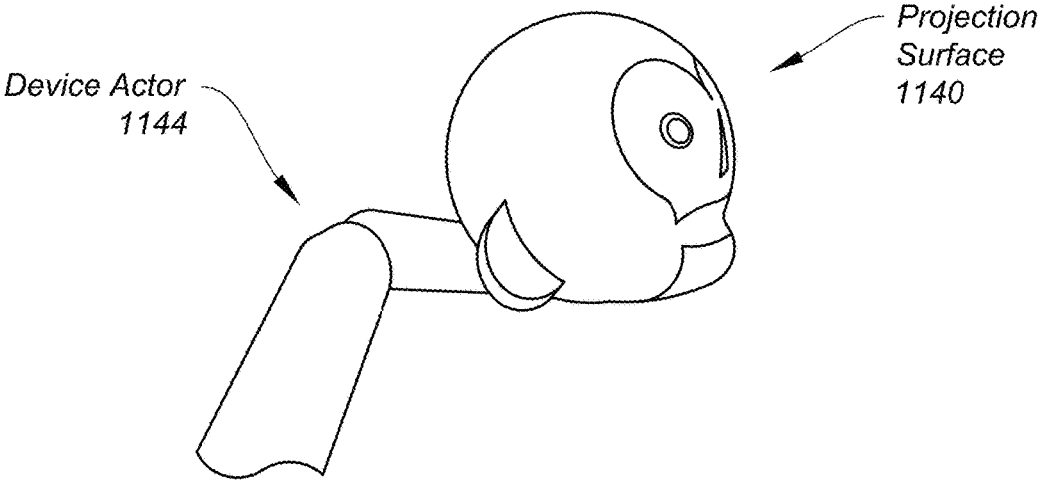
**FIG. 12**



**FIG. 13**



**FIG. 14**



**FIG. 15**

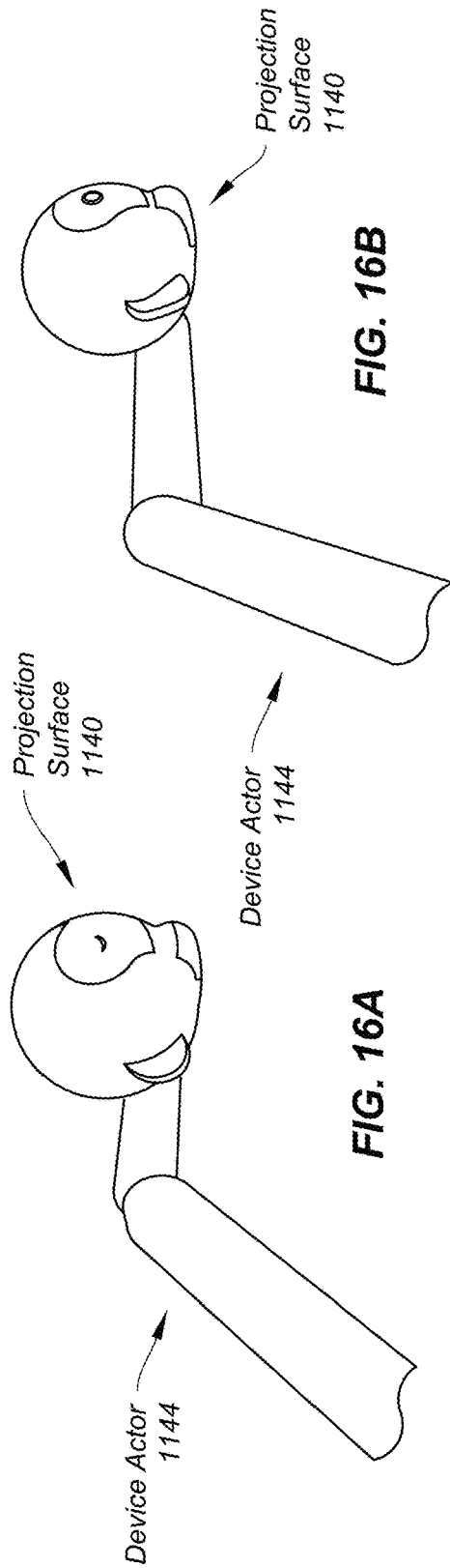


FIG. 16B

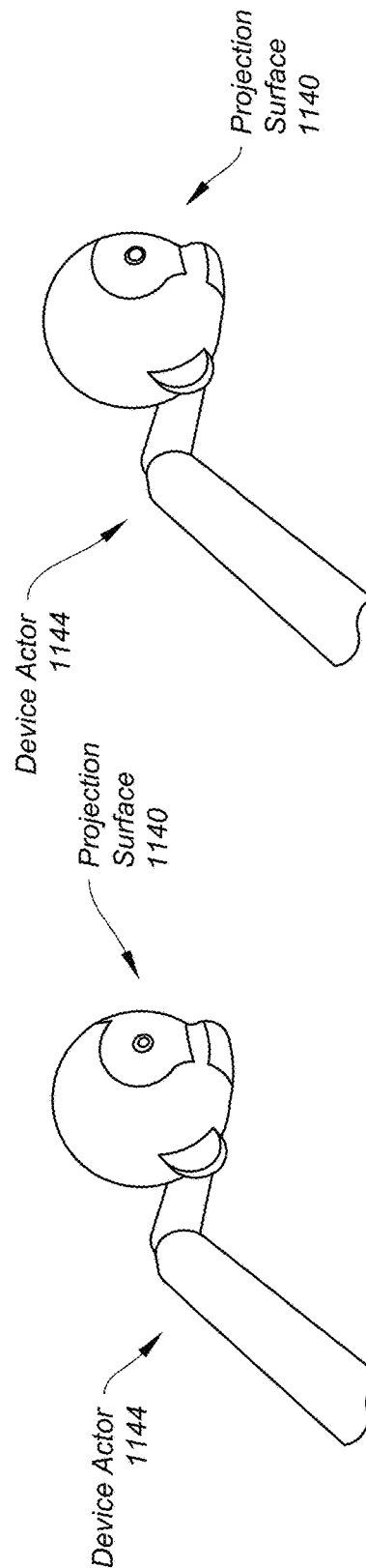


FIG. 16D

FIG. 16C

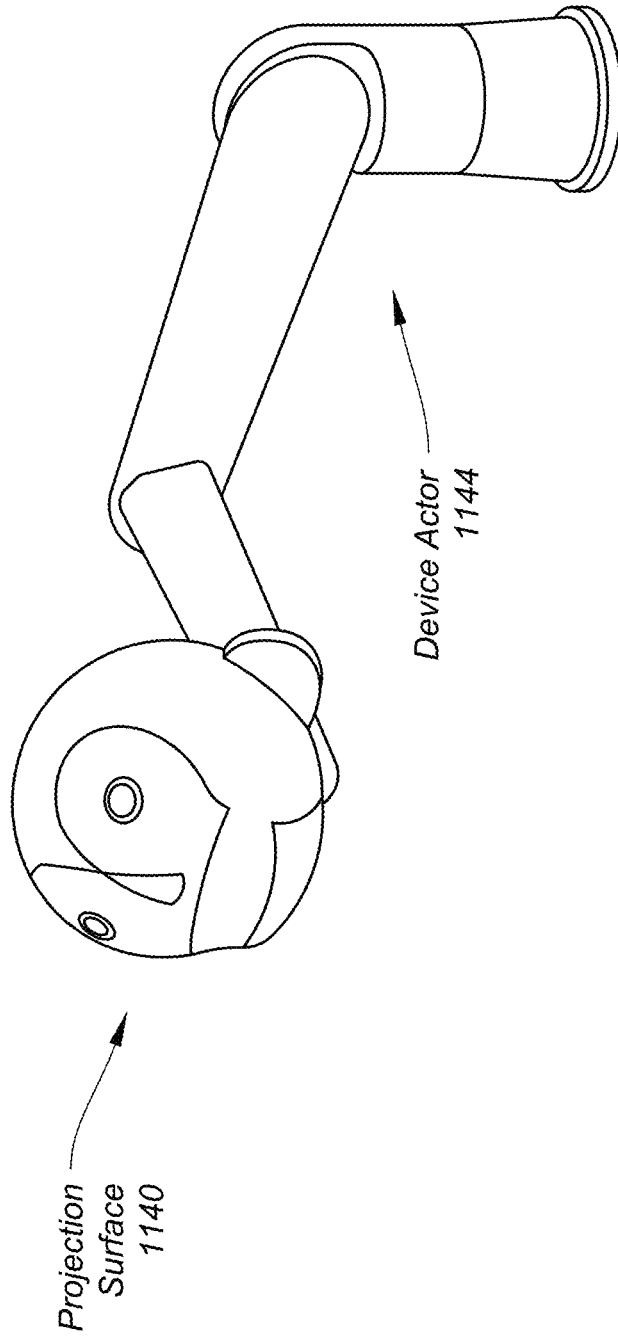
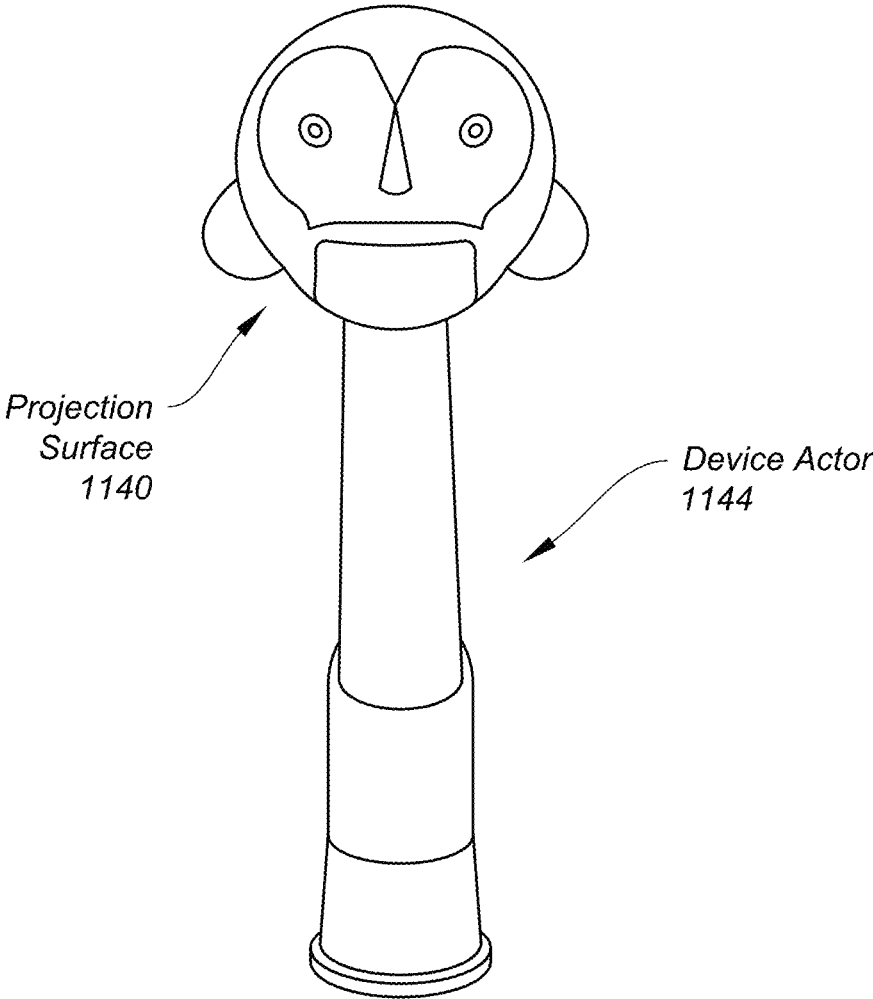


FIG. 17



**FIG. 18**



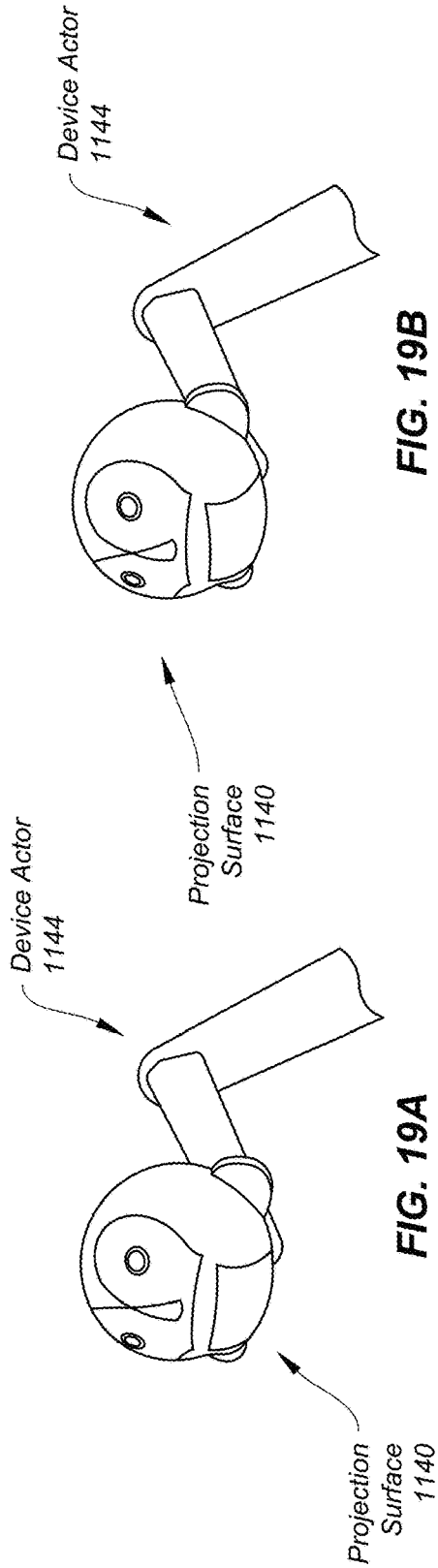


FIG. 19B

FIG. 19A

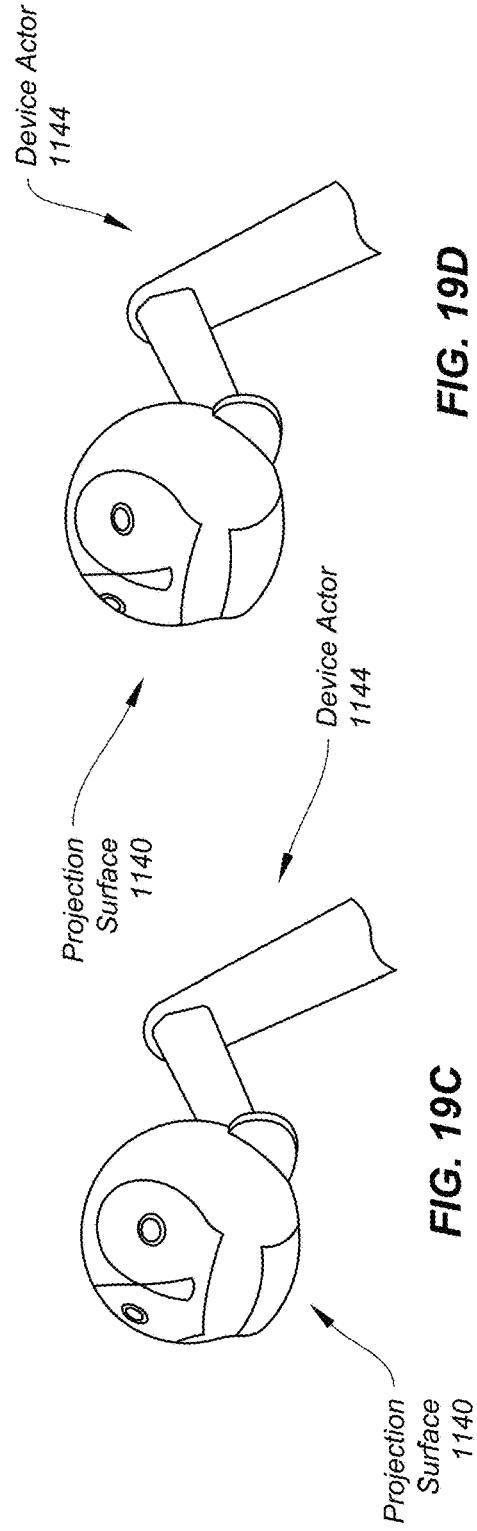


FIG. 19D

FIG. 19C

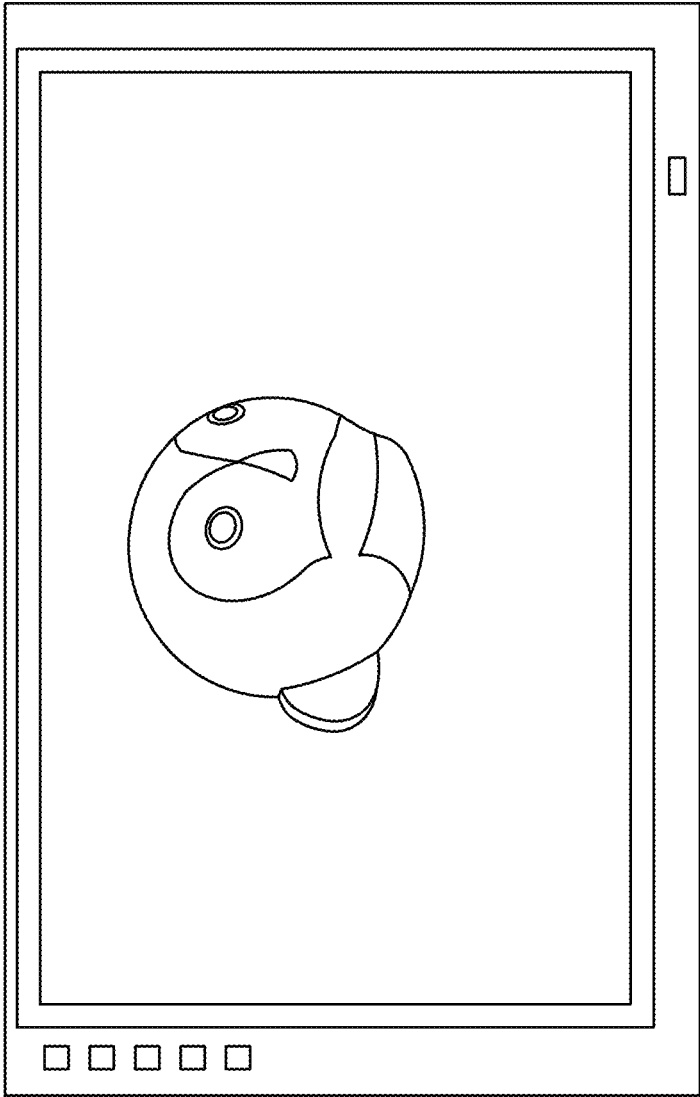


FIG. 20

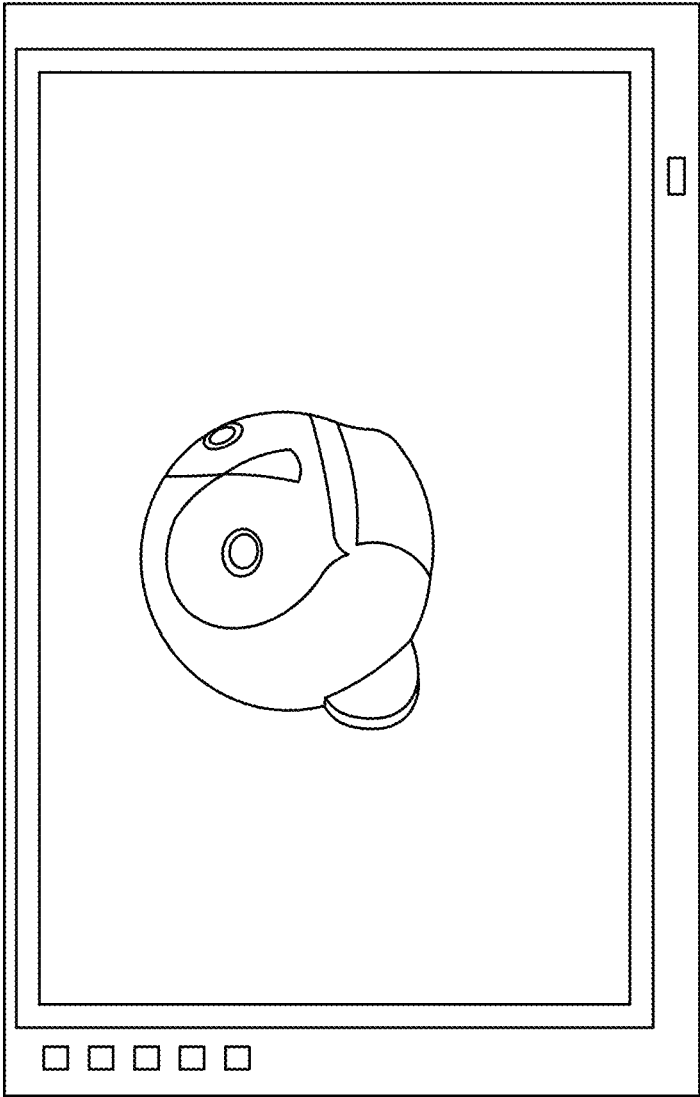


FIG. 21

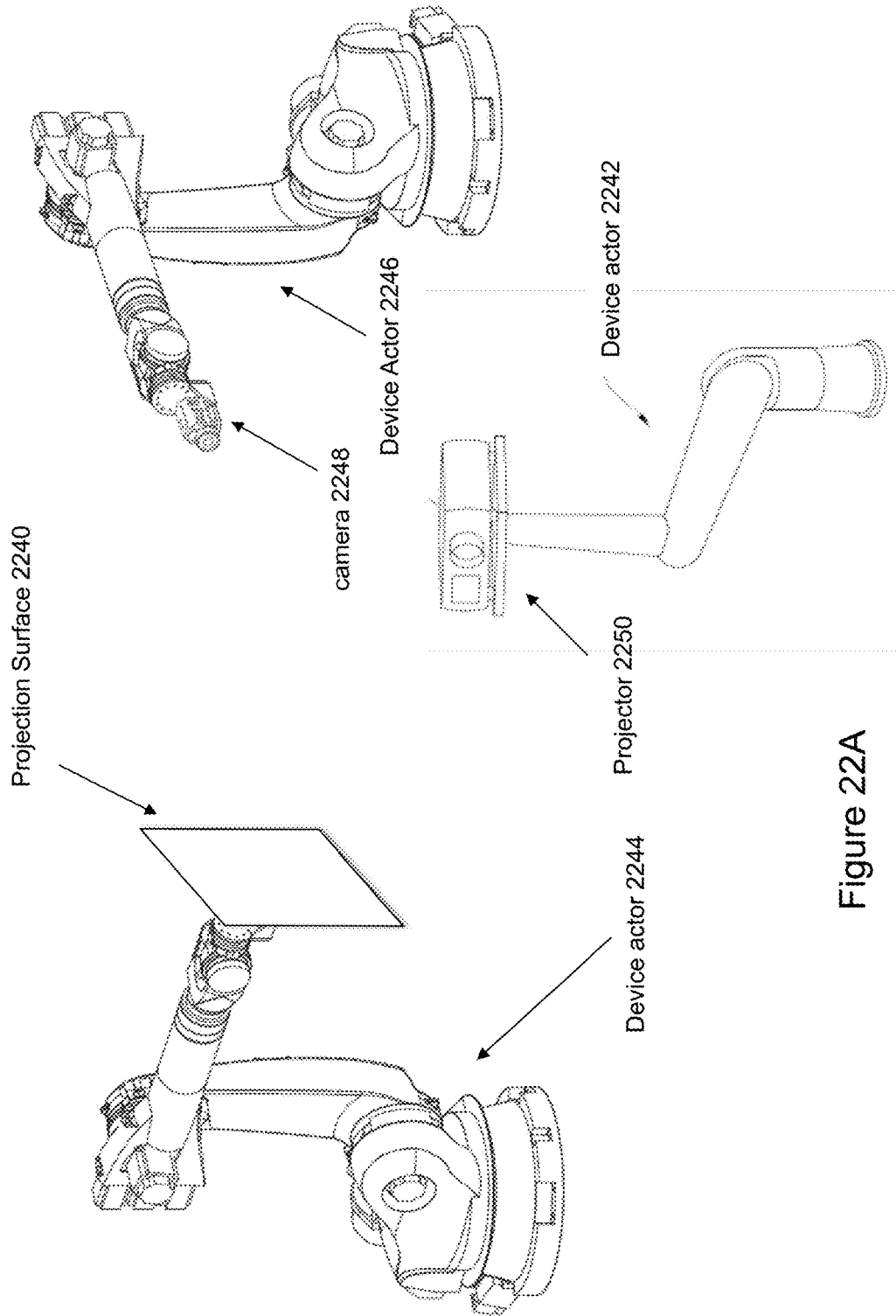


Figure 22A

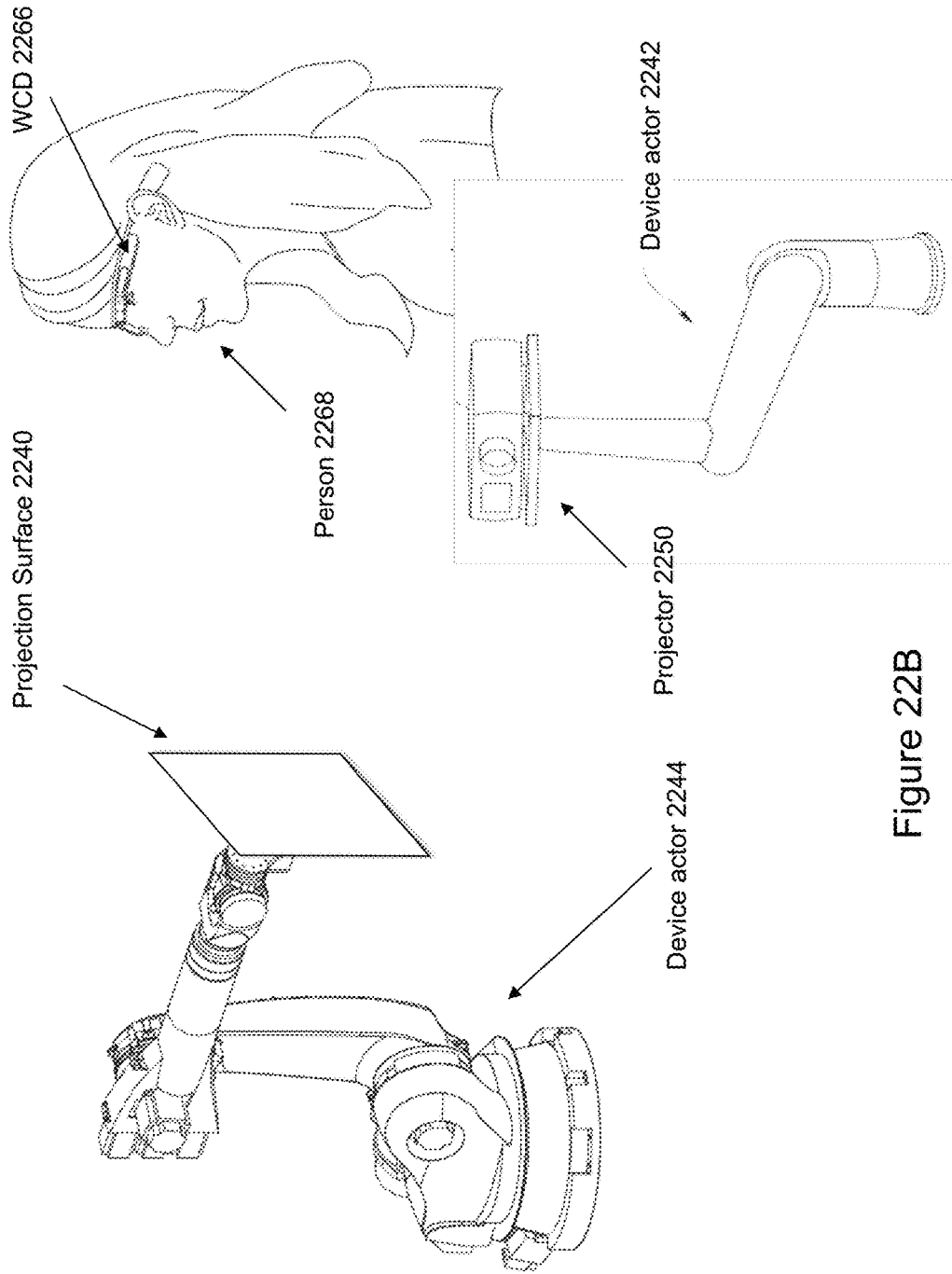


Figure 22B

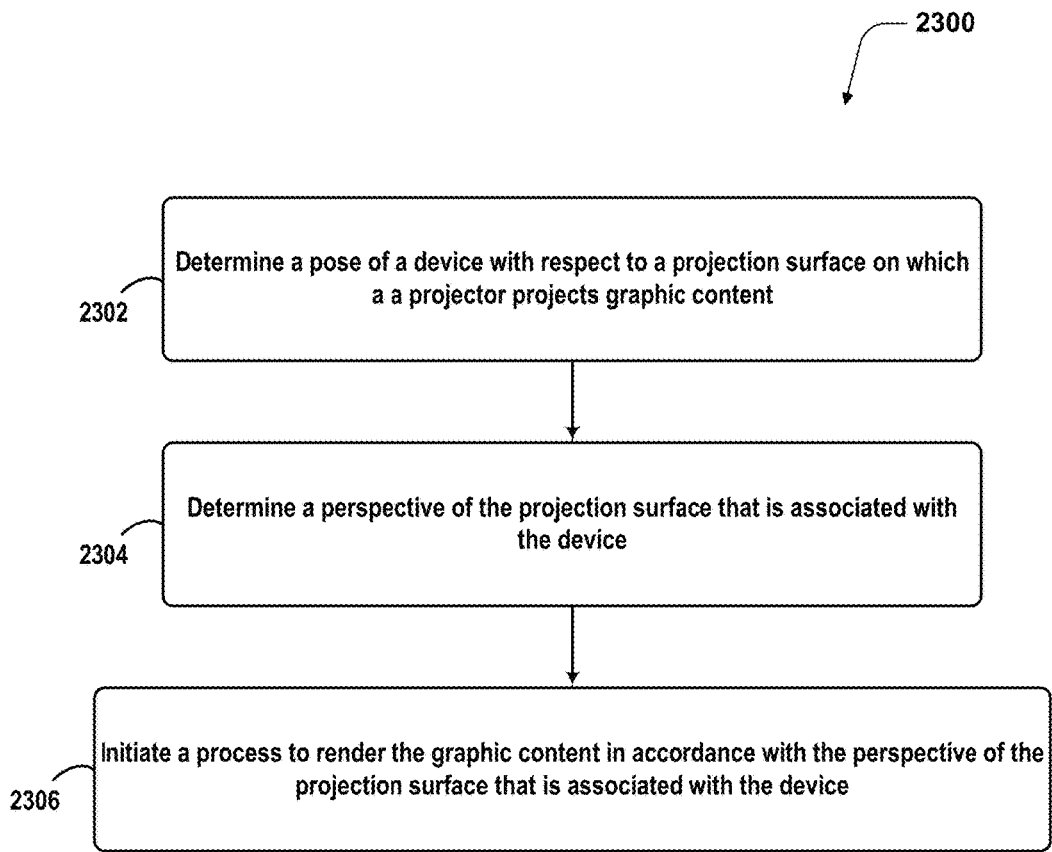


FIG. 23

# SYSTEM AND METHOD FOR 3D PROJECTION MAPPING WITH ROBOTICALLY CONTROLLED OBJECTS

## CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. patent application Ser. No. 14/190,091, filed on Feb. 26, 2014, now pending, which is a continuation-in-part of U.S. patent application Ser. No. 13/678,342, filed on Nov. 15, 2012, which claims priority to U.S. Provisional Patent Application No. 61/560,744, filed Nov. 16, 2011, all of which are incorporated by reference herein in their entirety for any and all purposes.

## BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Embodiments of the present invention relate to the use of automated systems and controls in the creation of audiovisual presentations. More specifically, embodiments of the invention relate to systems and methods of using a projection mapping with robotic motion control.

3D projection mapping is a technique to create the illusion of objects and environments where they don't physically exist. By projecting light on a surface that is rendered from a specific perspective the viewer perceives an environment that is not actually physically present.

Motion control is a type of automation, where the position of an object or objects is controlled using some type of device such as a robotic arm. In the production of videos, films, commercials, movies, and other such audiovisual works, the placement and movement of the camera and objects in a scene being captured by the camera is a major consideration and source of time and expense. The use of motion control is known in the film industry, where a camera is mounted and controlled as part of the creation and recording of a video scene. This technique is commonly referred to as motion control photography.

## SUMMARY

Various embodiments of motion control systems are presented. In one potential embodiment, a 3D projection surface is matched with a projector. Either or both items may be mounted on robotic arms which function as device actors for a scene that is set to vary over time and space, with the device actor moving the projection surface and the projector presenting a projected image onto the projection surface. In one embodiment, this enable motion control of a scene actor that is partially mechanically animated using the device actor and partially computer animated using the projection from the projector.

In one aspect, a system includes: (a) at least one projector, (b) a projection surface coupled to a first device actor, wherein the first device actor is configured to move the projection surface through a set of spatial coordinates, (c) a camera configured to capture image data of the at least one projection surface as the projection surface moves through the set of spatial coordinates, wherein the camera comprises a shutter; and (d) a control system configured to synchronize operation of the projector with operation of the shutter while (i) the projector projects a projection on the projection

surface and (ii) the camera captures image data of the projection surface with the projection thereon.

In another aspect, a method involves a computing system: (a) determining a pose of a device with respect to a projection surface, wherein a projector projects graphic content onto the projection surface, wherein the projection surface is coupled to a first device actor such that the projection surface is movable through a set of spatial coordinates, and wherein the device is movable through at least a portion of the set of spatial coordinates, (b) determining, by the computing system, a perspective of the projection surface that is associated with the device, wherein the perspective is determined based at least in part on the pose of the device, and (c) initiating, by the computing system, a process to render the graphic content in accordance with the perspective of the projection surface that is associated with the device.

In yet another aspect, a system includes: (a) a projection surface coupled to a first device actor, wherein the first device actor is configured to move the projection surface through a set of spatial coordinates, (b) at least one projector, wherein the projector is configured to render graphic content for projection onto the projection surface, and wherein the projector is configured to keep the graphic content projected onto coordinates of the projection surface as the projection surface moves, (c) a device configured to operate at a location with a vantage point of the at least one projection surface, wherein the device is movable through at least a portion of the set of spatial coordinates, and (d) a control system configured to: (i) determine a pose of the device, (ii) determine, based at least in part on the pose of the device, a perspective of the projection surface that is associated with the device, and (iii) cause the projector to render the graphic content in accordance with the perspective of the projection surface that is associated with the device.

These as well as other aspects, advantages, and alternatives will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a block diagram of a motion control photography system including a master scene control according to one embodiment of the innovations herein.

FIG. 2 shows a perspective view of a robot for use with a motion control photography system according to one embodiment of the innovations herein.

FIG. 3a shows a view of a robot with 7 degrees of freedom according to one embodiment of the innovations herein.

FIG. 3b shows a view of a robot with an attached camera according to one embodiment of the innovations herein.

FIG. 3c shows a view of a robot with an attached lighting unit according to one embodiment of the innovations herein.

FIG. 4a shows a view of wrist mount for use with a robotic arm in accordance with one embodiment of the innovations herein.

FIG. 4b shows a view of a robot with an attached wrist mount according to one embodiment of the innovations herein.

FIG. 5a shows one potential embodiment of a master input for use with a motion control system according to one embodiment of the innovations herein.

FIG. 5b illustrates a global timeline coordinating device actor positions through a master control according to one embodiment of the innovations herein.

FIG. 6a shows a block diagram of a motion control photography system including a master scene control according to one embodiment of the innovations herein.

FIG. 6b illustrates a method of control according to one embodiment of the innovations presented herein.

FIG. 7 shows one potential implementation of a computer or electronic device in accordance with various embodiments of the present innovations.

FIG. 8 illustrates a potential user interface for a software control according to one embodiment of the innovations herein.

FIG. 9 illustrates a potential user interface for a software control according to one embodiment of the innovations herein.

FIG. 10 shows a block diagram of a motion control photography system including a master scene control according to one embodiment of the innovations herein.

FIG. 11 shows one potential implementation of a system including 3D projection mapping.

FIG. 12 shows one potential implementation of a projector in a system including 3D projection mapping.

FIG. 13 shows one potential implementation of a system including 3D projection mapping.

FIG. 14 shows one potential implementation of a system including 3D projection mapping.

FIG. 15 shows one potential implementation of a system including 3D projection mapping.

FIGS. 16A to 16D show potential implementation of a system including 3D projection mapping.

FIG. 17 shows one potential implementation of a system including 3D projection mapping.

FIG. 18 shows one potential implementation of a system including 3D projection mapping.

FIGS. 19A to 19D show potential implementations of a system including 3D projection mapping.

FIG. 20 shows one potential implementation of a user interface for a system including 3D projection mapping.

FIG. 21 shows one potential implementation of a user interface for a system including 3D projection mapping.

FIG. 22A describes an illustrative embodiment of a 3D projection mapped audiovisual presentation system.

FIG. 22B describes an illustrative embodiment of a 3D projection mapped audiovisual presentation system.

FIG. 23 is flow chart illustrating a method, according to an illustrative embodiment.

### DETAILED DESCRIPTION

Example methods and systems are described herein. It should be understood that the words “example,” “exemplary,” and “illustrative” are used herein to mean “serving as an example, instance, or illustration.” Any embodiment or feature described herein as being an “example,” being “exemplary,” or being “illustrative” is not necessarily to be construed as preferred or advantageous over other embodiments or features. The example embodiments described herein are not meant to be limiting. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

Embodiments of the innovations disclosed herein include systems and methods for providing enhanced motion control with three dimensional (3D) projection mapping. In particular, systems and methods describe a system with a three dimensional projection surface attached to a controllable

robotic arm, a projector for projecting an animated projection onto the 3D projection surface, and an attached system for synchronizing movement of the 3D projection with projection from the projector onto the 3D projection surface.

One potential embodiment is used in the field of animatronics, or creating animated robots that appear lifelike. In such an embodiment, a projection surface is shaped in the form of a represented creature such as a dinosaur, a monkey, or some other creature. Certain portions of the creature is difficult to create using physical mechanical devices. Facial features such as eyes and lips, in particular, have historically be difficult to recreate mechanically. One or more projectors is positioned with an optical path from the projector to all or part of the projection surface, and an animated projection of eyes and a mouth is projected onto the projection surface. The projection surface is then be moved to imitate walking, head movement, or other characteristic movement of the creature being simulated. As this movement of the projections surface occurs, the projection of eyes and a mouth matches the movement of the projection surface, so the position of the eyes and mouth remain relatively stationary on the projection surface, while the illusions of blinking eyes and mouth moment occurs. If such a system includes sufficiently powerful computer animation software, the motion of the projected features is controlled real-time to, for example, match mouth movements to sounds being created which enables non-scripted conversation with the animatronic robot.

Further, some embodiments of such a projection system include multiple projection surfaces, multiple projectors, and additional system devices such as sound, ambient lighting, and other such effects that is integrated into a master control system to enable forward and reverse motion through a series of scripted and synchronized sets and a controllable rate. Additional embodiments further include integrated safety features for preventing collisions between devices or persons operating within an area where the devices are moving.

FIG. 1 describes a motion control system 100. Motion control system 100 is part of a motion controlled set used to film a scene using motion control photography. Motion control system comprises a master control 10, input and feedback systems 20, device actors 40 (including first device actor 42 and second device actor 44), and safety systems 90. From the most basic perspective, motion control system 100 functions when an input system 20 provides instructions to a device actor 40 via master control 10.

For the purposes of the present invention, a scene comprises a set of motions and actions by device actors 40 over a continuous period of time, such that a set of players in front of a camera is recorded in video, sound, or both. The players are people, stationary objects, or objects controlled or moved by one or more devices of device actors 40. In one embodiment, the camera is mounted to a robot arm of device actors 40. At a beginning of a scene, a camera and a plurality of players begin in a first position. Motion control of device actors 40 moves the camera and the players through a sequence of motions to the end of a scene, with players and sound from the scene recorded using the camera and potentially other audio and video recording equipment to capture the motion.

In one potential embodiment as part of a motion control system 100, input and feedback systems 20 include a database 22, a master input 24, a software control 26, and an independent manual control 28. As part of the input and feedback systems 20, database 22 operates to provide a set of timing and position data to direct all or a portion of device



actors **40**. Alternatively, database **22** stores data being created by manual or individual movement or data input related to operation and function of device actors **40**. Database **22** also stores data created independently of device actors **40**, such as data created using software modeling features of a software control **26**.

A master input **24** is any device that functions to operate all of the device actors **40** associated with a particular scene being created with motion control system **100**. Master input **24** functions by sending input control signals to master control **10**. Master control **10** then adapts the signal from master input **24** to send individual control signals to a plurality of actors operating as device actors **40** for the particular scene. In one potential embodiment, every individual device of device actors **40** is provided a control signal from master control **10** when a signal is received from master input **24**, including a signal to maintain a status quo or non-action to devices that are not operating as device actors **40** for a particular scene. In an alternative embodiment, a portion of the device actors connected as part of motion control system **100** are not sent any signal from master control **10** as part of the operation of motion control system **100** for a particular scene.

Software control **26** acts as a replacement for master input **24** in sending control signals to the plurality of actors via the master control **10**. Alternately, software control **26** controls individual devices from among device actors **40** to alternate, change, or experiment with motions of the individual device. In other potential embodiments, software control **26** functions to model the behavior of individual devices of device actors **40** within a virtual environment. In such an embodiment, software control **26** contains a software model for an individual device, which allows control signals to be created for the device without actually sending the control signals to the device. The control signals are then be stored in the software control **26**, in database **22**, within a computer memory component that is part of master control **10**, or within computer memory that is part of the device of device actors **40** for which the controls are being created. After the control signal is created by software control **26** and propagated to the appropriate storage location, a master control signal from software control **26** or from master input **24** activates the control signal for the individual device to act in conjunction with other device actors **40**.

Certain devices of device actors **40** additionally have an independent manual control **28**. As described above with respect to software control **26**, control signals for an individual device are created in software modeling. Similarly, a device may have independent manual control **28** that is used to operate a device of device actors **40**. For example, in one potential embodiment, a device that is one of device actors **40** is a follow focus that controls the focus of a camera. The follow focus may have a control device that is designed to control the focus of the camera that may operate as an independent manual control. When a set of instructions is being created for the entire scene, the independent manual control **28** is given input commands over time that are recorded to database **22** or a memory device of master control **10**. During creation of a set of instructions using independent manual control **28**, the independent manual control **28** may communicate directly with the associated device of device actors **40**. Alternatively, the independent manual control **28** may send the control signal to master control **10**, which then conveys the signal to the associated device of device actors **40**. The control signal may then be created either from the signal of the independent manual control **28**, of from a measured feedback reading created by

the operation of the associated device. Additionally, although in many situations it is preferable to have the independent manual control **28** actually control the associated device during control signal creation in order to view the results, control signals is created without controlling the device. For example, if expected input signals are expected for certain time marks, an independent manual control **28** is operated independent of the related device, and the control operation recorded. These function as ways in which instructions for individual device actors of device actors **40** is integrated into a motion controlled scene as part of motion control system **100**.

The result of the integration described above is considered as a global timeline for a motion controlled scene. FIG. **5b**, described in more detail below, provides an illustrated example, where the actions of multiple motion controlled actors are integrated into a global timeline using a master control. In FIG. **5b**, various actors such as camera and lighting robots move at certain points during a scene. The actors is receiving control signals during the entire scene from time a to time f, or may only receive controls when they actually move or act. Certain other actors, such as 1<sup>st</sup> and 2<sup>nd</sup> special effects (fx) actors only receive single commands to act at one specific time, such as 1<sup>st</sup> fx actor acting at time b in the global timeline of FIG. **5b**. Such an integration into a global timeline allows simplified user control of complex actions impacting an entire scene that may save significant amounts of time in modifying a particular scene with a given timeline. This allows scrubbing through time forward and backwards as well as seeking to specific frame number or timecode for all actors in a particular scene, and slowing down or speeding up the performance of the entire set (system) in real time via hardware device

Although embodiments will be illustrated with reference to specific implementations, a person of ordinary skill in the art will understand that these implementations describe innovations which may have broad use other than the specifically described implementations. As described below, enhanced control may comprise systems and methods for a variety of functions, including safety systems, playback speed control, forward and reverse position scrubbing, and integrated detection systems, among others.

Such a system includes advantages over systems currently known in the art by providing accessible and highly sophisticated robotic controls in an art environment dominated by custom toolsets without simple or malleable integration toolsets. Such a use of highly accurate control systems with cameras is considered, in certain embodiments, to be "cinematic automation" or "3D projection automation" which allows the ambitions of visual story tellers to be matched through the application of automation systems. For example, improved control systems can coordinate sub-millimeter position of a camera in space with the position of the light, an actress, a robotic actor comprising a 3D projection surface, and special effects (pyrotechnics, video playback, sound cues, etc.). This allows execution of highly complex shots that would previously have required the coordination of several film departments with manual human positioning. Such control systems remove inaccuracy and introduced the repeatability of robotics, through highly accurate computer synchronization of events. In addition to developing a faster, more rigid, safer, and easier to program robotic arm system, embodiments of the present innovations include interfaces that allow a creative director to make very quick on-set adjustments. In the high pressure environment of feature films and commercial productions, it is critical that a director

or visual effects supervisor is able to make very quick creative or technical calls, and the systems described herein enable this in a way not known in the previous art.

As a further example, if a system implementation of the innovations is being used in presentation of a scene in a live play, the system might be synchronizing a large robotic arm, a custom robotic rig to move the arm, video playback of a wall of LED's that serve as the light source, and the motion of a piece of background, and an animatronic actor with facial features animated from a projector attached to an animation computer with arm and leg movement animated by robotics. This is a highly technical, pre-programmed scene that has been pre-visualized in a computer, and the interplay of all the elements have been choreographed using the system. Real time during the play, if the actors are delivering their lines at a slower than normal rate, or there is a need to pause for extra applause, a play director may compensate real time by pausing the entire set or by simply turning a knob at the right moment to accommodate the actors. The robot slows down, the robotic rig complies, and the entire scene of the play decelerates. All of this happens in synchronicity. Plus the system can provide integrated enhanced safety to prevent the actors from being injured.

Referring now to FIGS. 2-4, several non-limiting examples of device actors 40 will be described. Although these figures focus on the use of robotic arms, device actors is other types of devices that is stationary, such as sensors, stationary lights, and signal sources, as will be described later.

FIG. 2 describes device actor 242. Device actor 242 comprises robotic arm 246, mounting point 248, and rail 244. Device actor 242 is described in FIG. 2 with no specific functionality attached at any mounting point such as mounting point 248. Mounting point 248 is configured to hold a camera, a light, a player that will be filmed by a camera, or any other relevant device or object. In certain embodiments, instructions is given to position mounting point 248 at a specific location, and the positions of the axis of robotic arm 246 and of rail 244 is calculated by a process of the related motion control system. In alternative embodiments, each axis of robotic arm 246 and the position of rail 244 require separate, individual settings and control commands.

FIG. 3a describes device actor 342, comprising a robotic arm with axis A1-A6, with axis A0 associated with a rail which is not shown that allows side to side movement of the other eight axes. FIG. 3b describes device actor 342 with a camera mount 352 placed at a mounting point, and camera 350 attached to camera mount 352. FIG. 3c describes device actor 342 with light 360 placed at a mounting point.

FIGS. 4a and 4b describe an embodiment where a device actor 442 comprises a robotic arm 444 with a wrist mount 410 and a wrist mount interface 412. Wrist mount 410 and wrist mount interface 412 enables multiple device actors to be mounted to robotic arm 444 in addition to standard mounts such as a camera or lighting fixture. In certain embodiments, the wrist mount interface enables temperature sensors, laser range detectors, microphones, speakers, fans, or other mechanical activated or special effects devices.

FIG. 5a describes master input 524 which is one potential implementation of a master input such as master input 24 of FIG. 1. Master input 524 comprises a display interface 510, and engage control 540, a mode select 530, and an analog interface 520. The function of master input 524 will be described in conjunction with the global timeline of FIG. 5b.

FIG. 5b illustrates a global timeline associated with one potential embodiment of a motion controlled scene implemented in a motion control system such as motion control

system 100 of FIG. 1. FIG. 5b includes a number of actors, as defined above, which operate during a scene with a nominal or standard running time from time a to time f. The global timeline is nominal and not referring to real clock time because, as will be detailed further below, master input controls alters the rate at which actors progress through motions from the beginning of a scene to the end of a scene. The global timeline may therefore alternately be thought of as a coordinated position chart for actors. During the scene running time, an actor may act or move during the entire scene, during a portion of the scene, or only for one instant of a scene. Each actor, though, will have a predetermined point for each nominal time from the beginning to the end of the scene. The predetermined points for each actor are associated with predetermined points for each other actor.

In one potential embodiment, individual control signals for specific device actors are coordinated into a single file within a memory of a master control with a common base time provided by a master clock within the master control. During operation, master control extracts control signals for each device actor and provides individual control signals to each device actor at the appropriate intervals. In an alternative embodiment, a master control maintains separate individual control signal files and timing data for different device actors, and synchronizes the different control signals separately from the individual control files.

In another alternative embodiment, the control data for a portion of the device actors is transferred by a master control to a memory within an associated individual device actor. During operation, device actors having control data within memory receive only a synchronization signal that indicates a location in a global timeline, a rate of progress through a global timeline, or both.

The specific embodiment described in FIG. 5b includes a camera robot, a follow focus, two lighting robots, a player robot that controls an object that is to appear in front of a camera, and two special effects actors. As described above, each actor has a path to follow through the scene from beginning at time a to end at time f. In the specific embodiment of FIG. 5b, each actor begins at a preset position. As described by the global timeline, only the player robot moves from time a to time b. This will be true whether b occurs 10 seconds after starting time a, or 20 seconds after time a due to modification of the rate at which the scene progresses by a master input, as is further detailed below. At time b, 1<sup>st</sup> special effects actor is activated with a single command, player robot continues moving, and follow focus and camera robot begin moving.

The chart of FIG. 5b is not meant to indicate that non-moving actors such as 1<sup>st</sup> lighting robot, 2<sup>nd</sup> lighting robot, and 2<sup>nd</sup> fx actor during time a to time b are not receiving input commands. FIG. 5b merely illustrates a global position timeline. In certain embodiments they may not be receiving input commands from a master control. In alternative embodiments, however, non-moving actors such as 1<sup>st</sup> lighting robot may periodically or continuously receive commands from a master control, even when not moving, where the command is an instruction not to move. Such a command may function to maintain synchronization, acting as a clock or a timing heartbeat to maintain synchronization. In some embodiments, real time adjustments are made to an actor during a scene. Such a clock or timing heartbeat further serves to provide synchronization data as the adjustments feed back to the master control to update and change the global timeline.

Referring back to FIG. 5a, master input 524 includes a display interface 510. Display interface 510 is a modular

touch screen device that displays status information related to actors or the global timeline. For example, display interface 510 includes a scene time associated with the current position of the actors in the global timeline, or a frame number for a current scene associated with the current timeline. In such a display, time a, for example, or frame 1, is displayed when the actors are in position for the beginning of the scene. In one potential embodiment, display interface 510 is a portable electronic device or a cellular telephone with an interface application that communicates with a master control.

Master input 524 additionally comprises an engage control 540. Because of the size and force that many actors, particularly large industrial robot arms carrying heavy cameras moving at up to several meters per second, are capable of conveying in a collision, safety controls is extremely important for many embodiments of a motion controlled scene. Engage control 540 acts as an input regulator to prevent master input 524 from being operated by accident, such that engage control must be depressed at all times prior to any other input command being conveyed and acted upon from master input 524.

As shown in FIG. 5a, master input 524 also comprises a mode select 530 and an analog interface 520. Analog interface 520 is any input device capable of defining a range of inputs by a user control. In one potential embodiment, analog interface 520 is a wheel with a spring action that returns the wheel to a central position in the absence of user manipulation. In other potential embodiments, analog interface is a lever, a sliding tab, or any other input control to enable a user to input a signal. Master input 524 may comprise multiple input modes. In one potential embodiment, master input 524 comprise a reset mode, a play mode, and a scan mode, with the mode selectable via mode select 530.

In a reset mode, operation of engage control 540 and analog interface 520 operates to cause each actor within a scene to move to an initial position for the beginning of a global timeline. Additionally, a specific scene or frame number is selected by use of display interface 510, and operation causes each actor to move to a position associated with that frame or time in the global timeline. Such a mode may allow device actors that are out of position for a particular time to be reset to a correct position.

In a play mode, operation of analog interface 520 may serve to speed up or slow down progress through a scene in a global timeline. For example, in a scene with actors set in position at global time a, selecting engage control 540 may serve to begin the action of all actors through the global timeline at a base rate, where each second of time is associated with one second of progress through the global timeline. Operation of analog interface 520 in a first direction then serves to slow down progress through the global timeline, such that 1 second of real time is associated with 0.5 seconds of progress through the global timeline. If the analog interface 520 is then set back to center, the progress through the global timeline will revert to a one to one ratio with real time, but with the remaining actions being delayed from the initial start by the previous slowdown. Conversely, if analog interface 520 is operated in a second direction opposite from the first direction, progress through the global timeline is increased. If, for example, the nominal time from time a to time b is 10 seconds, increasing progress through the global timeline by 10% may reduce that actual time required for the motion controlled scene to progress from the positions of time a to the positions of time b by approximately 0.9 seconds and the actual time required the progress

from time a to time b with analog interface set to increase playback being approximately 9.1 seconds. This may provide use when a human player being recorded by a camera as part of a motion controlled scene is delivering lines more slowly or more quickly than expected, and there is a desire to match the actions of the motion controlled scenes with the actions of human players that are not motion controlled.

In a scan mode, selecting the engage control 540 and then operating analog interface 520 may operate to shuttle or scan forwards or backwards through the global timeline in a continuous fashion. For example, if a motion controlled set currently has actors in positions associated with time c, selecting shuttle mode and operating analog interface 520 in a first direction may cause all actors to move continuously forward through the positions associated with the global timeline to reach time d. Moving analog interface 520 in a second direction may cause all actors to move continuously backwards through the positions associated with the global timeline to reach the positions associated with time b. In one potential embodiment, a particular time or frame is selected using display interface 510. Operation of analog interface 520 may shuttle continuously through the positions of the global timeline until the particular time or frame is reached. Master input 524 may then cease to control device actors until a selection in display interface 510 is activated acknowledging that the previously selected point has been reached, or until analog interface 520 is returned to a central position.

FIG. 6a describes a block diagram of a motion control system 600. Motion control system 600 comprises a master control 610, as well as details of one potential embodiment of input, feedback, and device actor sub-systems. In the embodiment disclosed by motion control system 600, master control 610 comprises an operating system 614, master control logic 612, master clock 616, network support 618, control logic 696, and feedback 698. The elements of master control 610 are implemented in a computer system comprising a general function processor and memory hardware system. Alternatively, master control 610 is implemented in custom designed processing, memory, and networking hardware devices, or is implemented in an abstracted software layer of a general purpose computing system. Master clock 616 functions as a real time clock to coordinate movement of the actors in the system. Master control logic 612 functions to integrate the individual control signals into a master timeline, and to correctly route control signals to the correct device, both during operation of the entire motion control scene through the master timeline, and through individual modification and setting of device actor positioning and function using control logic 696. Master control logic 612 also assists in coordination and routing of feedback 698. Feedback 698 may include actual position and setting signals received from monitors attached to device actors. One potential example is a location device attached to a robot arm. The actual position of the arm is tracked via the location device to provide feedback and calibration in relation to an input position command sent to the arm from either database 622, software control 657, or another control input for the robot arm. Operating system 614 includes special libraries and functionality for interacting with device actors, and may further serve to manage basic hardware computing functionality such as memory storage and processor usage. Operating system 614 may further enable networking capability via OS network 654 to communicate with various related devices.

Network support 618 may also enable communications from master control 610 to related devices, actors, and input

controls via network 620. In one potential embodiment, network 620 may comprise an Ethernet for Control Automation Technology (EtherCAT) network operating according to IEEE 1588. In such an embodiment, packets are no longer received, then interpreted and copied as process data at every connection. Instead, the frame is processed on the fly using a field bus memory management unit in each slave node. Each network node reads the data addressed to it, while the telegram is forwarded to the next device. Similarly, input data is inserted while the telegram passes through. The telegrams are only delayed by a few nanoseconds. On the master side commercially available standard network interface cards or on board Ethernet controller can be as hardware interface. The common feature of these interfaces is data transfer to the master control via direct memory access with no CPU capacity is taken up for the network access. The EtherCAT protocol uses an officially assigned Ether Type inside the Ethernet Frame. The use of this Ether Type allows transport of control data directly within the Ethernet frame without redefining the standard Ethernet frame. The frame may consist of several sub-telegrams, each serving a particular memory area of the logical process images that can be up to 4 gigabytes in size. Addressing of the Ethernet terminals can be in any order because the data sequence is independent of the physical order. Broadcast, Multicast and communication between slaves are possible. Transfer directly in the Ethernet frame is used in cases where EtherCAT components are operated in the same subnet as the master controller and where the control software has direct access to the Ethernet controller. Wiring flexibility in EtherCAT is further maximized through the choice of different cables. Flexible and inexpensive standard Ethernet patch cables transfer the signals optionally in Ethernet mode (100BASE-TX) or in E-Bus (LVDS) signal representation. Plastic optical fiber (POF) can be used in special applications for longer distances. The complete bandwidth of the Ethernet network, such as different fiber optics and copper cables, can be used in combination with switches or media converters. Fast Ethernet (100BASE-FX) or E-Bus can be selected based on distance requirements. The Fast Ethernet physics enables a cable length of 100 m between devices while the E-Bus line is intended for modular devices. The size of the network is almost unlimited since up to 65535 devices can be connected.

Further, such an embodiment using EtherCAT supports an approach for synchronization with accurate alignment of distributed clocks, as described in the IEEE 1588 standard. In contrast to fully synchronous communication, where synchronization quality suffers immediately in the event of a communication fault, distributed aligned clocks have a high degree of tolerance from possible fault-related delays within the communication system.

Thus, data exchange is completely hardware based on “mother” and “daughter” clocks. Each clock can simply and accurately determine the other clocks run-time offset because the communication utilizes a logical and full-duplex Ethernet physical ring structure. The distributed clocks are adjusted based on this value, which means that a very precise network-wide time base with a jitter of significantly less than 1 microsecond is available.

However, high-resolution distributed clocks are not only used for synchronization, but can also provide accurate information about the local timing of the data acquisition. For example, controls frequently calculate velocities from sequentially measured positions. Particularly with very short sampling times, even a small temporal jitter in the displacement measurement leads to large step changes in velocity. In

an embodiment comprising EtherCAT, the EtherCAT expanded data types (timestamp data type, oversampling data type) are introduced. The local time is linked to the measured value with a resolution of up to 10 ns, which is made possible by the large bandwidth offered by Ethernet. The accuracy of a velocity calculation then no longer depends on the jitter of the communication system. It is orders of magnitude better than that of measuring techniques based on jitter-free communication.

Finally, in an embodiment where network 620 comprises EtherCAT, a hot connect function enables parts of the network to be linked and decoupled or reconfigured “on the fly”. Many applications require a change in I/O configuration during operation. The protocol structure of the EtherCAT system takes account of these changing configurations.

As described in FIG. 6a, network 620 then interfaces with individual devices and actors via control data interface 650. Control data interface is part of network 620, or may comprise distributed components at the input of individual actors. Additionally, Input and feedback data interface is the same device as control data interface, acting as an opposite direction data flow of the same device interfacing with network 620. The actors interfacing with network 620 comprise camera control 632, secondary control 634, audio 636, digital output bank 648, camera robot 670, follow focus 672, light 674, master input 650, and master safety control 690.

In certain embodiments, some actors may communicate directly to network 620 via control data interface 650. For example, in the embodiment described above where network 620 is an EtherCAT network, camera control 632, secondary control 634, audio 636, and digital output bank 648 is able to communicate with no adapter through network 620. In such an embodiment, adapter 662a is an EtherCAT-provibus adapter for communicating with camera robot 670, adapter 662b is an EtherCAT-preston adapter for communicating with follow focus 672, and adapter 662c is an EtherCAT-dmx adapter for controlling light 674.

In addition to master control 610 and the devices communicating with master control 610 via network 620, motion control system 600 may comprise a plurality of other input, feedback, and devices such as OS network 654, database 622, database interface 652, master input (MI) display 656, software control 657, video output 658, and adapters 655a-c. In one potential embodiment, OS network 654 is an Ethernet network coupled to master control 610. MI display 656 may function as a display for master input 650 in a manner similar to the display described for master input 524 of FIG. 5a. Software control 657 may function as a software environment that may virtually create a global timeline for use with master control 610, and may also function to create a global timeline in real-time with live control of device actors. In one embodiment, software control 657 is a software program such as MAYA™ with supporting software add-ons. Finally, video output 658 is a real time video output associated with a camera in motion control system 600. As motion control system moves through a global timeline, video output may allow real time video review of a motion controlled set, such that individual device actors is modified, or a master input 650 controls is adjusted based on information from video output 658.

Motion control system 600 of FIG. 6a may then allow for function and creation of media in a variety of different ways, and described by FIG. 6b. In an embodiment described by FIG. 6b, a user may create control data using a software interface such as software control 657, as shown by block 1010. The control data may then be stored in database 622

for future use, as shown by block 1020. Alternatively or concurrently, the control data is sent to master control 610, as shown by block 1030. The master control then manages control logic 696 and creates a global timeline, such that any data required by specific devices prior to function is communicated to those devices, as shown by block 1040. For example, in one potential embodiment, camera robot 670 must have all position data prior to operation, with camera robot 670 functioning in synchronization with the global timeline by receiving a time or frame input and acting in response using previously received control information to move to the correct position for the current state of the global timeline. After the global timeline is prepared by master control 610, and all device actors are prepared, a user may use a master input 650 or a software control 657 to send an operation signal to master control 610, as shown by block 1050. The master control then sends the appropriate control signals to individual device actors given the global timeline position and synchronization, as shown by block 1060. The device actors then operate according to control signals, and send feedback signals via network 620 documenting actual operation, errors, and/or safety shutdown conditions, as shown by block 1080. The feedback data can then be used to update the control signal managed by master control 610 to modify or match the original control data from the database 622 or software control 657, as shown by block 1090.

In one potential embodiment, motion control system 600 comprises master safety control 690. Master safety control may comprise a hard wired shut down control connected directly to device actors identified as posing a safety risk. Such a shutdown control is attached to master input 650. In another potential embodiment, master safety control 690 comprises a safety computing system or a safety programmable logic controller (PLC) attached to safety sensors. Such safety sensors may comprise object proximity detectors attached to a device actor. When a scene is created in motion control system 600, the scene will have data for expected device actors and for players appearing in the scene. Object proximity detectors is programmed or coupled to a computing system to filter expected objects with expected locations from unexpected objects and locations. If an object is detected by an object proximity detector in an unexpected and unsafe location, a signal is sent to shut down the entire motion controlled scene, or at a minimum, device actors determined to pose a potential danger to the unexpected object. In another potential embodiment, boundaries for a motion controlled scene are determined. Proximity detectors or motion detectors is configured to detect movement across a scene boundary or a device actor boundary during operation of the motion control system, and to halt operation when an unsafe motion or object is detected. In this fashion, master safety control may observe an area proximate to various device actors and transmit a safety shutdown signal. In one potential embodiment, an object detector comprises a light detection and ranging unit (LIDAR). In another potential embodiment, the object detector is a passive infrared sensor (PIR).

FIG. 7 shows a block diagram of an exemplary computer apparatus that can be used in some embodiments of the invention (e.g., in the components shown in the prior Figures).

The subsystems shown in FIG. 7 are interconnected via a system bus 1110. Additional subsystems such as a printer 1108, keyboard 1118, fixed disk 1120 (or other memory comprising computer readable media), monitor 1114, which is coupled to display adapter 712, and others are shown.

Peripherals and input/output (I/O) devices, which couple to I/O controller 1102, can be connected to the computer system by any number of means known in the art, such as through serial port 1116. For example, serial port 1116 or external interface 1122 can be used to connect the computer apparatus to a wide area network such as the Internet, a mouse input device, or a scanner. The interconnection via system bus 1110 allows the central processor 1106 to communicate with each subsystem and to control the execution of instructions from system memory 1104 or the fixed disk 1120, as well as the exchange of information between subsystems. The system memory 1104 and/or the fixed disk 1120 may embody a computer readable medium.

FIG. 8 illustrates one potential embodiment of a user interface 1200 in a software control for use with a motion control photography system. Such an interface may enable a number of functions, including modeling of individual device actors, software control of individual device actors, creation of control data for individual device actors, and recording control or operation data for individual device actors. Similarly multiple devices are modeled simultaneously to model, control, or record operation of an entire motion controlled set using an interface such as user interface 1200.

User interface 1200 may include an actor panel with a plurality of interface buttons including an “actors” drop down menu to show a list of the current device actors is a scene, and “add actor” scene to bring up a prompt which allows selections of a name and/or type of device actor to be created or added to a scene, and a “delete actor” interface to allow deletion of an actor from a scene.

User interface 1200 may also include a selection panel. A selection panel may include an interface for “Select End Effector” which selects a controller on the robot which allows the user to drive the robot via a wrist. This controller, when selected and viewed through channel box editor, may house additional attributes that the user can control. These attributes may include:

Visibility—Toggles the visibility of the controller in a view port.

Disable Heads up Display (HUD) Updates—Disables all HUD updates in a view port.

A(1-6) Angle—Displays the current angle of each respective robot axis.

Track Robot (TR) Position—Displays the position of robot on the track axis.

Show Axes—Toggles the visibility of a skeleton in a view port.

FK IK (A1-A6)—Allows the switching settings for of individual joints.

A selection panel may also include a “select base control” interface which may select a controller on the robot which allows the user to position the robot from the base. Such a controller may, when selected and viewed through the channel box editor, houses additional attributes that the user can manipulate such as:

Translate Z—Moves the base along the track system.

Rotate Y—Changes the orientation of the base.

Column Height—Changes the base height of the robot.

A selection panel may also include additional interface controls such as:

Select Track Control—Selects a controller on the robot which allows the user to move and orient the track system to their liking.

Select Worldspace Mount—Selects a controller for adding a mount.

Select World Controls—Selects a master controller which allows the user to move and orient the entire robot and track system together.

Additionally, user interface **1200** may provide controls for adding and removing mounts to device actors within the software system, and for setting placement for mounts that are added to device actors. For example, FIG. **8** shows three potential positions for mounting a camera to a robot arm that is a device actor in the current system. The user interface **1200** may provide graphical or number input selections for choosing between various mounting options, and for adjusting the position variables associated with such a setting.

In one potential embodiment of a motion control photography system, user interface **1200** is integrated through a software control to a camera robot such as software control **657** and camera robot **670** of FIG. **6a** to enable an automated system calibration. One potential such calibration comprises a lens node calculation for determining a calibrated lens position in a camera mounted to a robot arm. One potential embodiment of such a calibration comprises providing software control **657** with information regarding the location and dimensions of a base, wrist or joint elements, and camera mounts for camera robot **670**. A calibration player with known characteristics such as location and size is also provided. When a calibrate command is selected via software control **657**, camera robot **670** records a plurality of images of the calibration player from different camera angles or locations. The images in conjunction with known data regarding the calibration player and camera robot **670** allows the lens node of the currently mounted camera to be calculated and incorporated into the device actor modeled in software control **657**.

In an alternative embodiment of a calibration, software interface **1200** may have a calibration command for altering size or location data in response to feedback from a temperature sensor. For example, software control **657** is receive data via digital output bank **658** from a temperature sensor attached to a rail that is part of camera robot **670**. Software control **657** is configured to adjust command signals due to known changes in rail characteristics over temperature, or is configured to signal a need to measure changes in device actor locations in response to temperature changes.

A software control such as software control **26** of FIG. **1** or software control **657** of FIG. **6a** may also comprise an analysis interface such as analysis interface **1300** of FIG. **9**. Analysis interface **1300** shows movement data for individual axis of a device actor. Data such as current velocity and current acceleration is displayed, along with graphs of these characteristics over time through a scene, maximum allowable limits for each characteristic, and maximum achieved value for each characteristic. The values presented in analysis interface **1300** are modeled from a global timeline created within a software control or recorded in a database. The values may also be values recorded from the actual physical motion of device actors playing through a scene. Use of such analysis data may provide for modifications to be made to a scene while quickly verifying that safe limits of device actor function are not mistakenly exceeded.

In addition to analysis of operation of individual device actors, software control is used for preventative safety in detecting potential collisions between device actors in modeling the motion of the actors through a global timeline, as shown by block **1070** of FIG. **6b**. Further, such modeling of a scene through a global timeline is used to set safety parameters for a safety system such as master safety control **690** of FIG. **6a**. Modeling of locations and velocities of device actors through a global timeline may enable identi-

fication of unsafe zones and unsafe times in an area or set around a motion control system. Such an identification is used to set sensing triggers of object detectors that are part of the safety system described above. For example, if an area within 5 feet of a certain device actor is determined to be at risk of collision, and a buffer zone of 10 additional feet is required to insure safety during operation, a LIDAR detector is configured to detect unexpected objects and movement within a 15 foot area of the device actor during operation, and to automatically create a safety shutdown if an object is detected. In an alternative embodiment, the LIDAR detector is configured to create a warning signal if an object is detected in a periphery of the danger zone, and only to create a shutdown if the detected object is moving toward a potential impact zone.

In an alternate embodiment, a software control includes modeling of actors and models of defined safe zones. Analysis of the motion of the actors in software control allows a modeled safety check to see if any actor collides with a defined safe zone. Safe zones are defined by entry of fixed volumes of space into software control, by image capture of a set location. Safe zones may also be defined to be variable based on a detected motion, jerk, velocity, or acceleration of an object in a safe zone. In an alternate embodiment a safe zone is defined by input from transponder device data. For example, a transponder location device is attached to a player, and a safe zone defined by a distance from the transponder. The transponder feeds location data to software control, which may update safe zones within a software control or within a master safety control. In another embodiment, fixed safe zones are defined within software control, and published prior to a safety PLC within master safety control prior to operation of the motion controlled set.

FIG. **10** describes an alternate embodiment of a motion control system according the present innovations. The function of and operation of motion control system **700** is understood in conjunction with the detailed description of motion control systems described above. In particular, motion control system **700** includes: a control wheel and display **724** (e.g., an embodiment in which analog interface **520** is a wheel), a camera focus control **728** (e.g., follow focus **672**), lighting control **729** (e.g., an EtherCAT-DMX adapter for controlling light **674**), database **722**, software control **726** (e.g., software control **657**), video output **702** (e.g., video output **658**), master control **710**, secondary device **786**, secondary motion control systems **764** (e.g., secondary control **634**), second player robot **754** (e.g., as shown in FIG. **22C**), safety systems **790** (e.g., safety systems **90**), a first player robot **752** with player movement control **762** (e.g., as shown in FIG. **22C**). Further, system **700** includes a camera robot **740** with a camera **742**, axis control **744**, track control **745**, camera head **747**, camera focus **748**, and wrist device **749** (e.g., as shown in FIGS. **2**, **3a**, **3b**, **4a**, & **4b**). System **700** also includes a lighting robot **756** with light control **767** and axis control **766** (e.g., as shown in FIG. **3c**), and a robot sync module **780** (e.g., as described in par. **00123** below).

The previous description of the embodiments is provided to enable any person skilled in the art to practice the invention. The various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein are applied to other embodiments without the use of inventive faculty. Thus, the present invention is not intended to be limited to the embodiments shown herein, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

Embodiments of the invention are not limited to the above-described embodiments. For example, throughout the description, various examples of device actors and robots are presented for use in a motion control photography system. The embodiments are not limited to the general or specific examples provided herein, but may include other embodiments apparent to a person of ordinary skill in the art from the above descriptions. By further example, the above description provides an illustration of three modes selectable as input modes for a master input. The embodiments of the invention are not limited to these modes, but additional modes is used that may differ from the modes presented.

It should be understood that the present invention as described above can be implemented in the form of control logic using computer software in a modular or integrated manner. Based on the disclosure and teachings provided herein, a person of ordinary skill in the art can know and appreciate other ways and/or methods to implement the present invention using hardware and a combination of hardware and software.

Any of the software components or functions described in this application, is implemented as software code to be executed by a processor using any suitable computer language such as, for example, Java, C, or Perl using, for example, conventional or object-oriented techniques. The software code is stored as a series of instructions, or commands on a computer readable medium, such as a random access memory (RAM), a read only memory (ROM), a magnetic medium such as a hard-drive or a floppy disk, or an optical medium such as a CDROM. Any such computer readable medium may reside on or within a single computational apparatus, and is present on or within different computational apparatuses within a system or network.

The above description is illustrative and is not restrictive. Many variations of the invention will become apparent to those skilled in the art upon review of the disclosure. The scope of the invention should, therefore, be determined not solely with reference to the above description, but instead should be determined with reference to the pending claims along with their full scope or equivalents.

One or more features from any embodiment is combined with one or more features of any other embodiment without departing from the scope of the invention. For the purposes of the present application, a recitation of “a”, “an” or “the” is intended to mean “one or more” unless specifically indicated to the contrary. Descriptions of alternative embodiments recite that certain portions of an embodiment “may” be present in the specific alternative embodiment being described, and that certain embodiments include the described element.

In addition to the above described embodiments, certain implementations involve motion control combined with 3D projection mapping. In 3D projection mapping, a viewer is presented with the visual projection an environment that is not actually physically present, when light is projected on a surface that is rendered from a specific perspective.

In 3D projection mapping, the knowledge of the physical spatial dimensions and coordinates of the projection surface or object is necessary to achieve the desired effect. Traditionally, these dimensions and/or the location are stationary, and are therefore not varying.

In some embodiments, the projection surface is in motion through a volume. Specifically the surface is moved by a first device actor, such as by robotic (servo) actuation, whereby the exact physical location of the projection surface is known to the system via pre-determined data or a real-time data stream. In addition to the concept of moving the

projection surface via a controlled method, embodiments also include movement of the projector via a controlled method to known coordinates. For example, the projection surface may be coupled to second device actor that can move the projector. This might serve, for example, to provide an accurate representation from a correctly rendered perspective to a viewer that is on a motion platform (i.e., a passenger car on a ride or exhibit).

By placing a projection surface on the end effector of a robotic platform or arm, certain embodiments of the system are able to move the projection surface or object to a specific known coordinate in x, y, z (Cartesian) space. Since the exact location of the object is known (through robot encoder feedback, as well as programmed position), we are able to project imagery on the surface through mapping in 3D (virtual) space (in real-time).

Embodiments of the system thus create this effect in a traditional 3D projection mapping methodology whereby we create a 3D model (virtual) representation of the projection surface/object to calculate the proper render considering point of view and perspective. This render is then projected as light onto the object.

Such a system is incorporated with any of the above described software control or master control systems to create an audiovisual presentation that is controlled, programmed, and modified to enable improved editing and creation of 3D projection mapped audiovisual presentations that are integrated with lighting, safety, and software systems described above.

FIG. 11 describes one potential embodiment of a 3D projection mapped audiovisual presentation system. FIG. 11 shows device actor 1142, projector 1150 mounted on device actor 1142, device actor 1144, and projection surface 1140 mounted on device actor 1144. Projector 1150 may receive or include signal information for projecting an image onto projection surface 1140 as projection surface 1140 is moved through a set of spatial coordinates by device actor 1144. In alternative embodiments, both device actors 1142 and 1144 is moving through spatial coordinates, or only device actor 1142 is moving. The spatial coordinates is provided by a master control system, a computer, or any other known means for controlling a device actor. As part of the system, the image projected onto the surface 1140 is created based on the known information of the movement of the device actor 1144 through the set of spatial coordinates.

For example, device actors 1142 and/or 1144 are coupled to a software control system such as software control 26 of FIG. 1 or software control 657 with video output 658 of motion control system 600. The system has imbedded information related to the projection surface 1140 and a desired visual representation. A manual control allows a user to manually adjust projection surface 1140's spatial position, and a software control is programmed to automatically adjust a graphical output from the projector to create the desired visual presentation. Alternately, a software control uses animation to describe a desired visual representation, and the software control automatically adjusts projector 1150 and projection surface 1140 using device actors 1142 and 1144 to create the desired audiovisual representation on projection surface 1140.

In one potential embodiment, and animation control system coupled to a projector projects an animation onto a projection surface. The animation control system includes an interface for modifying a 3D animation of the projection. The animation control system may include a relative coordinate representation of the projection surface and the current location of the projection surface based on control

information received from a device actor that physically controls the location of the projection surface. The interface may thus enable modification of the animation within the relative coordinate system presented for the projection surface. As the projection surface is moved by a device actor, the animation control system receives a signal indicating this movement. The system then compensates based on any adjustment angle to create the appropriate presentation and perspective of the 3D projection. For example, as the projection surface angles away from a position normal to the projector, the projection is transformed to present a narrower output from the projector that will spread across the angled projector to maintain a constant image from the projection surface. The optical output power from the projector may similarly be increased to maintain a constant brightness from the projection surface. The output signal from the animation control system will automatically adjust the projection at the projector to maintain the animation at the appropriate location in the relative coordinate system on the projection surface. In one embodiment, multiple projectors may project the same 3D animation onto the projection surface at the same or alternating times. If the projection surface rotates such that a first projector's optical path to the projection surface is blocked, a second projector in a second location with an unblocked optical path may then project the same 3D animation onto the projection surface.

In additional embodiments, set models and movement of a set through a scene may further include modeling of an optical path from a projector to a projection surface. A master control or animation computer system that adjusts a set and scene movements may create an alert if changes to the set and scene create an obstruction of an optical path that would block part of the 3D projection and prevent presentation of the 3D projection at the projection surface.

FIGS. 12 to 21 show additional details of potential implementations of a 3D motion control projection system in accordance with the present innovations. FIG. 12 shows one potential implementation of a 3D projection with projector 1150 projecting onto projection surface 1140. FIGS. 13-19 show one implementation of a projection surface 1140 mounted on a device actor 1144. In these figures, a roughly spherical projection object has a computer generated face projected onto the surface. This is an example of a projection. As the device actor moves the projection surface, the projected image of the face maintains an appropriate position on the projection surface, and the features of the face are animated to produce blinking eyes, a moving mouth, and other 3D animation on the moving projection surface. This may be matched to a set of coordinates associated with the projection surface. The projection surface 1140 is moved or translated through a set of coordinates, and the relative location of the face projection on projection surface 1140 may remain stable within a projection coordinate system on the projection surface as the projection surface is moved through the set of coordinates in space. This essentially presents the illusion of animation and mobility with the potential for extremely complex facial animation beyond what is possible using mechanical facial animation. FIGS. 20 and 21 show a computer model of the projection surface in a user interface 2010 in a display. The projection that operates concurrently with the motion of the device actor and the projection of the image onto the projection screen. The software may enable visualization and use of spatial information from the device actor, and adjustment or control of the projected image in real time or near real time.

In various embodiments, the projection surface is then be integrated with a scene as described above in the master

control system. Movement of the entire scene is be matched to the timeline, and the animation of the 3D projection is additionally matched to the timeline, such that when manual or control system adjustments to the speed of the scene are made, the animation and movement of the 3D projection surface are also adjusted and matched to the movement of the entire scene. In one potential embodiment, a projection surface is a non-planar projection surface. In an alternate embodiment, the projection surface is a rear projection surface. In another alternate embodiment, a set includes a planar projection surface and a non-planar 3D projection surface.

In additional embodiments, the 3D computer animated projection is both part of a scene in a master control timeline, but also have certain portions of the animation matched to a real time input. For example, if a voice and spoken words from an actor are presented as coming from the animated device actor, the 3D projection of mouth movement is matched in real time to the words spoken by the human actor. Movement of the projection surface and certain parts of the 3D projection animation such as eye blinking is predetermined and automated, while projection of the mouth movement is specifically adapted to a human actor that is hidden from the audience.

In various embodiments, then a system for 3D projection with motion control comprises a projector; and a projection surface coupled to a first device actor, wherein the first device actor moves the projection surface through a set of spatial coordinates, and a 3D projection from the projector is projected onto a set of coordinates of the projection surface and matches the 3D projection to the set of coordinates of the projection surface as the projection surface moves through the set of spatial coordinates. Additional alternative embodiments comprise an animation computer system coupled to the projector that maps the 3D projection onto the projection surface and animates the 3D projection while matching the 3D projection to the set of coordinates of the projection surface as the non-planar projection surface moves through the set of spatial coordinates. In alternative embodiments, animation computer system is further coupled to the device actor, and the animation computer system provides the set of spatial coordinates to the device actor to instruct the device actor to move the non-planar projection surface through the set of spatial coordinates.

Additional alternative embodiments comprise a master control that receives a plurality of control signals comprising control data for a plurality of device actors including the first device actor and synchronizes the plurality of control signals with a global timeline to create a plurality of synchronized signals, such that control data for each actor of the device actors is associated with a corresponding position in the global timeline; and a master input that conveys a master input signal to the master control indicating a position in the global timeline and a rate of progression through the global timeline; wherein the master control responds to the master input signal by communicating the plurality of synchronized signals associated with the position in the global timeline to the plurality of device actors, and the control data for each actor of the device actors is sent to respective device actors at the rate of progression through the global timeline.

In additional alternative embodiments, the master input comprises an analog input, a mode selector, and an analog input action control; the analog input action control returns the analog input to a first position when no force is applied to the analog input; for a first selected mode of the master input, adjustment of the analog input in a first direction increases the rate of progress through the global timeline



from a predetermined standard forward rate; for the first selected mode of the master input, adjustment of the analog input in a second direction different from the first direction decreases the rate of progress through the global timeline from the predetermined standard forward rate; for a second selected mode of the master input, adjustments to the analog input in the first direction creates a variable rate of progress in the forward direction from a stationary rate; and for the second selected mode of the master input, adjustments to the analog input in the second direction creates a variable rate of progress in a reverse direction from the stationary rate.

In additional alternative embodiments, the animation computer system comprises a real time input for modifying the 3D projection while maintaining the 3D projection within the set of coordinates of the projection surface as the projection surface moves through the set of spatial coordinates.

Additional alternative embodiments comprise an object detector that observes an area proximate to a first device actor of the plurality of device actors and transmits a safety shutdown signal to the first device actor when the object detector senses an object.

Additional alternative embodiments comprise a master safety control; wherein the master safety control comprises a programmable logic circuit; and wherein the safety shutdown signal is transmitted to each of the plurality of device actors via the programmable logic circuit.

In additional alternative embodiments, the first device actor is a robotic arm, the object detector is attached to a mounting point of the robotic arm, and wherein the area proximate to the first device actor comprises an area extending a fixed distance from the object detector.

In additional alternative embodiments, the area proximate to the first device actor varies over time in a predetermined manner determined in association with the position in the global timeline and the rate of progress through the global timeline.

Another alternative embodiment comprises a method for motion control. One embodiment of the method comprises moving a projection surface through a set of spatial coordinates using a first device actor coupled to the projection surface; projecting from a projection device using a signal from an animation computer, a 3D projection onto the projection surface; and mapping, using the animation computer, the 3D projection onto the projection surface to match a 3D projection movement with the movement of the projection surface through the set of spatial coordinates.

Additional alternative embodiments comprise receiving control data for a plurality of device actors including the first device actor at a master control; synchronizing a plurality of control signals, using the master control, with a global timeline to create a plurality of synchronized signals, such that the control data for each actor of the device actors is associated with a corresponding position in the global timeline; receiving, at the master control, a master input signal indicating a position in the global timeline and a rate of progression through the global timeline; and communicating, in response to the master input signal, the plurality of synchronized signals associated with the position in the global timeline from the master control to the plurality of device actors, wherein the plurality of synchronized signals are sent to the plurality of device actors at the rate of progression through the global timeline indicated by the master input signal.

Additional alternative embodiments comprise detecting, using at least one object detector, an area proximate to the plurality of device actors; and transmitting, from the at least

one object detector, a safety shutdown signal that prevents the plurality of device actors from operating.

Additional alternative embodiments comprise methods where the rate of progress through the global timeline comprises a reverse rate of progress through the global timeline.

Additional alternative embodiments comprise receiving at the master control, during the communicating of the plurality of synchronized signals, a modifying control input for a first device actor of the plurality of device actors from an independent manual control; synchronizing the modifying control input with the plurality of synchronized signals to create an updated plurality of synchronized signals during the communication of the plurality of synchronized signals; and communicating the updated plurality of synchronized signals in place of the synchronized signals.

Additional alternative embodiments comprise storing the updated plurality of synchronized signals in a database, wherein the control data is received at the master control from the database.

Additional alternative embodiments comprise receiving at the master control, feedback data from the plurality of device actors describing an operating characteristic associated with the synchronized control signals; and modifying the synchronized control signals in response to the feedback data.

Additional alternative embodiments comprise adjusting in real time, the signal from the animation computer, to create a real time computer animation at the projection surface based on a user input at the animation computer.

Additional alternative embodiments comprise a computer readable medium storing instructions for execution by a computing system for implementing a method of creating a film using motion control, the method comprising: modeling physical characteristics and locations, using a software control comprising a computing device; for a plurality of device actors, at least one projector, and at least one projection surface in a motion control set; modeling movement characteristics and an optical path from the at least one projector to the at least one projection surface, using the software control, for the plurality of device actors in the motion control set to create control data for the plurality of device actors; analyzing the modeling of the movements, physical characteristics, and locations of the plurality of device actors, using the software control, to detect collisions, obstruction of the optical path, and to detect device actor motion that exceeds a set of predetermined operating limits; and communicating the control data to a master control that synchronizes the control data and transmits the control data to the plurality of device actors.

In additional alternative embodiments, the method further comprises analyzing the modeling of the movements, physical characteristics, and locations of the plurality of device actors, using the software control, to determine a set of locations proximate to the device actors that include a collision risk and transmitting the set of locations to a master safety control comprising at least one object detector.

Filming Projections on Moving Surfaces with a Camera  
 FIG. 22A describes an illustrative embodiment of a 3D projection mapped audiovisual presentation system. FIG. 22 shows device actor 2242, projector 2250 mounted on device actor 2242, projection surface 2240 mounted on device actor 2244, device actor 2246, and camera 2248 mounted on device actor 2246. Projector 2250 may receive or include signal information for projecting an image onto projection surface 2240 as projection surface 2240 is moved through a set of spatial coordinates by device actor 2244. Further,

device actors 2242, 2244, and 2246 may all be moveable, such that projector 2250, projection surface 2240, and camera 2248 are separately movable through a set of spatial coordinates. The spatial coordinates may be provided by a control system (e.g., a master control system, a computer, or any other known means for controlling a device actor).

Note that in other configurations, the camera 2248 may be moveable via another mechanism or possibly even hand held. In yet other configurations the camera may be mounted or otherwise positioned in a fixed location, such that it does not move while capturing image data of the projection surface.

#### a. Shutter Synchronization

In some embodiments, when an object or scene including a projection mapping is being captured on video by a camera, such as by camera 2248 of system 2200, it may be desirable to synchronize the camera's shutter with the operation of the projector(s) in the system. Such synchronization may help to reduce, and hopefully eliminate, ghosting effects in the resulting video. Note, however, that such benefits are not required, and other benefits are also possible.

For instance, consider a control system that is implemented in conjunction with the system 2200 shown in FIG. 22A. Such a control system may be configured to synchronize operation of the projector 2250 with operation of the shutter of camera 2248 as (a) the projector 2250 projects a projection on the projection surface 2240 and (b) the camera 2248 captures image data of the projection surface 2240 with the projection thereon. In some embodiments, the control system may include a master clock and/or have access to an external clock or a system, which provides timing information that is used to maintain synchronization between the camera 2248, projector 2250, and/or other devices, such as robots and/or device actors.

To help synchronize the camera 2248 and the projector 2250, the control system may determine both (a) one or more shutter parameters for the operation of the shutter of camera 2248 and (b) one or more projection parameters for the operation of the projector 2250. The control system may then generate a camera control signal based on the one or more shutter parameters. The control system may additionally or alternatively generate a projector control signal based on the one or more projection parameters for the operation of the shutter. The camera control signal and/or the projector control signal may then be sent to the camera 2248 and/or the projector 2250, respectively, to help synchronize the operation of the camera 2248 and the projector 2250.

In some embodiments, the camera control signal and the projector control signals may be electrical signals that are sent by a control system to the (a) the video card or video cards rendering the content that is projected by a projector 2250, and (b) the a shutter control interface of the camera 2248. Such control signals may be sent to the camera and/or to the projector using various types of interfaces, such as a serial interface, a web interface, and various other types of electrical interfaces, among other possibilities.

In an illustrative embodiment, the one or more shutter parameters and the one or more projection parameters are determined such that the operation of the camera's shutter and the operation of the projector are substantially synchronized. For example, the one or more shutter parameters may indicate one or more of: (a) a frame rate, (b) a phase offset, and (c) a trigger time or start time, among other possibilities. Similarly, the one or more projection parameters may indicate one or more of: (a) a frame rate, (b) a phase offset, and (c) a trigger time or start time, among other possibilities.

In an illustrative embodiment, the one or more shutter parameters and/or the one or more projection parameters may indicate a frame rate to the camera 2248 and/or to the projector 2250, such that the shutter of camera 2248 opens and closes at the same frame rate as the projector 2250 is projecting image data onto projection surface 2240. Further, the one or more shutter parameters and/or the one or more projection parameters may indicate a phase offset or offsets, and/or a trigger time or times, to the camera 2248 and/or to the projector 2250, that accounts for differences in delay times between the signal paths to the camera 2248 and/or to the projector 2250. As such, the camera's shutter may be synchronized with the projector by periodically triggering the shutter at the same rate as projector 2250 refreshes the image data that is projected onto the projection surface 2240, and aligning the phase at which the shutter is periodically triggered with the phase of the projection.

In some embodiments, the control system may be configured to control a pre-arranged scene by sending control signals to both the camera 2248 and the projector 2250 (and possibly to other devices, such as device actors and/or other robots). In other embodiments, the control system may control the camera 2248, but not the projector 2250. As an example, the control system may receive data indicating the manner in which the camera 2248 is operating, which may include one or more shutter parameters, for instance. The control system may then generate control signals for the projector 2250 in real time, such that the operation of the projector 2250 is synchronized with the operation of the camera 2248.

In yet other embodiments, the control system may control the projector 2250, but not the camera 2248. As an example, the control system may receive data indicating the manner in which the camera 2248 is operating, which may include the camera's frame rate and/or a timing signal indicating phase of the camera's shutter operation, for instance. The control system may then generate control signals for the projector in real time, such that the operation of the projector is synchronized with the operation of the camera.

Further, note that in some examples, projector 2250 may not be mounted to a device actor on a robotic arm. In such an example, the projector 2250 may instead be mounted on a ball mount or another mechanical feature that is operable to rotate and/or move the projector 2250 such that the projected image remains projected onto the projection surface or surfaces as the projection surface or surfaces move throughout the set of spatial coordinates. Additionally or alternatively, the projector 2250 may include a lens mechanism that is configured to move the projected image in the set of spatial coordinates, such that the projected image remains projected onto the projection surface or surfaces as the projection surface or surfaces move throughout the set of spatial coordinates. Further, in some cases, the projector 2250 may project an image that is smaller than the entire area it could cover with a projection (which is referred to as the "cone of projection"). In such case, the projector may not need to move or change its pose to move the projected image with the projection surface. Instead, so long as the projection surface stays within the cone or projection, the projector can follow movements of the projection surface by changing the location of the projected image within the cone of projection.

Further, note that some embodiments may include multiple projectors. Each of these projectors may operate in a similar manner as described above in reference to projector 2250. Further, a control system may synchronize the operation of these projectors, e.g., by adjusting the phase and/or

frame rate of projections so that the projected images appear synchronized on the projections surface or surface, and so that that the operation of each projector is synchronized with the operation of camera 2248. In yet other embodiments, the control system could synchronize multiple cameras with a single projector or with multiple projectors. Other variations are also possible.

b. Synchronizing a Projection with a Moving Camera

In an illustrative embodiment, the content that is projected onto the surface 2240 is created based on both (a) the known information of the movement of the device actor 2244 through the set of spatial coordinates and/or (b) the known information of the movement of the camera 2248 through the set of spatial coordinates. For example, device actors 2242, 2244, and 2246 may be coupled to a software control system such as software control 26 of FIG. 1 or software control 726 with video output 702 of motion control system 700. The system has imbedded information related to the projection surface 2240 and a desired visual representation.

In some implementations, a manual control allows a user to manually adjust projection surface 2240's spatial position, and a manual control allows a user to adjust the spatial position of camera 2248. A control system may accordingly be programmed to automatically adjust a graphical output from the projector to create the desired visual presentation, given the spatial position of the projection surface 2240 and the perspective that camera 2248 has of the projection surface 2240 (e.g., as may be determined based at least in part the spatial coordinates of camera 2248).

In other implementations, a control system (e.g., a software control) may be programmed to automatically move the projection surface 2240, and a manual control may allow a user to adjust the spatial position of camera 2248. A control system may accordingly be programmed to automatically adjust a graphical output from the projector to create the desired visual presentation, given the known spatial position of the projection surface 2240 and the dynamically changing perspective that camera 2248 has of the projection surface 2240.

In yet other implementations, a control system (e.g., a software control) uses animation to describe a desired visual representation, and also automatically adjusts the spatial positions of projector 2250, projection surface 2240, and camera 2248 using device actors 2242, 2244, and 2246, in order to create the desired visual representation on projection surface 2240.

Accordingly, in system 2200, device actors 2244, 2242, and 2246 may be respectively configured or controlled to move the projection surface 2240, projector 2250, and camera 2248, through a set of spatial coordinates in a volume. In particular, device actors 2244 and 2242 may move the projection surface 2240 and projector 2250 such that the projection from projector 2250 remains projected on to the coordinates of the projection surface as the projection surface moves. Further, while camera 2248 is capturing image data of the projection surface 2240, device actor 2246 may be configured or controlled to move camera 2248 according to a pre-determined data path through the set of spatial coordinates, which may be specified by a pre-determined sequence of (x, y, z) coordinates in the volume.

In some embodiments, a control system is configured to receive pre-determined data indicating the pose of the camera 2248, the pose of projection surface 2248, and/or the pose of projector 2250 during the course of a scene may be pre-determined or received before the scene is performed by the device actors 2242, 2244, and 2246. In such case, a timing signal or signals that synchronize the operation of the

projector with the operation of the camera's shutter may also be pre-determined or received before the scene is performed. Alternatively, data indicating the pose of the camera 2248, the pose of projection surface 2248, and/or the pose of projector 2250 may be received in real-time, as a scene is being performed. In such case, a timing signal or signals that synchronize the operation of the projector with the operation of the camera's shutter may also be generated in realtime.

In a real-time example, sensor data indicating the position and/or orientation of the camera 2248 may be received by the control system in real-time. Such sensor data may be generated by sensors on the camera 2248 (e.g., by a GPS system, accelerometer(s), gyroscope(s), and/or magnetometer(s)), and/or by sensors in the environment configured to determine the position and/or the movement of camera 2248 and sent to the control system in real-time.

In an example embodiment, the graphic content may be rendered such that the graphic content that is projected onto the projection surface 2240, is presented to the camera's perspective of the projection surface. More specifically, as a real-time signal indicating the pose (e.g., position and/or orientation) of the camera 2248 is received, the control system or another system may generate projection content that is directed to the camera's perspective of the projection surface 2240. As such, the perspective to which the graphic content is rendered may be varied in real-time as the camera's perspective of projection surface 2240 changes due to movement of the camera 2248 and/or due to movement of the projection surface 2240, such that the projected graphic content remains directed to the camera's perspective.

For instance, based on both (a) the position and/or orientation of projection surface 2248 over time (e.g., over the course of a scene) and (b) the position and/or orientation of the camera 2248 over the same time (e.g., during the same scene), the control system may determine the camera's perspective of the projection surface over that time, or at least determine data that is indicative of the camera's perspective. Such data may thus indicate variations in the camera 2248's perspective of projection surface 2240 over time, and the graphic content may be rendered accordingly.

c. Synchronizing a Projection with a Moving Vantage Point

At a high level, a moving camera may be thought of as providing a moving vantage point. Accordingly, embodiments herein may be capable of updating a projection onto a moving projection surface such that a 3D effect is provided at a moving vantage point. For example, methods and systems described herein may be applied to provide a projection mapping on a moving surface, such that a desired 3D effect is provided to a human who is viewing the projection surface live and is free to move about in the environment (e.g., such that the human's location can change with respect to the projection surface).

In some examples, a person may wear or hold a wearable computing device (WCD). The WCD may generate position data, location data, and/or movement data that indicates or can be used to determine the pose of the person. The WCD may generate and send such data to a control system in real-time. The control system can therefore determine the person's pose, and provide real-time control of a 3D projection mapping onto a surface or surfaces in the person's environment such that 3D projection mapping is updated according to the person's pose. The real-time control of the 3D projection mapping may be accomplished in various ways, such as by using the techniques described herein to

control one or more projectors, one or more cameras, and/or one or more projection surfaces; some or all of which may be attached to device actors.

FIG. 22B describes another potential embodiment of a 3D projection mapped audiovisual presentation system. FIG. 22 shows device actor 2242, projector 2250 mounted on device actor 2242, projection surface 2240 mounted on device actor 2244, and a wearable computing device 2266 that is worn by a person 2268. Projector 2250 may receive or include signal information for projecting an image onto projection surface 2240 as projection surface 2240 is moved through a set of spatial coordinates by device actor 2244. Further, device actors 2242 and 2244 may all be moveable, such that projector 2250 and projection surface 2240 are separately movable through a set of spatial coordinates. Yet further, while wearing a WCD 2266, the person 2268 may move with respect to projection surface 2240. The WCD 2266 may include sensors that provide data that is indicative of a location, orientation, and/or movement of the WCD. Such data can thus be used as a proxy of the location and/or pose of person 2268. Accordingly, while person 2268 is wearer WCD 2266, spatial coordinates corresponding to person 2268 may be determined based on sensor data from WCD 2266.

The spatial coordinates may be provided by a control system (e.g., a master control system, a computer, or any other known means for controlling a device actor. As part of the system, the image projected onto the surface 2240 is created based on both (a) the known information of the movement of the device actor 2244 through the set of spatial coordinates and/or (b) the known information of the movement of the WCD 2246 through the set of spatial coordinates.

For example, device actors 2242, 2244 and WCD 2246 may all be coupled to a control system such as software control 26 of FIG. 1 or software control 726 with video output 702 of motion control system 700. The system may have imbedded information related to the projection surface 2240 and a desired visual representation. In some implementations, a manual control allows a user to manually adjust projection surface 2240's spatial position. A control system may accordingly be programmed to automatically adjust a graphical output from the projector to create the desired visual presentation, given the spatial position of the projection surface 2240 and the perspective that person 2268 is determined to have of the projection surface 2240 (e.g., as may be determined based at least in part the sensor data provided by device 2248). Further, the control system may be configured to adjust the graphical output in real-time, as the person 2268's perspective of the projection surface changes.

Accordingly, in system 2280, device actors 2244 and 2242 may be respectively configured or controlled to move the projection surface 2240 and projector 2250 through a set of spatial coordinates in a volume. In particular, device actors 2244 and 2242 may move the projection surface 2240 and projector 2250 such that the projection from projector 2250 remains projected on to the coordinates of the projection surface as the projection surface moves.

Further, in conjunction with system 2280, a control system may be configured to receive real-time data indicating the pose of the WCD 2266, during the performance of a scene. As the real-time signal indicating the pose of the device is received, the control system or another system may generate projection content that is directed to the perspective of the projection surface from the WCD 2266. As such, the perspective to which the graphic content is directed may

vary in real-time based on the pose of the device. That is, the perspective to which the graphic content may be varied in real-time as the person 2268's perspective of projection surface 2240 changes due to movement of the person 2268 and/or due to movement of the projection surface 2240.

In the illustrated example, WCD 2266 is a head-mountable device (HMD). However, other types of wearable computing devices may be utilized, such as a smartwatch, for instance. Further, a device such as mobile phone, tablet, or even a laptop computer may function as WCD if person 2268 carries such a device with them while moving about (e.g., in their pocket or in their arms). Other types of wearable computing devices are also possible.

In an illustrative embodiment, the WCD 2266 may include one or more sensors that provide data that indicates or can be used to determine the location and/or the pose of person 2268. Such sensors may include a GPS system, accelerometer(s), gyroscope(s), and/or magnetometer(s), among other possibilities. The WCD 2266 and/or the control system may use data from such sensors to determine the location and/or orientation of the WCD 2266, which in turn may be used to determine a location and/or orientation of the person 2268 with respect to the projection surface 2240.

Note that determining the location and/or the pose of person 2268 with respect to a projection surface 2240 may involve determining the location of the WCD with respect to the wearer's head or eyes. Accordingly, in some embodiments, the WCD 2266 may determine and/or provide a control system with other information to facilitate determining the location and/or the pose of person 2268. Such information may include the type of WCD 2266 (e.g., wearable device, mobile phone, etc.), a location on the person's body and/or the manner in which the WCD 2266 is being worn (e.g., on the person's head, on the person's waist, in the person's pocket), for example. Further, in the event that the user has opted to make such information available, the WCD 2266 may determine and/or provide a control system with data indicating a person's body size and/or shape, which may be helpful in determining how the person's head and/or eyes are positioned and/or oriented with respect to the WCD 2266.

#### Illustrative Methods

FIG. 23 is flow chart illustrating a method 2300, according to an illustrative embodiment. Method 2300 may be carried out by a control system, such as those described in the above description of FIGS. 22A and 22B. However, it should be understood that method 2300 may also be carried out by other types of computing systems.

As shown, method 2300 involves a computing system determining a pose of a device with respect to a projection surface, wherein a projector projects graphic content onto the projection surface, as shown by block 2302. In an illustrative embodiment, the projection surface is coupled to a first device actor such that the projection surface is movable through a set of spatial coordinates, and the device is movable through at least a portion of the set of spatial coordinates.

Based at least in part on the pose of the device, the computing system may determine a perspective of the projection surface that is associated with the device, as shown by block 2304. For example, if the device is a camera, such as camera 2248 shown in FIG. 22A, the computing system may determine the location and/or orientation of the camera with respect to the projection surface.

As another example, if the device is a wearable computing device, such as WCD 2266 shown in FIG. 22B, the computing system may first determine the location and/or ori-

entation of the WCD with respect to the projection surface. The computing system may further determine or receive data that indicates the location and/or orientation of the WCD with respect to the wearer's vantage point (e.g., with respect to the wearer's head or eyes). The computing system may then use the combination of (a) the location and/or orientation of the WCD with respect to the projection surface and (b) the location and/or orientation of the WCD with respect to the wearer's vantage point, to determine the location and/or orientation of the wearer's vantage point with respect to the projection surface.

Once the computing system has determined the perspective of the projection surface, the computing system may initiate a process to render the graphic content in accordance with the perspective of the projection surface that is associated with the device, as shown by block **2306**.

Further, the computing system may periodically repeat method **2300** in order to periodically or continuously update the graphic content that is projected onto the projection surface such that the graphic content is directed to the associated perspective as the device and/or projection surface move throughout the set of spatial coordinates. For example, the computing system may periodically: (a) re-determine the pose of the device, (b) re-determine the devices' perspective of the projection surface based at least in part on the re-determined pose, and (c) initiate a process to render the graphic content in accordance with the re-determined perspective of the projection surface. Other examples are also possible.

In a further aspect, a computing system may simultaneously performing the method of claim **12** to render graphic content for projection onto each of the two or more projection surfaces in accordance with the device's respective perspective of each projection surface. For example, the computing system may implement method **2300** to determine a perspective of a first projection surface that is associated with a device, and to determine a perspective of a second projection surface that is associated with the same device. The computing system may then initiate a process to coordinate the respective projectors that are projecting graphic content onto each projection surface, to render the respective graphic content for the first and second projection surfaces in accordance with the respective associated perspective.

## CONCLUSION

The above detailed description describes various features and functions of the disclosed systems, devices, and methods with reference to the accompanying figures. In the figures, similar symbols typically identify similar components, unless context indicates otherwise. The illustrative embodiments described in the detailed description, figures, and claims are not meant to be limiting. Other embodiments can be utilized, and other changes can be made, without departing from the scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

In situations in which the systems discussed here collect personal information about users, or may make use of personal information, the users may be provided with an opportunity to control whether programs or features collect user information (e.g., information about a user's social network, social actions or activities, profession, a user's

preferences, or a user's current location), or to control whether and/or how to receive content from the content server that may be more relevant to the user. In addition, certain data may be treated in one or more ways before it is stored or used, so that personally identifiable information is removed. For example, a user's identity may be treated so that no personally identifiable information can be determined for the user, or a user's geographic location may be generalized where location information is obtained (such as to a city, ZIP code, or state level), so that a particular location of a user cannot be determined. Thus, the user may have control over how information is collected about the user and used by a content server.

The above detailed description describes various features and functions of the disclosed systems, devices, and methods with reference to the accompanying figures. In the figures, similar symbols typically identify similar components, unless context indicates otherwise. The illustrative embodiments described in the detailed description, figures, and claims are not meant to be limiting. Other embodiments can be utilized, and other changes can be made, without departing from the scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

I claim:

1. A computer-implemented method comprising:
  - determining, by a computing device, a first pose of a camera that is located at a first location in a set of spatial coordinates, wherein the camera is moveable through at least a portion of the set of spatial coordinates independently from a projector;
  - when the camera has the first pose at a first location in the set of special coordinates, causing the projector to render graphic content such that a three-dimensional effect of a projection of the graphic content on a projection surface corresponds to a first perspective of the projection surface from the first pose of the camera;
  - determining, by the computing device, a movement of the camera to a second pose at a second location in the set of spatial coordinates, wherein the movement to the second pose changes at least one of orientation or position of the camera with respect to the projector;
  - determining, by the computing device, a second perspective of the projection surface from the camera, wherein the second perspective corresponds to the second pose of the camera at the second location; and
  - updating, by the computing device, the graphic content so as to maintain a three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the camera changes from the first perspective to the second perspective.
2. The method of claim **1**, wherein the camera is coupled to a robotic arm, and wherein causing the movement of the camera to the second pose at the second location in the set of spatial coordinates comprises operating the robotic arm to move the camera to the second location.
3. The method of claim **1**, further comprising:
  - in order to maintain the three-dimensional effect of the projection of the graphic content on the projection surface, causing a movement of the projector in conjunction with the updating of the graphic content.
4. The method of claim **3**, wherein the projector is coupled to a robotic arm, and wherein causing the movement of the

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projector comprises operating the robotic arm to move the projector within the set of spatial coordinates.

5. The method of claim 1, wherein the projection surface is coupled to a robotic arm, the method further comprising: causing a movement of the projection surface comprises operating the robotic arm to move the projector within the set of spatial coordinates, such that perspective of the projection surface from the camera changes; and updating the graphic content so as to maintain a three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the camera changes due to movement of the projection surface.

6. A system comprising:

at least one projector located in an environment;

a projection surface located in the environment and coupled to a first device actor, wherein the first device actor is configured to move the projection surface through a set of spatial coordinates in the environment;

a camera located in the environment and coupled to a second device actor, wherein the camera is configured to capture image data of the environment or portions thereof as the projection surface moves through the set of spatial coordinates in the environment, and wherein the second device actor is configured to move the camera independently from the projector, through at least a portion of the set of spatial coordinates; and

a control system configured to:

(i) when the camera has a first pose at a first location in the set of spatial coordinates, cause the projector to render graphic content such that a three-dimensional effect of the projection of the graphic content on the projection surface corresponds to a first perspective of the projection surface from the first pose of the camera;

(ii) cause a movement of the camera to a second location in the set of spatial coordinates, which changes the position of the camera with respect to the projector;

(iii) determine a second perspective of the projection surface from the camera, wherein the second perspective corresponds to a second pose of the camera at the second location; and

(iv) coordinate an update of the graphic content so as to maintain the three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the camera changes from the first perspective to the second perspective of the projection surface from the camera.

7. A computer-implemented method comprising:

determining, by a computing device, a first pose of a camera with respect to a projection surface that is located at a first location in a set of spatial coordinates, wherein the camera is moveable through at least a portion of the set of spatial coordinates independently from a projector;

when the camera has the first pose with respect to the projection surface, causing a projector to render graphic content such that a three-dimensional effect of a projection of the graphic content on the projection surface corresponds to a first perspective of the projection surface from the first pose of the camera;

causing a movement of the projection surface a second location in the set of spatial coordinates, which changes the position of the camera with respect to the projector;

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determining, by the computing device, a second perspective of the projection surface from the camera, when the projection surface is at the second location; and

updating, by the computing device, the graphic content so as to maintain a three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the camera changes due to the movement of the projection surface.

8. The method of claim 7, wherein the projection surface is coupled to a robotic arm, and wherein causing the movement of the projection surface comprises operating the robotic arm to move the camera to the second location.

9. A method comprising:

determining, by a computing system, a first pose of a device with respect to a projection surface, wherein the projection surface is coupled to a first device actor such that the projection surface is movable through a set of spatial coordinates, and wherein the device is movable through at least a portion of the set of spatial coordinates independently from the projector;

when the device has a first pose at a first location in the set of special coordinates, causing the projector to render graphic content such that a three-dimensional effect of the projection of the graphic content on the projection surface corresponds to a first perspective of the projection surface from the first pose of the device; determining, by the computing system, a movement of the device to a second pose, which changes at least one of orientation or position of the device with respect to the projector;

determining, by the computing system, a second perspective of the projection surface from the device, wherein the second perspective corresponds to the second pose of the device; and

updating, by the computing device, the graphic content so as to maintain a three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the device changes from the first perspective to the second perspective.

10. The method of claim 9, further comprising, the control system computing system periodically:

re-determining pose of the device;

re-determining, based at least in part on the re-determined pose, the perspective of the projection surface that is associated with the device; and

initiating a process to render the graphic content in accordance with the re-determined perspective of the projection surface.

11. The method of claim 9, wherein the projection surface is a first projection surface; the method further comprising the computing system simultaneously performing the method of claim 9 to determine a respective perspective of each of two or more projection surfaces from the device, and to render respective graphic content for projection onto each of the two or more projection surfaces in accordance with the respectively associated perspective, wherein the two or more projection surfaces comprise the first projection surface and at least one other projection surface.

12. A system comprising:

a projection surface located in an environment and coupled to a first device actor, wherein the first device actor is configured to move the projection surface through a set of spatial coordinates in the environment;

a projector located in the environment;

a device located in the environment and moveable independently from the projector through at least a portion

of the set of spatial coordinates, wherein a pose of the device defines a perspective of the projection surface from the device; and

a control system configured to:

when the device has a first pose at a first location in the set of special coordinates, cause the projector to render graphic content such that a three-dimensional effect of the projection of the graphic content on the projection surface corresponds to a first perspective of the projection surface from the first pose of the device;

determine a movement of the device to a second pose, which changes at least one of orientation or position of the device with respect to the projector;

determine a second perspective of the projection surface from the device, wherein the second perspective corresponds to the second pose of the device; and coordinate an update of the graphic content so as to maintain the three-dimensional effect of the projection of the graphic content on the projection surface as perspective of the projection surface from the device changes from the first perspective to the second perspective.

13. The system of claim 12, wherein the device comprises a camera configured to capture image data of the at least one projection surface as the projection surface moves through the set of spatial coordinates, wherein the camera is coupled to a second device actor that is configured to move the camera through the set of spatial coordinates.

14. The system of claim 13, wherein a perspective of the projection surface from the camera changes according to

movement of at least one of the camera and the projection surface, and wherein the control system graphic content is rendered such that the projection of the graphic content changes over time such that the graphic content is directed to the perspective from the camera as the camera moves and/or the projection surface moves.

15. The system of claim 13, wherein the pose of the camera at a given time comprises coordinates of the camera, within the set of spatial coordinates, at the given time.

16. The system of claim 13, wherein the pose of the camera at a given time comprises an orientation of the camera at the given time.

17. The system of claim 12, wherein the control system is further configured to periodically:

determine a current perspective of the projection surface, which is associated with the device; and

cause the projector to update the rendered graphic content in accordance with the current perspective of the projection surface.

18. The system of claim 12, wherein the device comprises a wearable computing device, and wherein the perspective of the projection surface that is associated with the device comprises a perspective of a wearer of the wearable computing device.

19. The system of claim 18, wherein the wearable computing device is a head-mountable device (HMD).

20. The system of claim 18, wherein the wearable computing device is a mobile phone.

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