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Walker et al.

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(54) RENDERING IMAGES FOR NON-STANDARD DISPLAY DEVICES

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G06T 3/08	(2024.01)
G06T 15/20	(2011.01)
G06T 15/50	(2011.01)

(52) **U.S. Cl.**
CPC ***G06T 15/06*** (2013.01); ***G06T 3/08*** (2024.01); ***G06T 15/20*** (2013.01); ***G06T 15/50*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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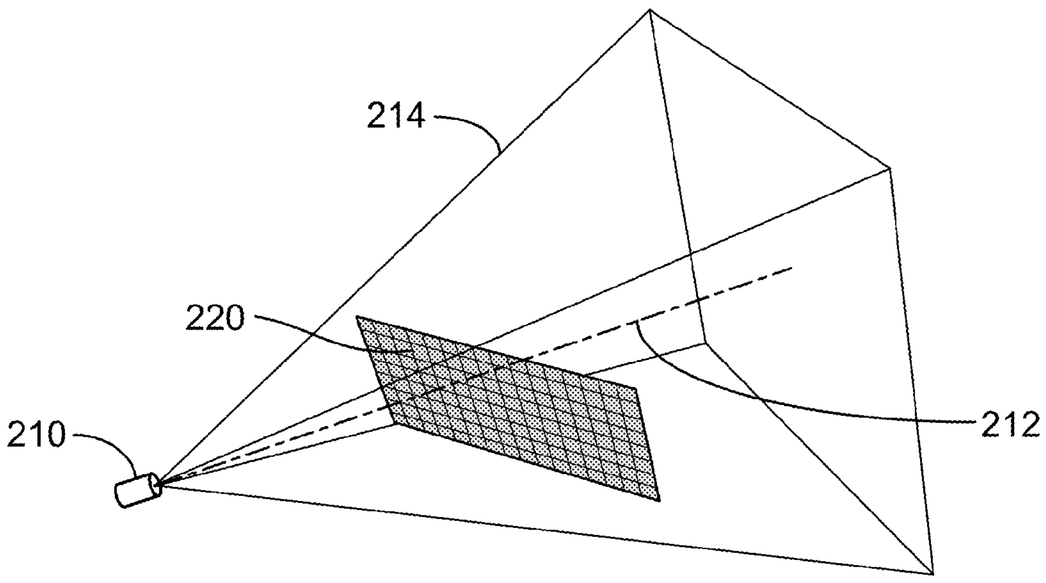
(57) ABSTRACT

A method of rendering an image includes receiving information of a virtual camera, including a camera position and a camera orientation defining a virtual screen; receiving information of a target screen, including a target screen position and a target screen orientation defining a plurality of pixels, each respective pixel corresponding to a respective UV coordinate on the target screen; for each respective pixel of the target screen: determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate; tracing one or more rays from the virtual camera through the corresponding point on the virtual screen toward a virtual scene; and estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

22 Claims, 15 Drawing Sheets



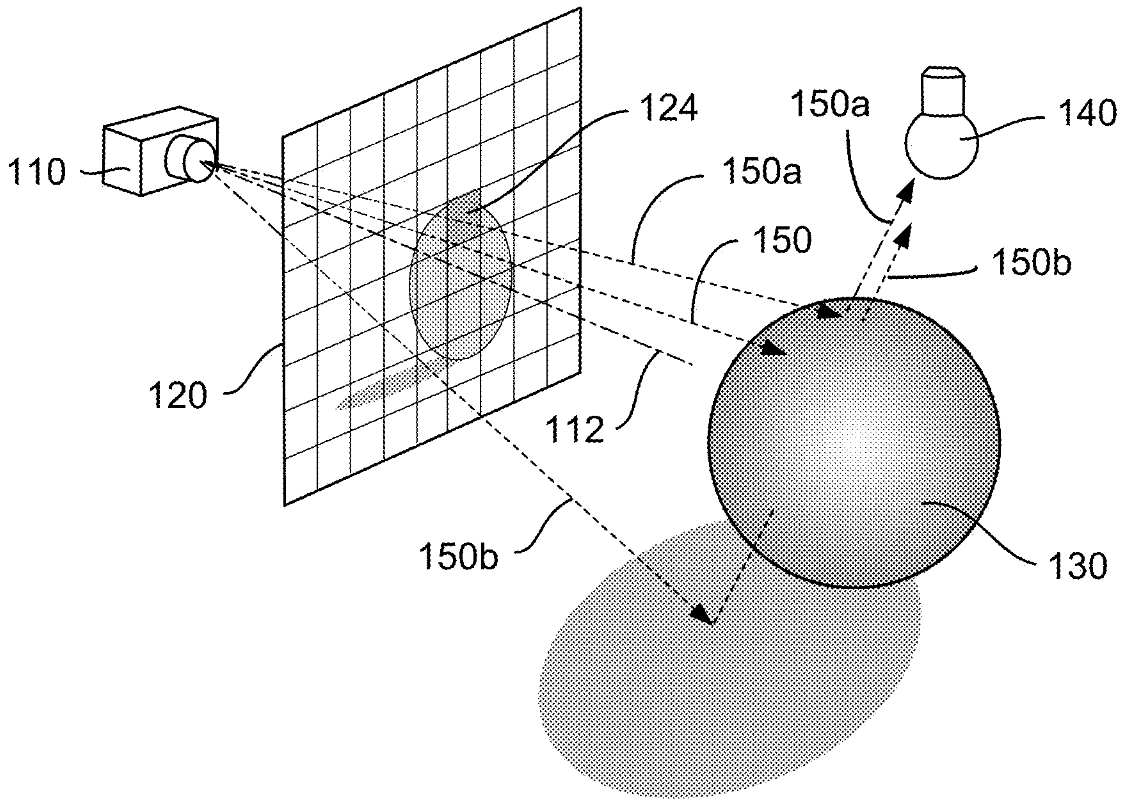


FIG. 1

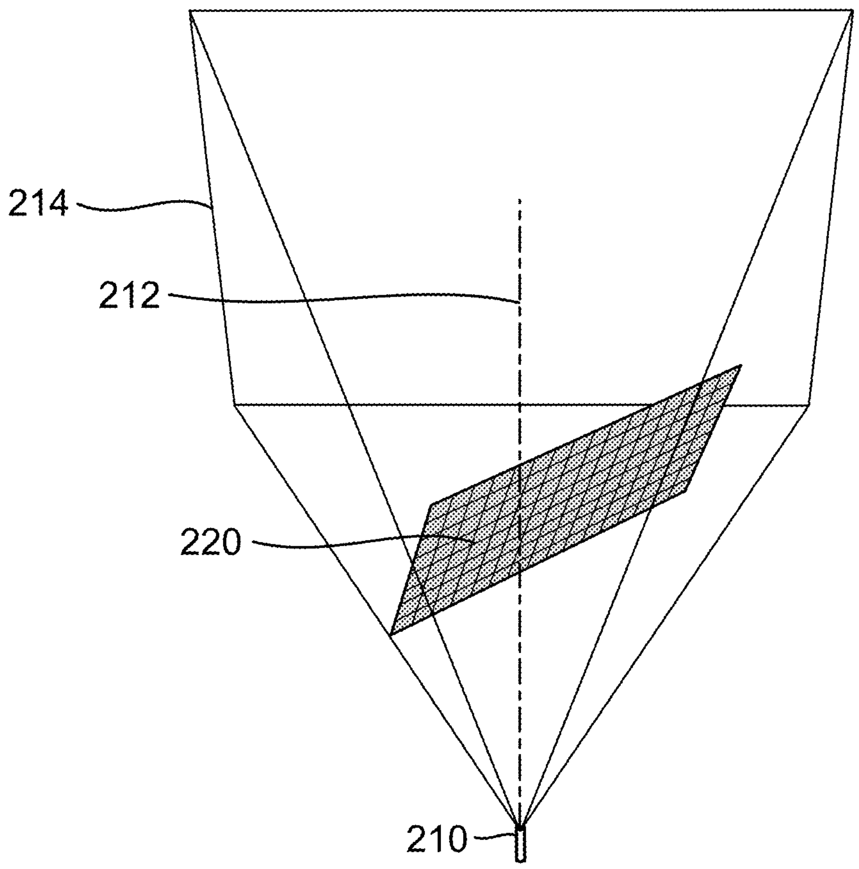


FIG. 2A

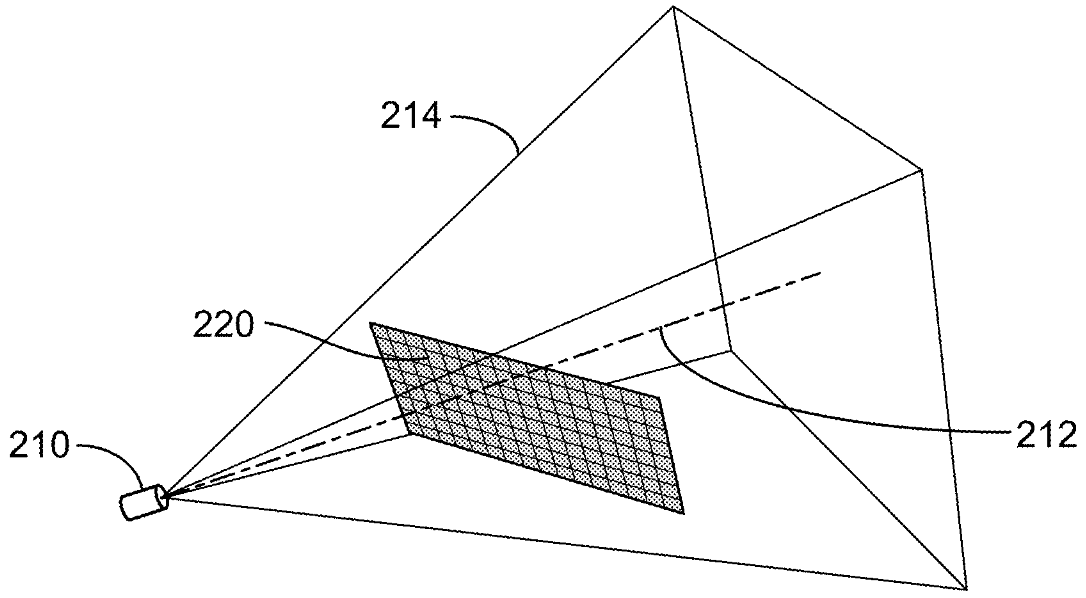


FIG. 2B

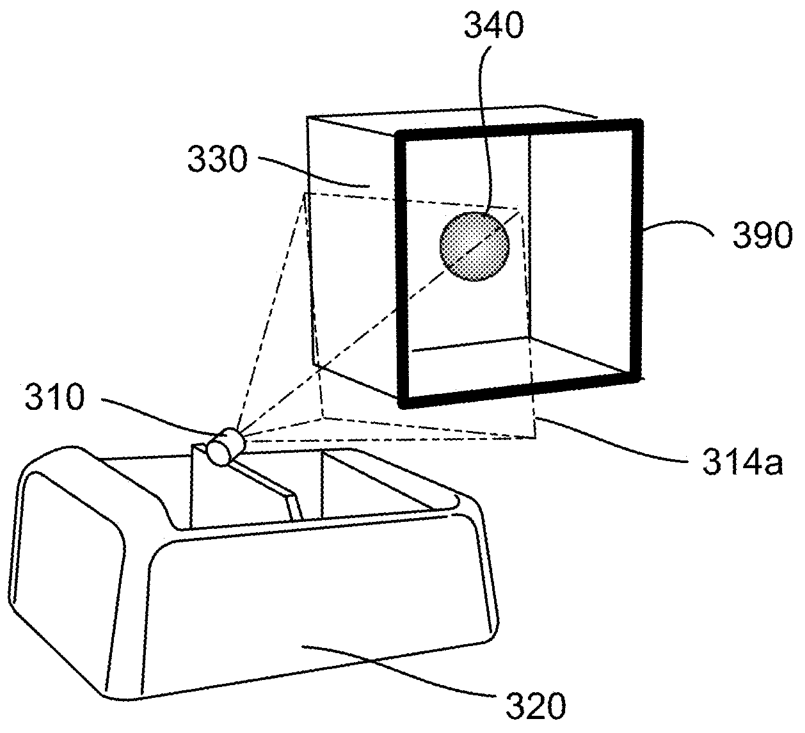


FIG. 3A

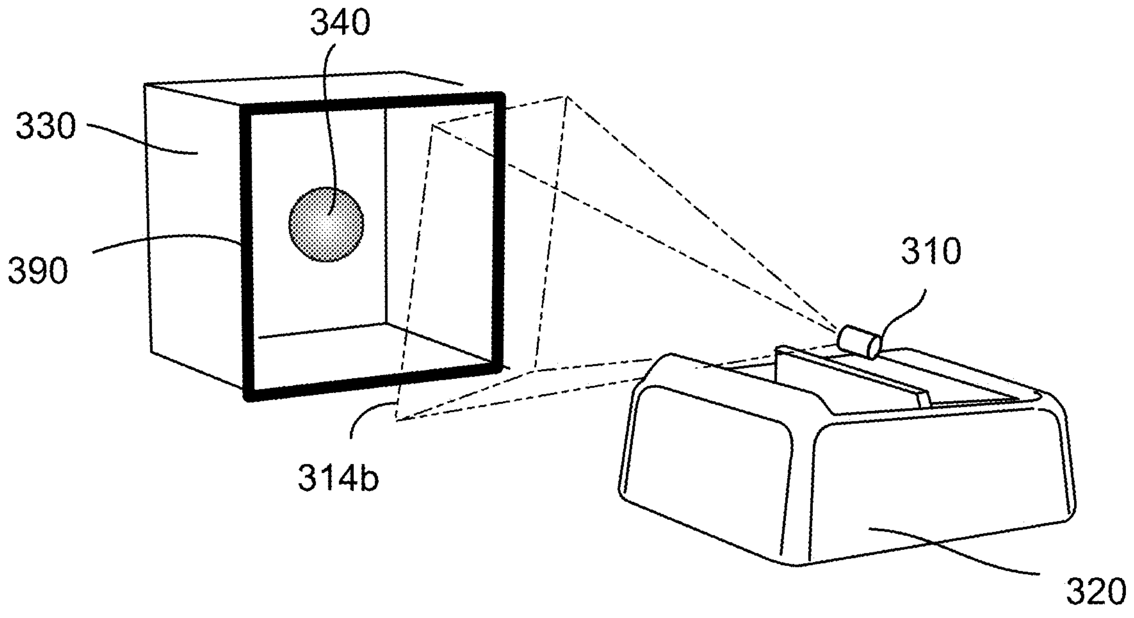


FIG. 3B

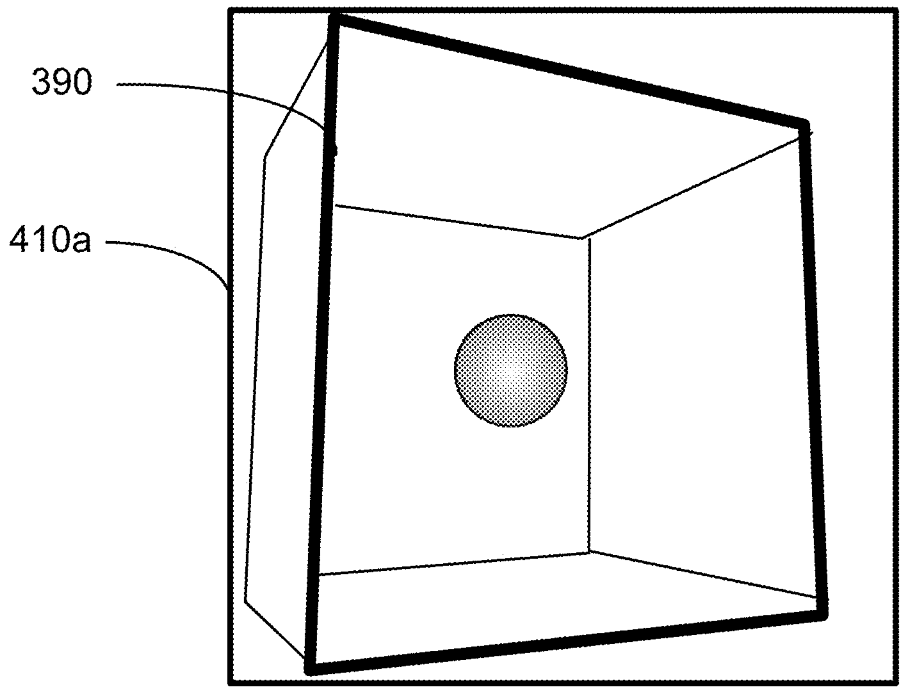


FIG. 4A

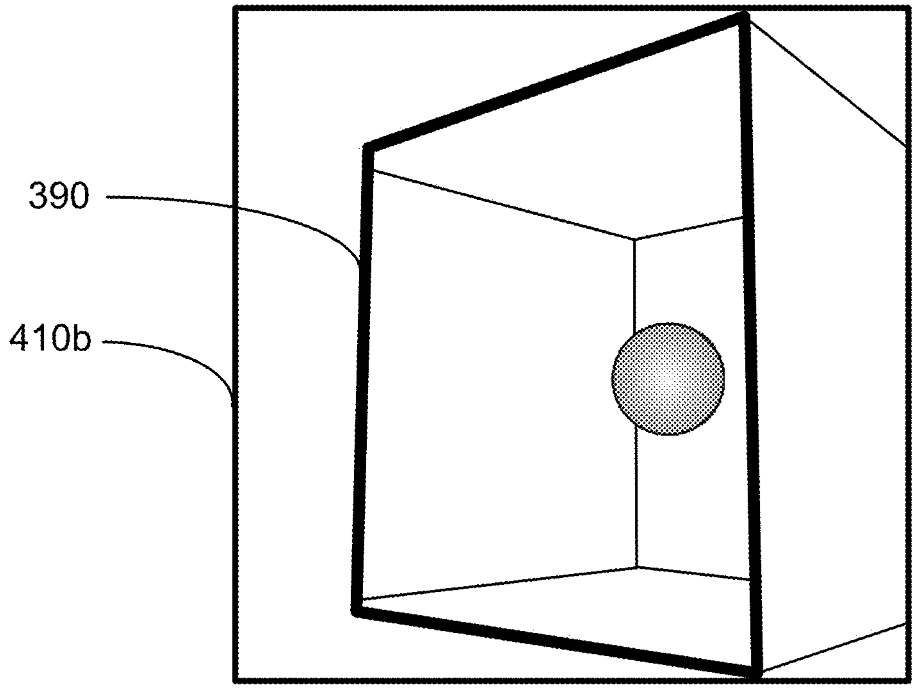


FIG. 4B

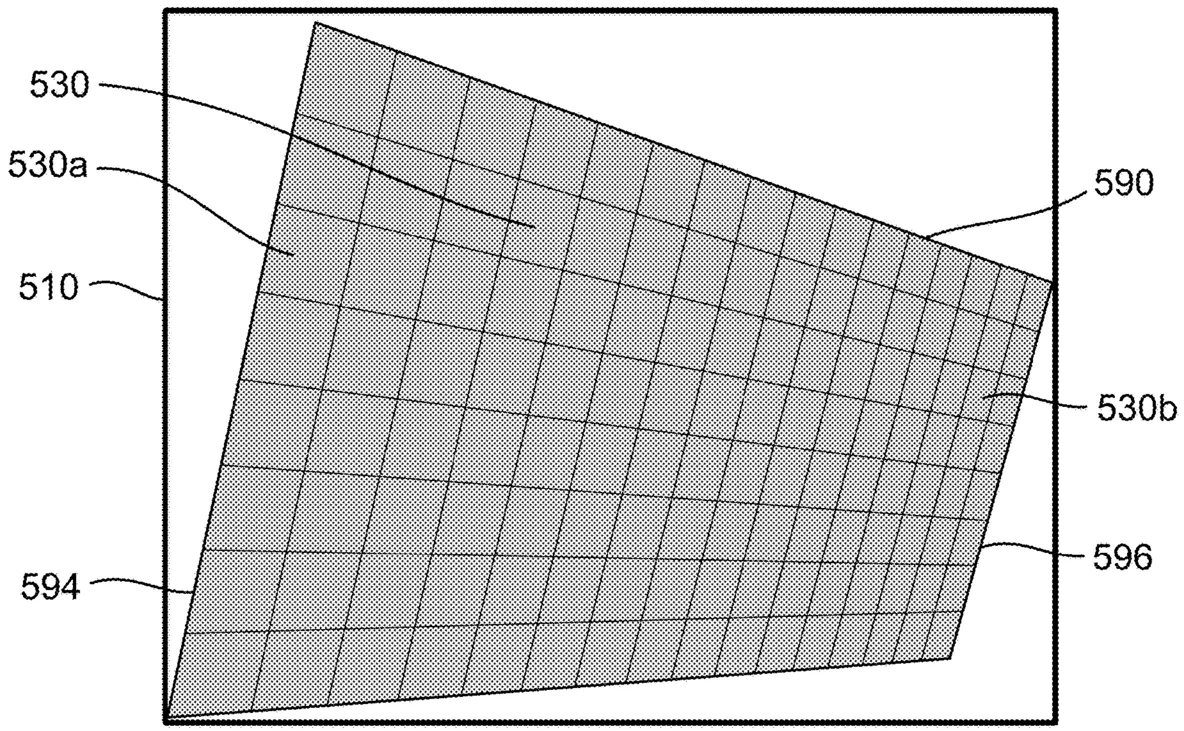


FIG. 5A

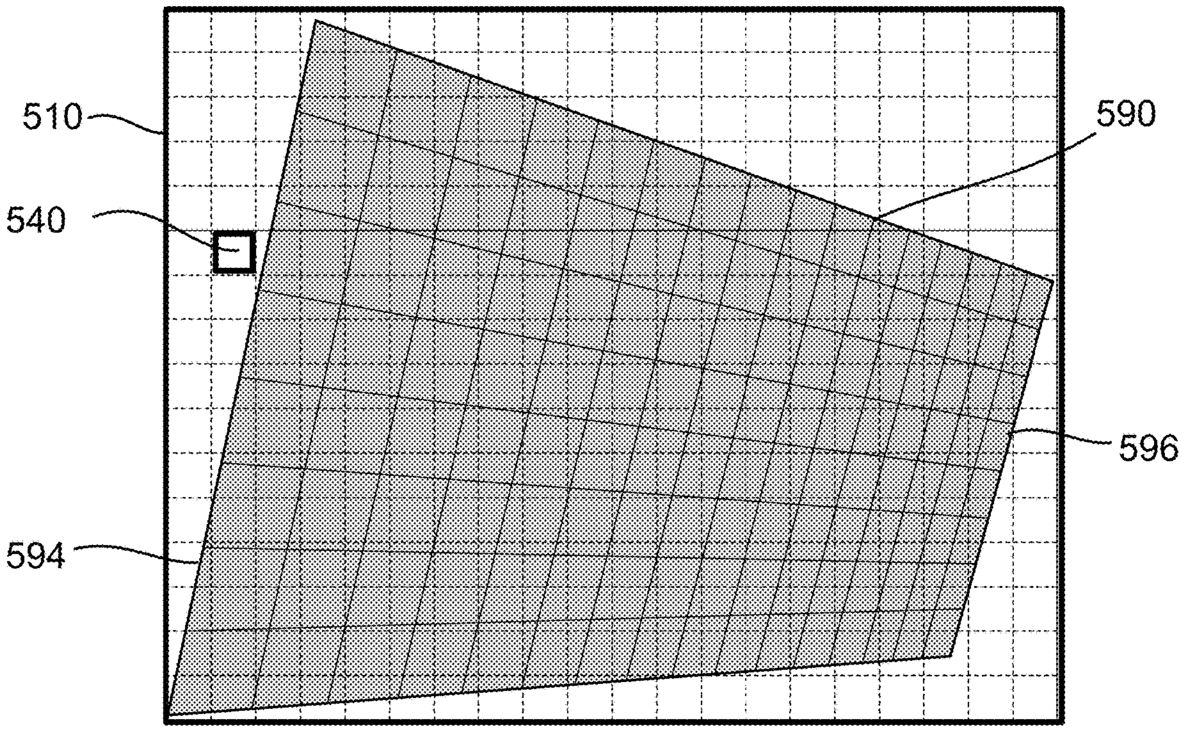


FIG. 5B

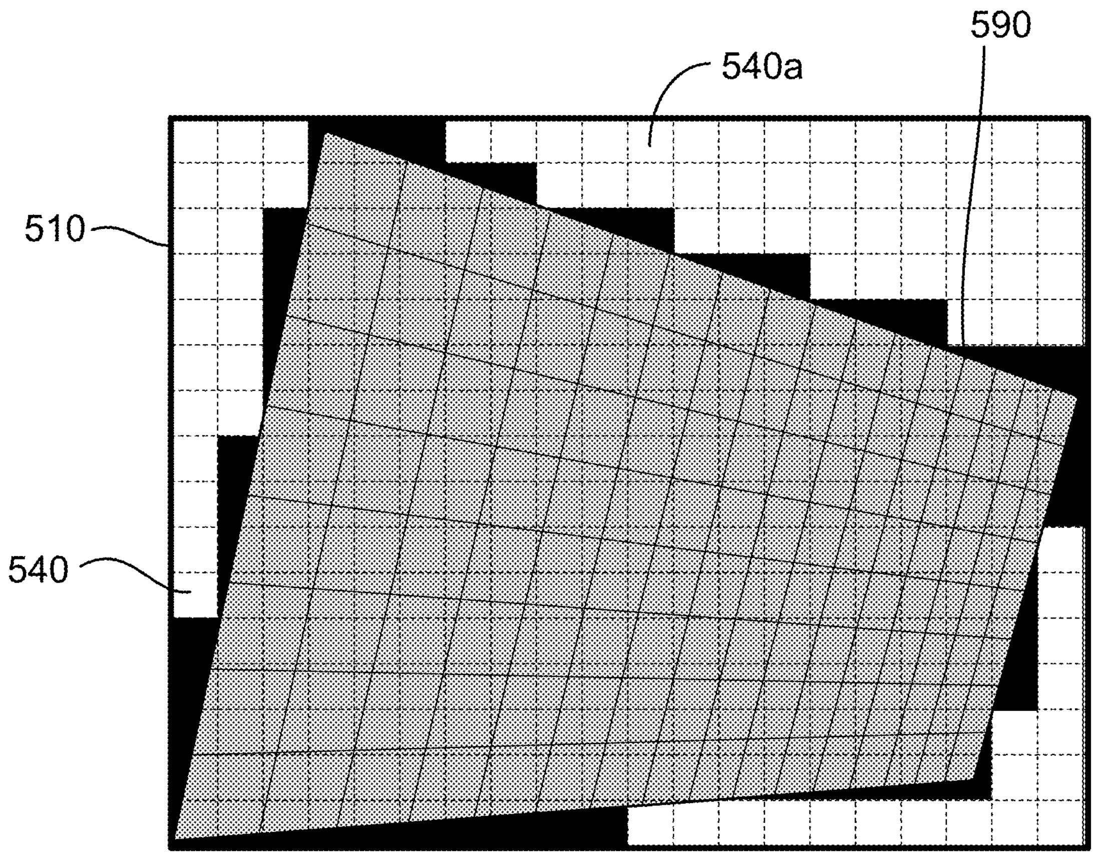


FIG. 5C

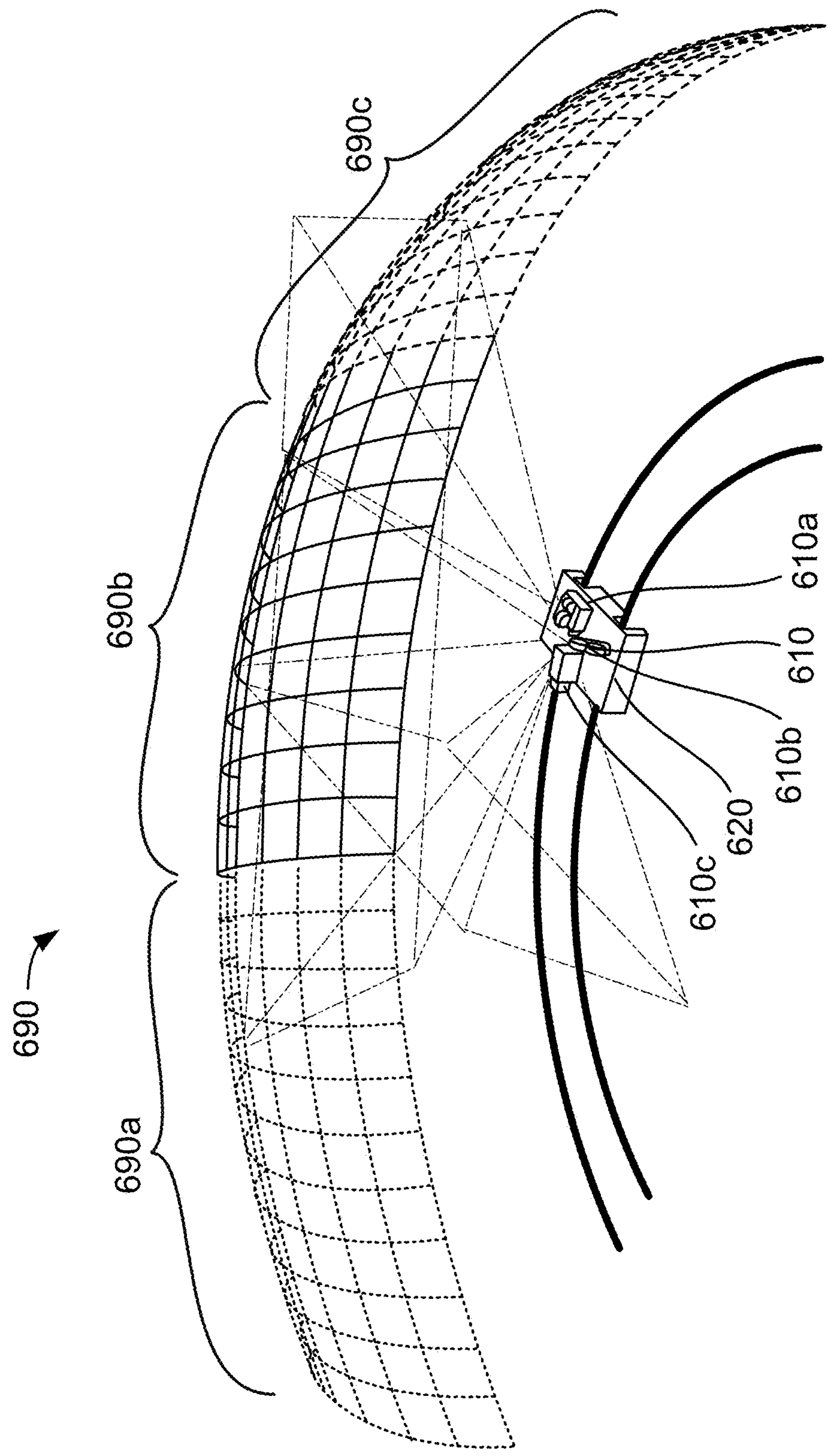


FIG. 6

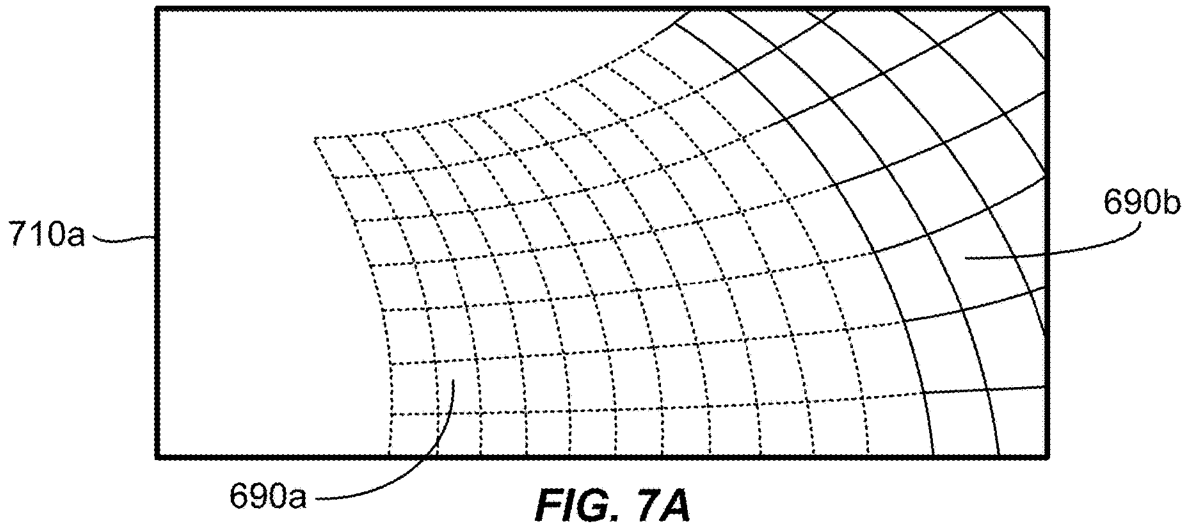


FIG. 7A

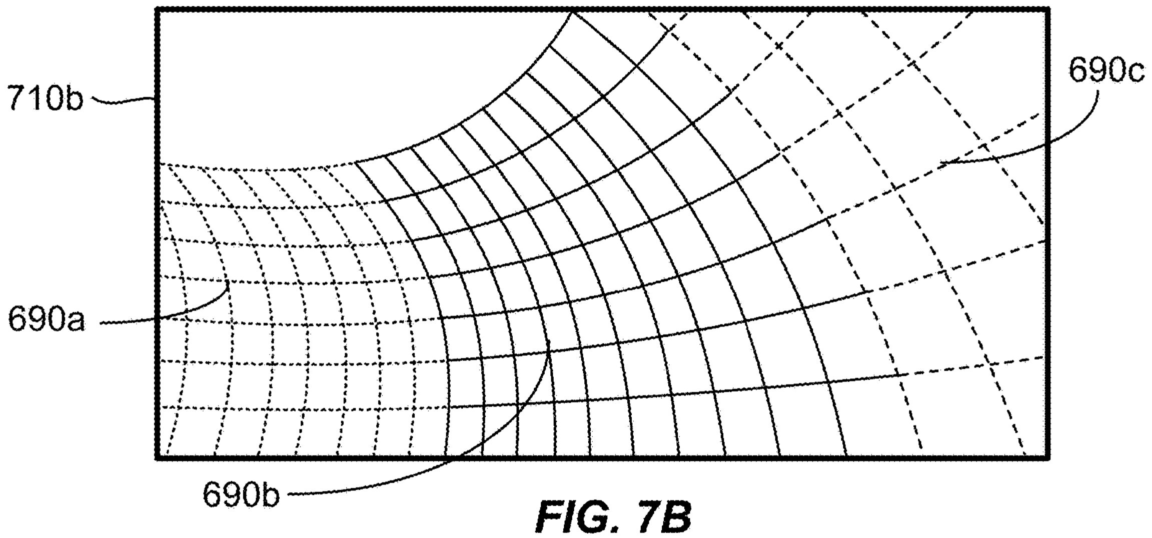


FIG. 7B

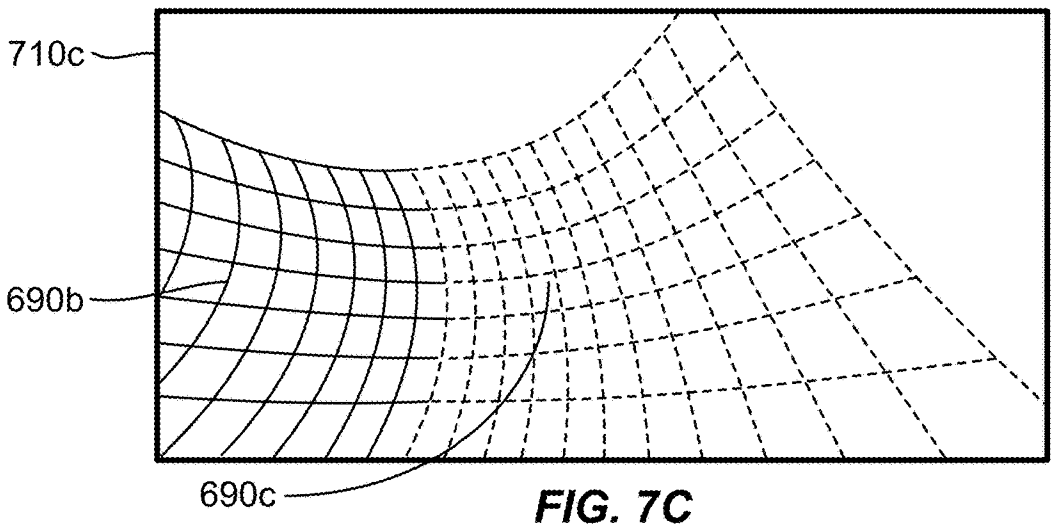


FIG. 7C

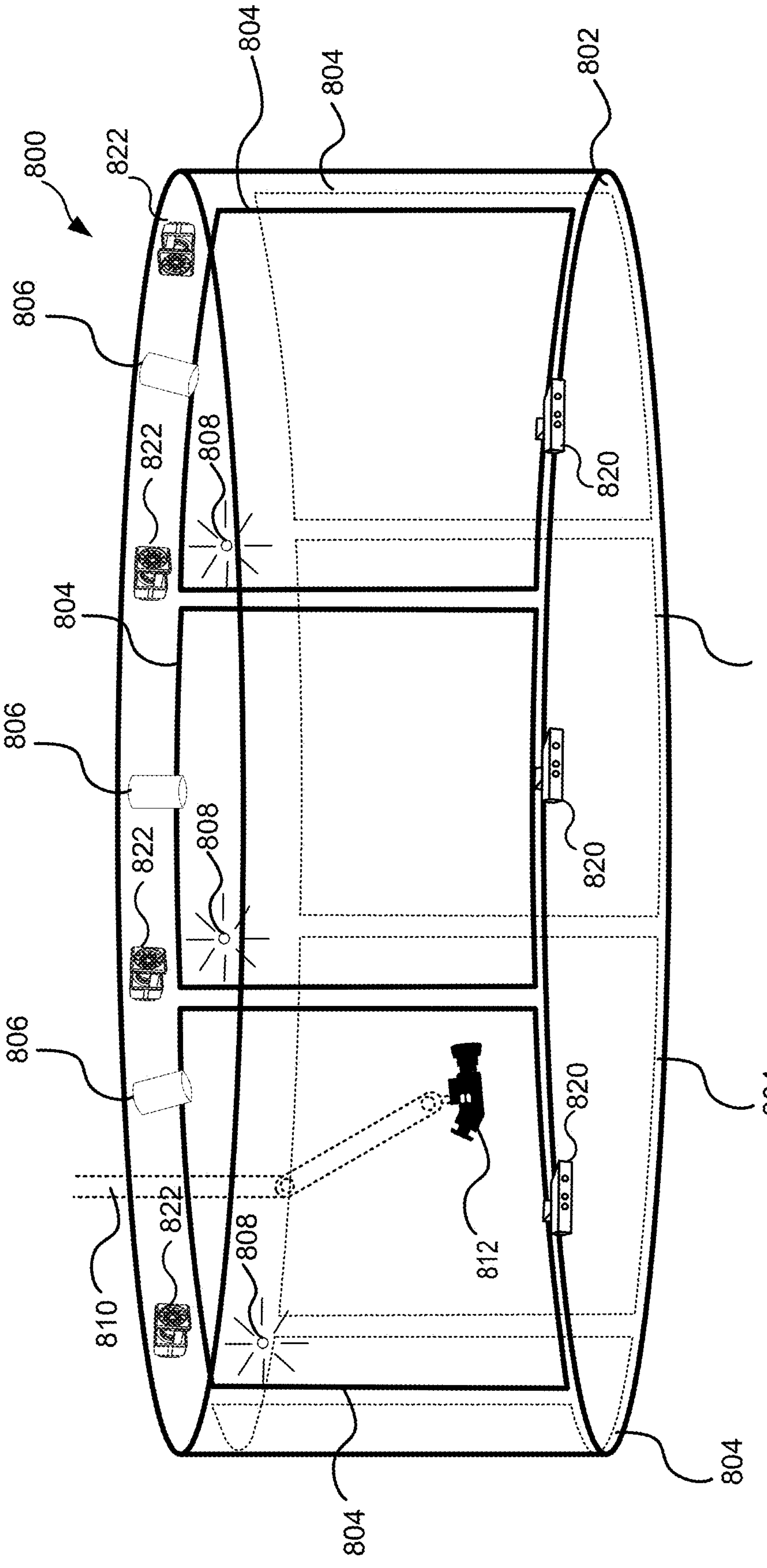


FIG. 8

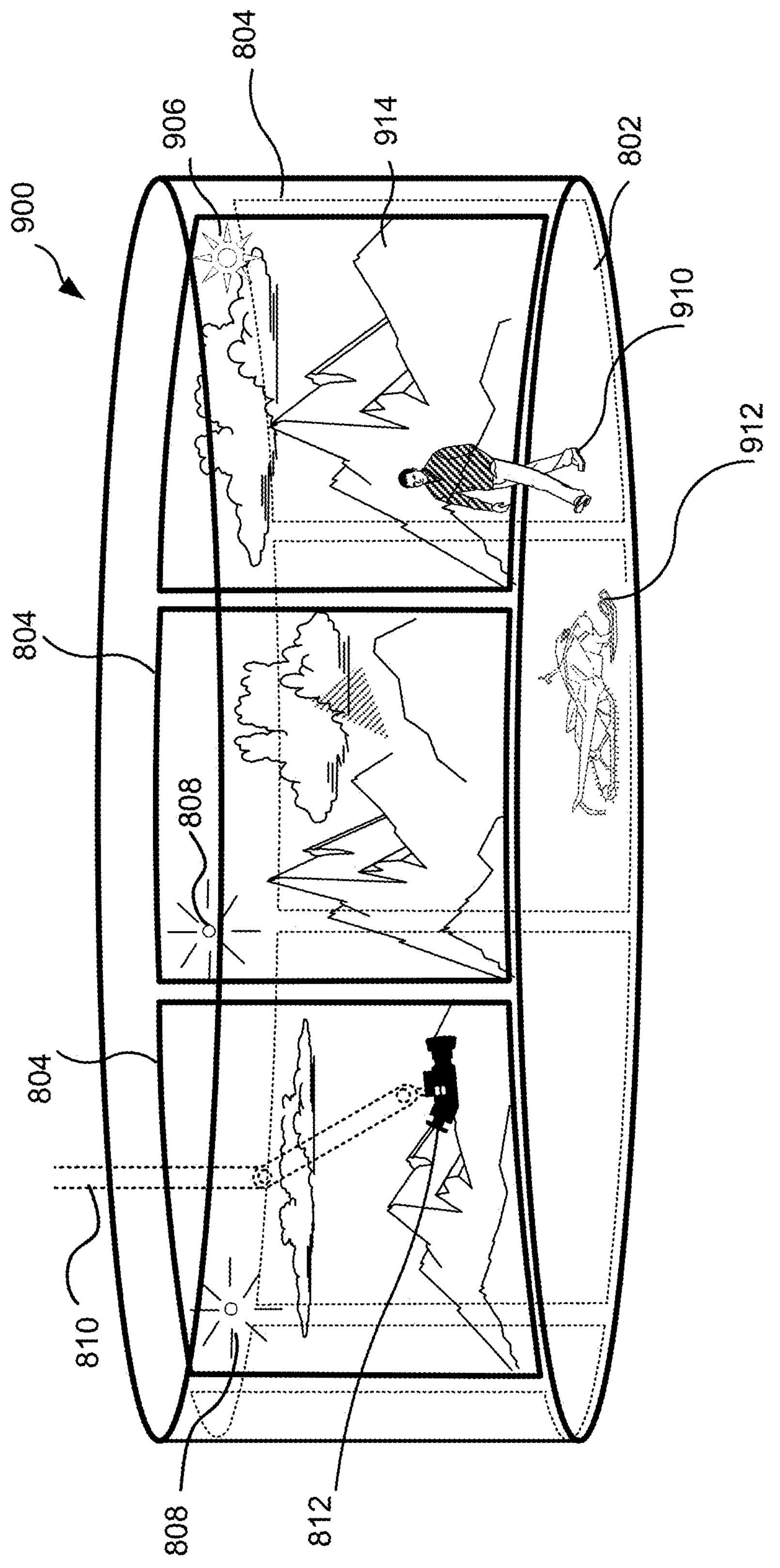


FIG. 9

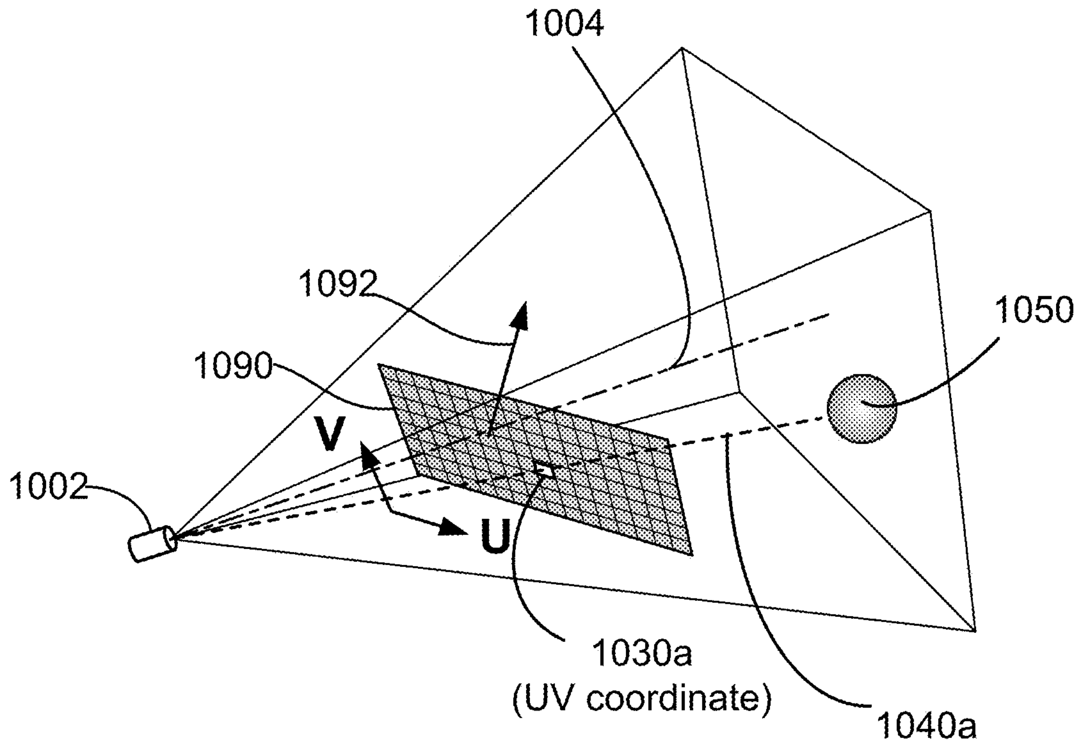


FIG. 10A

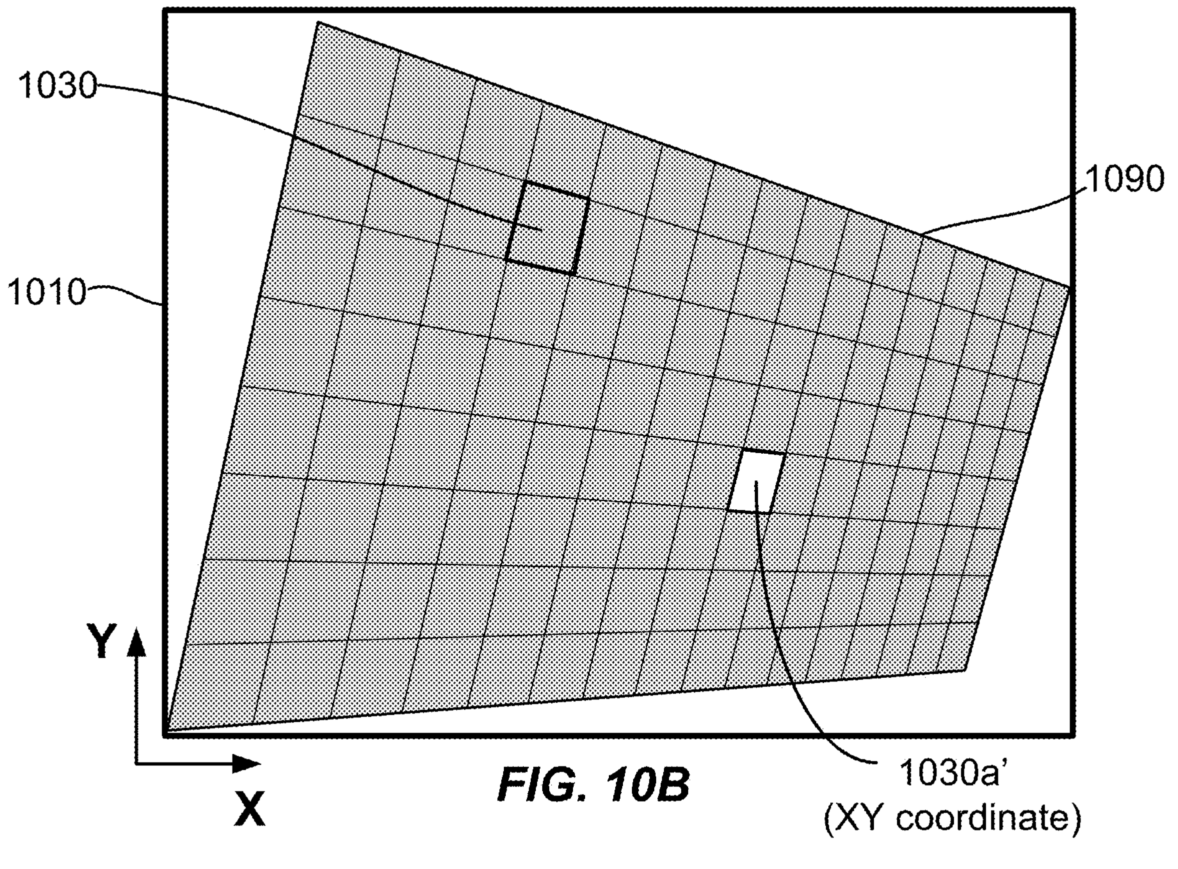


FIG. 10B

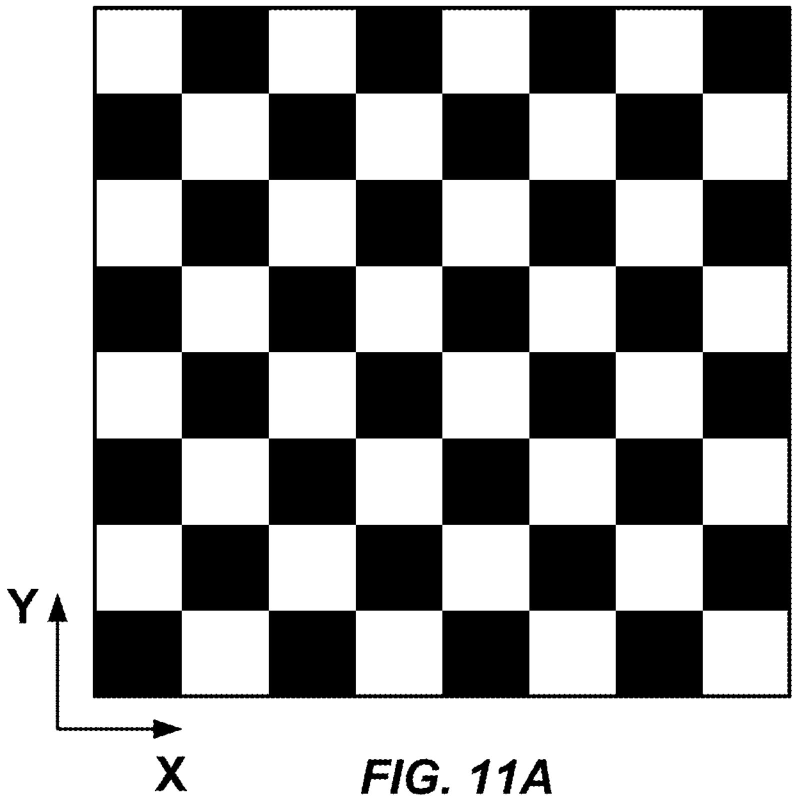


FIG. 11A

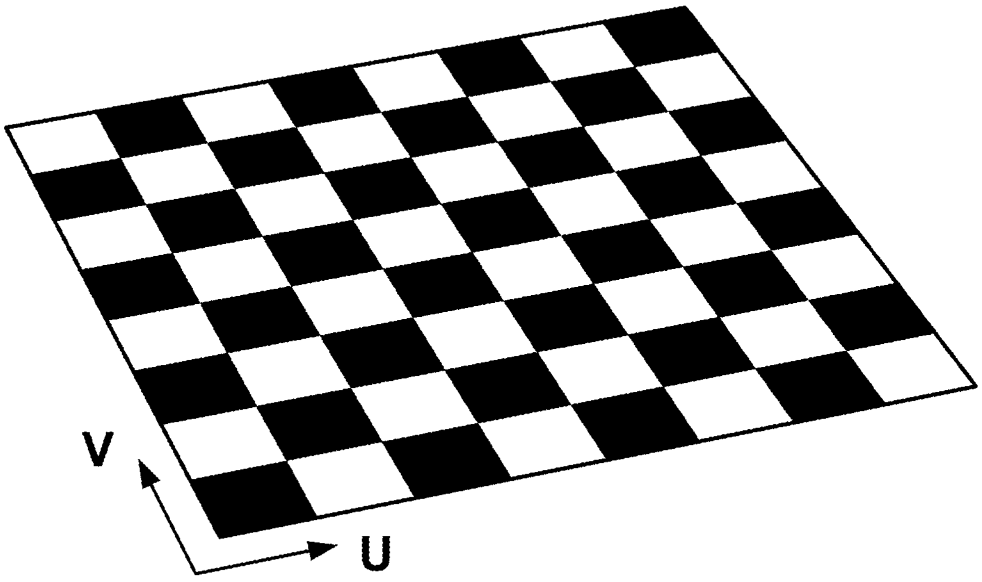


FIG.11B

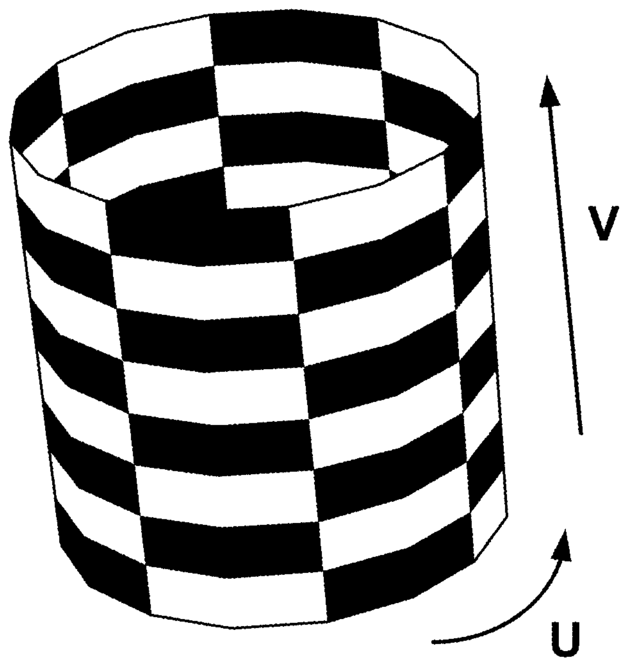


FIG. 11C

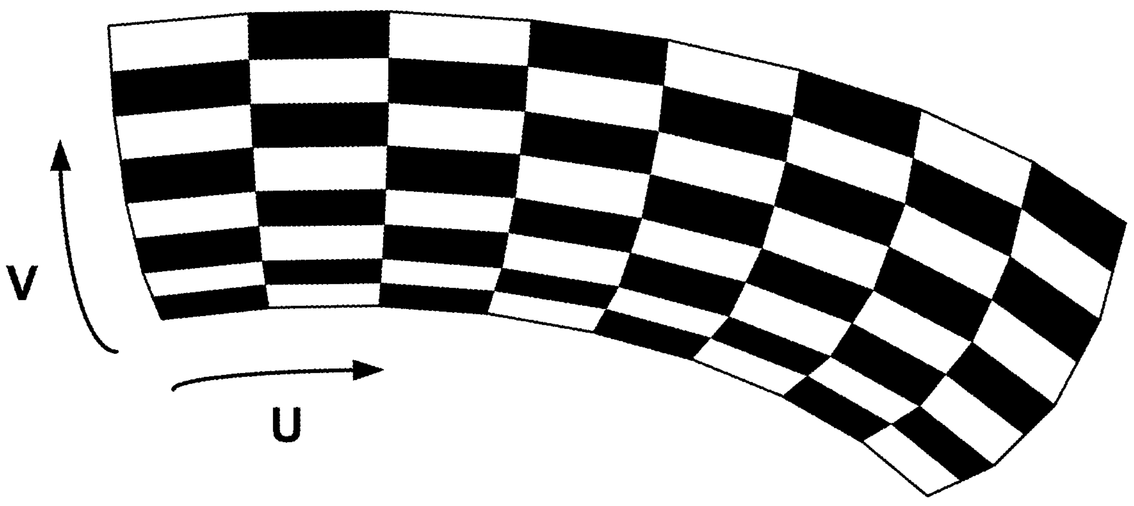
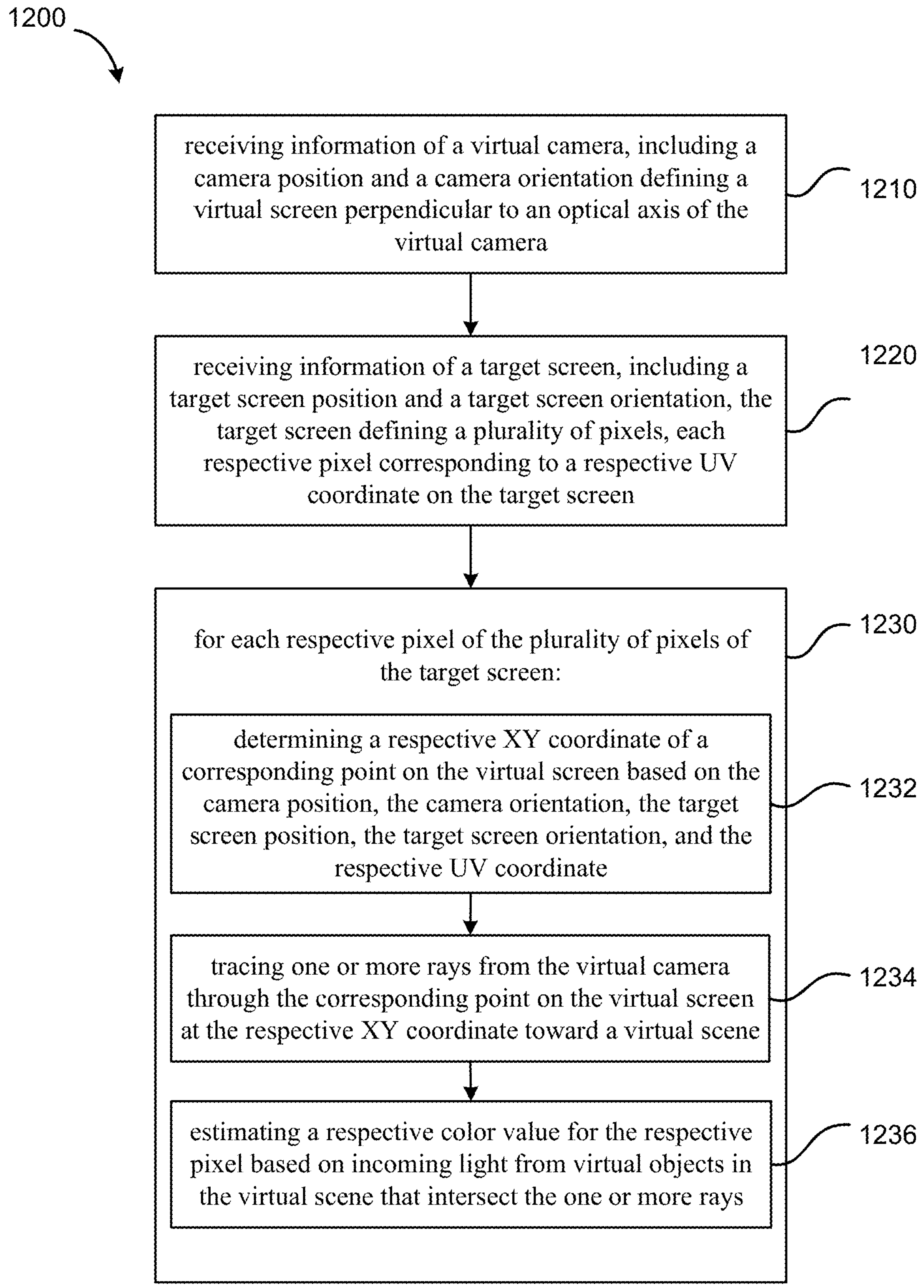


FIG. 11D



receiving information of a virtual camera, including a camera position and a camera orientation defining a virtual screen perpendicular to an optical axis of the virtual camera

receiving information of a target screen, including a target screen position and a target screen orientation, the target screen defining a plurality of pixels, each respective pixel corresponding to a respective UV coordinate on the target screen

for each respective pixel of the plurality of pixels of the target screen:

determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate

tracing one or more rays from the virtual camera through the corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene

estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays

FIG. 12

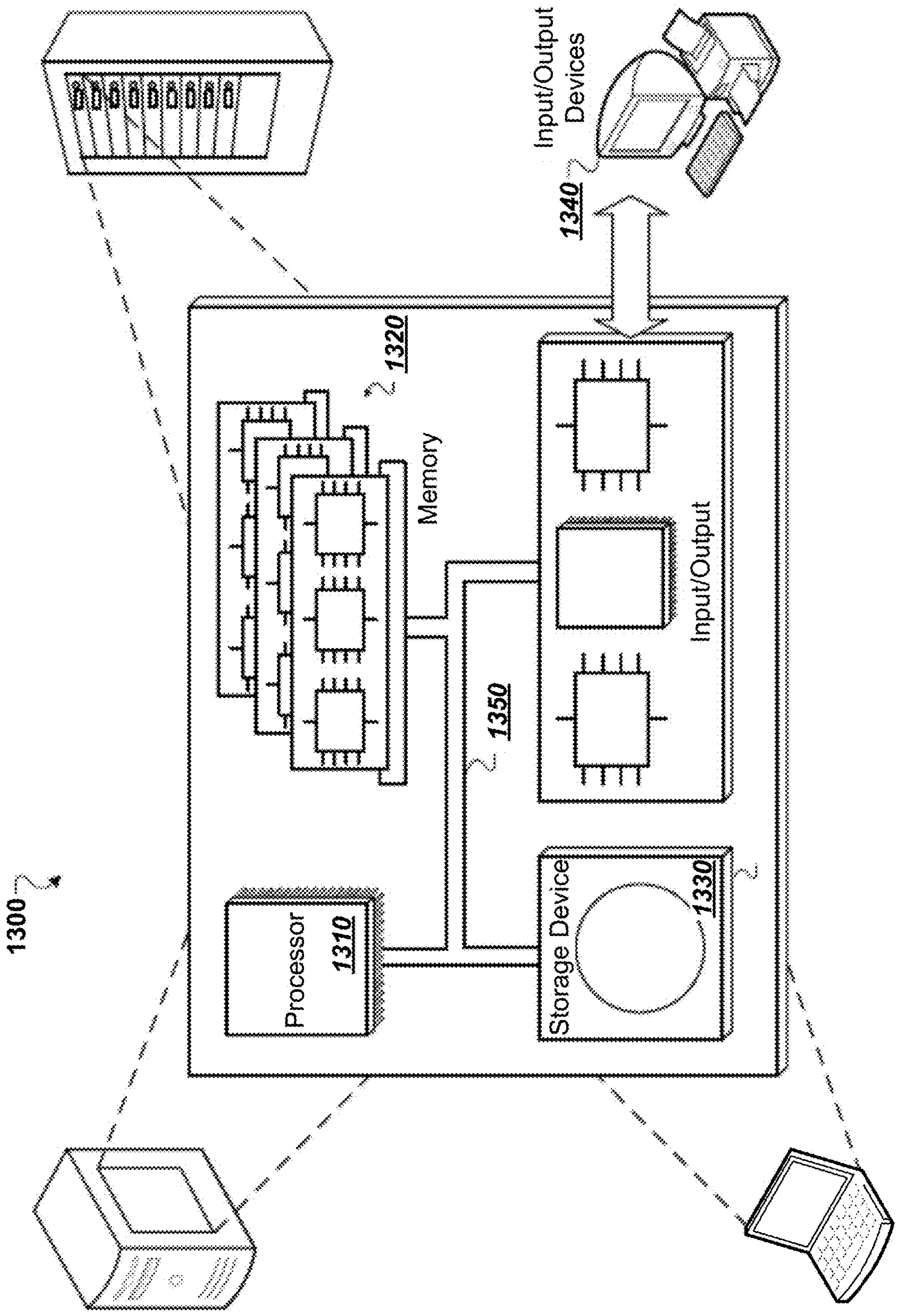

1300
Processor
1310
Memory
1320
Storage Device
1330
Input/Output
1340
Input/Output Devices
1350

FIG. 13

RENDERING IMAGES FOR NON-STANDARD DISPLAY DEVICES

BACKGROUND

In computer graphics, ray tracing is a rendering technique for generating an image by tracing the path of light as pixels in an image plane and simulating the effects of its encounters with virtual objects. Ray tracing is capable of producing a higher degree of visual realism than other rendering techniques (e.g., scanline rendering methods), but at a greater computational cost. Rendering by ray tracing for certain types of display screens (e.g., large screens, oddly shaped screens, and the like) can present particular challenges. Therefore, improved rendering techniques are needed.

SUMMARY

According to some embodiments, a method of rendering an image by ray tracing includes receiving information of a virtual camera. The information of the virtual camera includes a camera position and a camera orientation, which define a virtual screen perpendicular to an optical axis of the virtual camera. The method further includes receiving information of a target screen. The information of the target screen includes a target screen position and a target screen orientation. The target screen defines a plurality of pixels. Each respective pixel corresponds to a respective UV coordinate on the target screen. The method further includes, for each respective pixel of the plurality of pixels of the target screen: determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate; tracing one or more rays from the virtual camera through the corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

According to some embodiments, a computer product includes a non-transitory computer readable medium storing a plurality of instructions that, when executed, control a computer system to render an image by ray tracing. The instructions include receiving information of a virtual camera. The information of the virtual camera includes a camera position and a camera orientation, which define a virtual screen perpendicular to an optical axis of the virtual camera. The instructions further include receiving information of a target screen. The information of the target screen includes a target screen position and a target screen orientation. The target screen defines a plurality of pixels. Each respective pixel corresponds to a respective UV coordinate on the target screen. The instructions further include, for each respective pixel of the plurality of pixels of the target screen: determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate; tracing one or more rays from the virtual camera through the corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

According to some embodiments, a computer system includes one or more processors, and a non-transitory computer readable medium storing a plurality of instructions that, when executed, control the one or more processors to render an image by ray tracing. The instructions include receiving information of a virtual camera. The information of the virtual camera includes a camera position and a camera orientation, which define a virtual screen perpendicular to an optical axis of the virtual camera. The instructions further include receiving information of a target screen. The information of the target screen includes a target screen position and a target screen orientation. The target screen defines a plurality of pixels. Each respective pixel corresponds to a respective UV coordinate on the target screen. The instructions further include, for each respective pixel of the plurality of pixels of the target screen: determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate; tracing one or more rays from the virtual camera through the corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of rendering by ray tracing.

FIGS. **2**A and **2**B illustrate an example of a virtual screen that is not perpendicular to the optical axis of a virtual camera.

FIGS. **3**A and **3**B illustrate an example of rendering images to be viewed from moving eye points, in which non-standard display screens can be encountered.

FIGS. **4**A and **4**B illustrate virtual screens for an eye-point camera that can be used for rendering images in the example illustrated in FIGS. **3**A and **3**B.

FIGS. **5**A-**5**C illustrate a conventional method of rendering an image for a non-standard display screen.

FIG. **6** illustrates another example in which a non-standard display screen can be encountered.

FIGS. **7**A-**7**C show the three sections of the dome display screen shown in FIG. **6**, as seen by each respective camera.

FIGS. **8** and **9** illustrate simplified immersive content production systems.

FIGS. **10**A and **10**B illustrate a method of rendering an image by ray tracing for a non-standard display screen according to some embodiments.

FIGS. **11**A-**11**D illustrate UV-XY mapping.

FIG. **12** shows a simplified flowchart illustrating a method of rendering an image for a display screen by ray tracing according to some embodiments.

FIG. **13** shows a schematic diagram of an example of a computer system.

DETAILED DESCRIPTION

Ray tracing can involve tracing a path from an imaginary eye (or a virtual camera) through each pixel in a virtual screen, and calculating the color of the object visible through the pixel. FIG. **1** illustrates a ray tracing example. In this example, the virtual object **130** is a ball, which is in the field of view of a virtual camera **110**. A virtual screen **120** is in front of the virtual camera **110**. In this example, the virtual screen **120** is rectangular and is substantially perpendicular to the optical axis **112** of the virtual camera **110**. For example, the virtual screen **120** can be a viewing frustum of the virtual camera **110**. The virtual screen **120** includes regular grids of pixels **124**.

To render an image of the virtual scene on the virtual screen **120**, rays **150** can be launched from the virtual camera **110** through the pixels **124** of the virtual screen **120** toward the virtual scene. Some rays (e.g., the ray **150***a*) can be bounced off the surfaces of some objects (e.g., the surface of the ball **130**) and toward light sources (e.g., the light source **140**). Color values can be estimated for the pixels, for example, based on the material properties of the objects at the points of intersection. Some rays (e.g., the ray **150***b*) bounced off a surface of an object can be blocked by other objects (e.g., the ball **130**) toward a light source (e.g., the light source **140**), resulting in a shadow on the surface.

In some cases, each ray can be tested for intersection with some subset of all the virtual objects in the virtual scene. Once the nearest virtual object has been identified, the algorithm can estimate the incoming light at the point of intersection, examine the material properties of the virtual object, and combine this information to calculate the final color of the pixel.

In some situations, it can be necessary or advantageous to have a virtual screen that is not rectangular and/or not perpendicular to the optical axis of the virtual camera. FIGS. **2**A and **2**B illustrate an example. FIG. **2**A shows a virtual screen **220** as looking straight ahead into a viewing frustum **214** (e.g., field of view) of a virtual camera **210**; and FIG. **2**B shows a perspective view. As illustrated, the virtual screen **220** is not perpendicular to the optical axis **212** of the virtual camera **210**. Herein, the term non-standard display screens can refer to oddly shaped and/or oddly oriented display screens, as well as curved display screens and large-sized display screens.

Non-standard screens can be encountered, for example, in renderings to be viewed from moving eye-points (e.g., in three-dimensional or 3D rides in theme parks, immersive environments used in virtual content production, etc.). FIGS. **3**A and **3**B illustrate an example. A rider is riding in a vehicle **320**, which is moving passed a screen **390**. FIG. **3**A shows the position of the vehicle **320** at a first instance of time before it past the screen **390**; and FIG. **3**B shows the position of the vehicle **320** at a second instance of time after it passed the screen **390**. One wishes to render images that can be mapped onto the screen **390** that can give the rider the illusion of a room **330** behind the screen **390** (illustrated as a box with a ball **340** inside).

To provide the rider a more realistic 3D experience, the image can be rendered from a moving point of perspective to match the movement of the vehicle **320** (and the rider). A virtual camera **310** can be placed at where the rider is. The virtual camera **310** can remain pointed at the screen **390** as the vehicle **320** moves past the screen **390**. For example, at the first instance of time, the viewing frustum **314***a* of the virtual camera **310** is directed at the screen **390** at a certain angle with respect to the screen **390**, as illustrated in FIG. **3**A; and at the second instance of time, the viewing frustum **314***b* of the virtual camera **310** is directed at the screen **390** at a different angle with respect to the screen **390** so as to follow the movement of the virtual camera **390**, as illustrated in FIG. **3**B. Such a virtual camera can be referred to herein as an "eye-point camera."

Conventionally, for a non-standard display screen, one may need to render an image on an oversized virtual screen that keeps the full display screen in-frame. FIGS. **4**A and **4**B illustrate two virtual screens **410***a* and **410***b* that can be used for rendering images in the example illustrated in FIGS. **3**A

and **3**B, respectively. As illustrated in FIG. **4**A, the virtual screen **410***a* is large enough to include the entire display screen **390** as viewed from the eye-point camera **310** at the first instance of time as shown in FIG. **3**A. In other words, the field of view of the virtual camera **310** needs to be wide enough to encompass the entire display screen **390**. Similarly, as illustrated in FIG. **4**B, the virtual screen **410***b* is large enough to include the entire display screen **390** as viewed from the eye-point camera **310** at the second instance of time as shown in FIG. **3**B. The images rendered on the virtual screen **410***a* and **410***b* can then be projected onto the display screen **390**. The eye-point camera **310** can be reused as a projector for projecting the images onto the display screen **390**. Alternatively or additionally, the rendered images can also be displayed on a light-emitting diode (LED) display screen or a liquid crystal display (LCD) screen.

FIGS. **5**A-**5**C illustrate a conventional method of rendering for a non-standard display screen **590**. Referring to FIG. **5**A, the display screen **590** can be similar to the display screen **390** illustrated in FIG. **4**A, as seen from an eye-point camera. One side **594** of the display screen **590** can be closer to the eye-point camera than the other side **596** of the display screen **590**. The grids represent the native pixels **530** of the display screen **590**. The native pixels will be used to present the final image. As illustrated in FIG. **5**A, the native pixels **530** adjacent the side **594** that is closer to the eye-point camera (e.g., the native pixel **530***a*) can appear to be larger than those native pixels **530** adjacent the side **596** that is farther away from the camera (e.g., the native pixel **530***b*).

Referring to FIG. **5**B, a rectangular virtual screen **510** that is large enough to include the entire display screen **590** can be used for rendering. The grids in dashed lines represent the pixels **540** of the virtual screen **510** for rendering. The pixels **540** of the virtual screen **510** can be referred to herein as "virtual pixels." As illustrated, the size of the virtual pixels **540** is usually uniform across the virtual screen **510** (e.g., the grids are regularly spaced). In order to achieve a certain desirable spatial resolution at the far side **596** of the display screen **590**, the size of each virtual pixel **540** can be selected to be approximately equal to the size of a native pixel adjacent the far side **596** of the display screen **590** (e.g., the native pixel **530***b*). As a result, a native pixel **530** adjacent the near side **594** of the display screen **590** (e.g., the native pixel **530***a*) can include two or more virtual pixels **540** (e.g., as many as four virtual pixels **540**). Thus, when projecting the rendered image onto the native pixels **530** of the display screen **590**, the color values of multiple virtual pixels **540** can need to be combined into a single color value for some of the native pixels **530**. Therefore, one can need to render more pixels than necessary in order to achieve a desired resolution for all native pixels **530**.

Referring to FIG. **5**C, since the virtual screen **510** is oversized in order to keep the entire display screen **590** in-frame, some virtual pixels **540** (e.g., the virtual pixel **540***a*) can fall outside the display screen **590**. Thus, the rendering for those virtual pixels **540** that fall outside the display screen **590** will not be projected onto the display screen **590** and are wasted. In addition, when the rendered image is projected onto the display screen **590**, the virtual pixels **540** would need to be resampled onto the native pixels **530** of the display screen **590**. Because of the possible mismatch between the virtual pixels **540** and the native pixels **530**, some image fidelity can be lost in the resampling process. Therefore, conventional methods of rendering for a display screen that has an arbitrary shape and/or an arbitrary orientation can be less than ideal.

FIG. **6** illustrates another example in which non-standard display screens can be encountered. Here, a vehicle **620** with a rider in it is moving past a large dome display screen **690** (e.g., in a theme park ride). The dome display screen **690** can wrap around the rider for as much as 160 degrees or more. In addition, the dome display screen **690** can be curved. Because the dome display screen **690** is so large, conventional methods of rendering for the dome display screen **690** can need to divide the dome display screen **690** into multiple sections and use multiple eye-point cameras. For instance, in the example illustrated in FIG. **6**, the dome display screen **690** is divided into three sections **690***a*, **690***b*, and **690***c*. Three eye-point cameras **610***a*, **610***b*, and **610***c* can be used. A first camera **610***a* can be pointed toward the first section **690***a*; a second camera **610***b* can be pointed toward the second section **690***b*; and a third camera **610***c* can be pointed toward the third section **690***c*.

FIGS. **7A-7C** show the three sections **690***a*, **690***b*, and **690***c* of the dome display screen **690**, respectively, as seen by each respective camera **610***a*, **610***b*, or **610***c* (part of the neighboring section(s) are also shown). As discussed above, to render an image for each section of the dome display screen **690**, each of the virtual screens **710***a*, **710***b*, and **710***c* can need to be oversized to keep the entirety of each section in-frame. Rendering for those virtual pixels that fall outside the dome display screen **690** can be wasted. In this example, there can also be issues of blending the images of adjacent sections. For example, what is filling top-to-bottom of one section can be only a small vertical slice of the next section. In some cases, three cameras may not be enough to cover the entire viewing area, and as many as six cameras or more can be used, with three cameras across the top and three cameras across the bottom.

FIGS. **8** and **9** illustrate a further example in which non-standard display screens can be encountered. FIG. **8** is a simplified illustration of an immersive content production system **800**. The immersive content production system **800** can include a performance area **802** that is partially or completely surrounded by an image displays **804** (sometimes referred to herein as just "displays"). The content production system **800** can obtain virtual environment content and display the virtual environment content on the displays **804**.

The performance area **802** can be, for example, a movie or television set, a stage, a stadium, a park, or the like. In one aspect, the immersive content production system **800** presents images in real-time or at interactive frame rates to users of the content production system (e.g., performers within performance area **802**). Since the displays **804** surround or partially surround the performance area **802**, the content production system **800** can create an immersive environment (sometimes referred to as an immersive "cave" or immersive "walls") for performances that take place within the performance area. In this way, an actor or actress performing within the performance area **802** can appear to be in the virtual environment.

The displays **804** are light emitting diode (LED) display screens or liquid crystal display (LCD) display screens. For example, the performance area **802** can include one or more walls of LED or LCD displays **804** enclosing the performance area **802**. Alternatively, the performance area **802** can be partially or completely surrounded by projector screens and a set of projectors can be configured to project images on the projector screens. The performance area **802** can be surrounded by a combination of LED display screens, LCD display screens and/or projector screens.

In some cases, the displays can be, for example, 20-40 feet tall and the performance area **802** can be, for example, between 50-100 feet in diameter. Other sizes for the displays and the performance area are also possible. The displays **804** can include multiple displays **804** that are generally fixed in position and mostly surround the performance area along with additional moveable or mobile displays **804** that can be moved into positions that create an immersive environment that extends completely or almost completely (i.e., 300-360 degrees) around performance area **802**. As an example, the fixed position displays **804** can extend approximately 270 degrees around performance area **802** while moveable displays **804** can be used to augment the fixed position displays to further extend the immersive environment up to 320 degrees or up to 360 degrees around the performance area. Additionally, while not shown in FIG. **8**, the content production system **800** can further include one or more displays **804** as a ceiling on performance area **802** and/or as part of the floor of the performance area. Also, while for ease of illustration, the displays **804** are shown in FIG. **8** as having a small space or gap **805** between them, the displays **804** can be installed in the immersive environment **800** as to be seamless with less than a threshold distance or even no space between adjacent displays.

A taking camera **812** can be attached to a rig **810** and can be aimed at the performance area **802** to capture the performance of a performer as well as the virtual environment displayed by the displays **804**. Sensors can be used to determine the position and orientation of the taking camera during a performance. For example, GPS based sensors (not shown) can be attached to the taking camera to determine its position within or relative to the performance area. As another example, other cameras (e.g., motion capture cameras **822** discussed below) can be directed at the taking camera configured to capture the performance and one or more markers can be attached to the taking camera. During a performance, the other cameras can capture images of the taking camera as the taking camera is moved and/or oriented during the performance. The production system can use the images captured of the taking camera to determine the movement and orientation of the taking camera during the performance. Such information can be used to support the content production process. For example, such information regarding the orientation and movement of the taking camera can be used to determine the distance of the taking camera from the performer over a performance. Based on the orientation and movement (and other attributes such as lens aperture and focal length) of the taking camera, the content production system can adjust the virtual environment displayed by the immersive cave or walls in real-time or at interactive frame rates to correspond to orientation and position of the taking camera. In this way, images of the virtual environment can be perspective-correct over a performance of the performer.

In some cases, the immersive cave or walls can include one more lighting elements to provide lighting for performance area **802**. For example, the immersive cave or walls can include supplemental LED lights **806** separate from displays **804** that can light the performance area **802** (including the performer) and create various desired lighting effects. Thus, the lights **806** can include the ability to project lighting levels of different intensities and project such light from different locations around the stage. In some cases, the additional LED lights **806** can be controlled during a performance in order to change the intensity of the lighting of performance area **802** (including the performer).

In some cases, the additional lighting elements can be created within one or more portions of the various displays **804** that create the virtual environment. For example, instead of depicting the virtual environment in a portion of one or more of the displays **804** surrounding the performance area, that portion of the display **804** can simulate an LED light **808** that illuminates the performance area. The content production system can include multiple simulated lights **808** the location of each of which on the displays **804** can be selected in order to achieve a desired lighting effect. The selection and placement of the simulated lights **808** can be made by a director, lighting technician or other user of content production system **800** prior to a performance taking place within performance area **802** and being filmed by taking camera **812**, but the number and location of the simulated lights can be readily adjusted at any time during the performance.

Since each simulated light **808** is created by the displays **804** and are thus part of the displays **804**, such simulated lights are sometimes referred to as "embedded lights" or "virtual lights". The simulated lights **808** can be in addition to or instead of the supplemental lights, such as lights **806**. Thus, in some cases, the immersive content system **800** includes the simulated lights **808** without any lights **806**. Additionally, in some cases the taking camera(s) and/or the associated camera rigs capturing images of the performance area do not include any attached lights. For example, in some cases the taking camera **812** used to capture action within the performance area **802** does not include a ring of LED lights or other form of light for illuminating the performance area that might otherwise be used with such cameras.

In some cases, content production system **800** can further include one or more depth sensors **820** and/or one or more motion capture cameras **822**. During a performance performed within the performance area **802**, the content production system **800** can detect the motion and/or positioning of one or more performers within the performance area. Such detection can be based on markers or sensors worn by a performer as well as by depth and/or other motion detection sensors **820** and/or by motion capture cameras **822**. For example, an array of depth sensors **820** can be positioned in proximity to and directed at the performance area **802**. For instance, the depth sensors **820** can surround the perimeter of the performance area. In some cases, the depth sensors **820** measure the depth of different parts of a performer in performance area **802** over the duration of a performance. The depth information can then be stored and used by the content production system to determine the positioning of the performer over the course of the performance.

The depth sensors **820** can include a motion-sensing input device with a depth sensor **820**. The depth sensor **820** can include a monochrome complementary metal-oxide semiconductor (CMOS) sensor and infrared projector. The infrared projector can project infrared light throughout the first performance area **802**, and the CMOS sensor can measure the distance of each point of reflected infrared (IR) radiation in the performance area **802** by measuring a time it takes for the emitted infrared light to return to the CMOS sensor. Software in the depth sensors **820** can process the IR information received from the depth sensor **820** and use an artificial intelligence machine-learning algorithm to map the visual data and create three-dimensional (3-D) depth models of solid objects in the first performance area **802**. For example, the one or more depth sensors **820** can receive emitted infrared radiation to generate 3-D depth models of a performer, along with the floor, walls, and/or ceiling of the first performance area **802**. In one test example, the first performance area **802** was surrounded by six to eight Kinect® cameras to capture depth information of objects and performers in the first performance area **802**.

The motion cameras **822** can be part of a motion capture system that can track the movement of performers or objects within system **800**. In some instances, the motion cameras **822** can be used to track the movement of the taking camera **812** and provide a location of the taking camera to content production system **800** as part of the process that determines what portion of the displays **804** are rendered from the tracked position of and the perspective of the taking camera.

FIG. **9** is a simplified illustration of an immersive content production system **900** that can be similar or identical to the immersive content production system **800** and thus includes many or all of the same components as described with respect to FIG. **8**. As shown in FIG. **9**, the content production system **900** includes performance area **802**, displays **804**, simulated lights **808** and a taking camera **812** attached to rig **810**, but does not include depth sensors **820** or motion cameras **822**.

A performer **910** is also shown within performance area **802** and the performance area can include one or more props **912** (e.g., the snowmobile depicted in FIG. **9**.). Scenery images **914** of the virtual environment can be presented on the displays **804** to generate the immersive environment in which performer **910** can conduct his or her performance (e.g., act out a scene in a movie being produced). In some cases, the scenery images **914** can be seamlessly presented across several displays **804** as described with respect to FIG. **8**. Scenery images **914** can include one or more virtual light sources **906** that can be, for example, an image of a sun, a moon, stars, street lights, or other natural or manmade light sources displayed in the scenery images **914**.

Scenery images **914** can also provide background for the video content captured by a taking camera **812** (e.g., a visible light camera). The taking camera **812** can capture a view of performance area **902** from a single perspective. In some cases, the taking camera **812** can be stationary, while in other cases, the taking camera **812** can be mounted to a track **810** that can move the taking camera during the performance.

In some cases, perspective-correct images (as rendered from the tracked position and perspective of taking camera **812**) can be generated and displayed on portions of the surrounding image display walls that are within the field of view (i.e., the frustum) of the taking camera. Areas of the displays **804** outside the field of view of taking camera **812** can be displayed according to a global view perspective.

According to some embodiments, rendering can be performed directly in the native image space of a display screen. The new rendering techniques can eliminate certain intermediate steps (e.g., resampling from the virtual screen to the display screen, stitching together multiple sections of the display screen, and the like), save rendering cycles, eliminate wasteful renderings on unused pixels, and prevent generational losses (e.g., possible loss of some image fidelity in the resampling process). Therefore, the new rendering techniques can afford the ability to create cheaper, faster, and higher-quality images, especially for non-standard display screens.

According to the new rendering techniques, a ray-tracing renderer is programmed to account for the geometry, the UV mapping, and the desired pixel resolution of the target screen onto which a rendered image can be projected. The ray-tracing renderer can use this information to perform ray tracing by tracing one ray per pixel (or several rays per pixel) in the native image space of the target screen.

FIGS. **10**A and **10**B illustrate a method of rendering an image by ray tracing according to some embodiments. FIG. **10**A shows a target screen **1090** in front of a virtual camera **1002**. The target screen **1090** can be not perpendicular to the optical axis **1004** of the virtual camera **1002** (e.g., a normal **1092** of the target screen **1090** can form a non-zero angle with respect to the optical axis **1004** of the virtual camera **1002**). FIG. **10**B shows the target screen **1090** as viewed on a viewing frustum **1010** of the virtual camera **1002**. The grids on the target screen **1090** represent the native pixels **1030** of the target screen **1090** (note that FIG. **10**B is similar to FIG. **5**A). A native pixel **1030** of the target screen **1090** can be referred herein as just a "pixel." It should be noted that, although FIG. **10**A shows the target screen **1090** to be substantially flat, the target screen **1090** can be of any arbitrary shape, including those curved or warped (e.g., part of a spherical surface, part of a toroidal surface, or the like).

The process of acquiring color data for a given pixel along a given ray can be the same as in conventional rendering methods. The difference is how to determine which rays to sight down. For example, with reference to FIG. **5**B, in a conventional rendering method, one ray per virtual pixel **540** can be traced; whereas in a new rendering method, with reference to FIG. **10**B, one ray per native pixel **1030** can be traced.

Referring to FIG. **10**A, for a given pixel **1030**a on the target screen **1090**, a ray **1040***a* can be traced from the virtual camera **1002** **1010** through the pixel **1030***a*, toward a virtual scene. Color data for the pixel **1030***a* can be estimated based on incoming light from a virtual object in the virtual scene that the ray **1040***a* intersects. For example, the ray **1040***a* can intersect a ball **1050** in the virtual scene. The color data for the pixel **1030***a* can be estimated by light reflected and/or scattered by the ball **1050**.

The position of each pixel **1030** on the target screen **1090** can be defined by a UV coordinate, as illustrated in FIG. **10**A. To define a ray **1040***a* that originates from the virtual camera **1002** and passes through a given pixel **1030***a* on the target screen **1090** in the viewing frustum **1010** of the virtual camera **1002**, the UV coordinate of the given pixel **1030***a* can be mapped into the XY coordinate of a corresponding point **1030***a'* on the viewing frustum **1010**, as illustrated in FIG. **10**B.

UV-XY mapping (maybe referred to as UV mapping) is a process of projecting a two-dimensional (2D) image onto a surface of a three-dimensional (3D) object. A non-planar surface of a 3D object can be considered as a warped 2D space. Each point on the surface of a 3D object can be defined by a UV coordinate. The UV axes can correspond to two orthogonal axes of the surface of the 3D object.

FIGS. **11**A-**11**D illustrate some examples of UV-XY mapping. FIG. **11**A shows a square 2D image. It can be analogous to a rendered image that will be mapped onto a display screen. For the purpose of illustration, the 2D image shown in FIG. **11**A is a simple checkered grid. Each point on the 2D image can be defined by an XY coordinate, where the X-axis is the horizontal axis, and the Y-axis is the vertical axis.

The 2D image shown in FIG. 11A can be mapped onto a surface of a 3D object. FIGS. **11**B-**11**D show three different exemplary 3D surfaces: FIG. **11**B shows a flat surface; FIG. **11**C shows a cylindrical surface; and FIG. **11**D shows an arbitrary surface that appears to be a warped surface. For the flat surface shown in FIG. **11**B, the UV axes can be the two orthogonal axes along the two adjacent edges of the square.

The UV mapping of the 2D image shown in FIG. **11**A to the flat surface shown in FIG. **11**B can be straightforward. For the cylindrical surface shown in FIG. **11**C, the U axis can be along the circumference of the cylinder, and the V axis can be along the vertical direction. Mapping the 2D image shown in FIG. **11**A onto the cylindrical surface shown in FIG. **11**C can be analogous to wrapping a label onto the surface of a can. For the arbitrary curved surface shown in FIG. **11**D, the 2D image shown in FIG. **11**A can be "warped" to fit the curved surface.

Referring again to FIGS. **10**A and **10**B, to render an image directly in the native image space of the target screen **1090**, for each respective pixel **1030***a* of the target screen **1090** with a respective UV coordinate, the XY coordinate of a corresponding point **1030***a'* on the viewing frustum **1010** of the virtual camera **1002** can be determined. The UV-XY mapping can be determined based on, for example, the position and orientation of the virtual camera **1002**, and the position and orientation of the target screen **1090**. Alternatively, the UV-XY mapping can be determined based on the position and the orientation of the target screen **1090** relative to the position and the orientation, respectively, of the virtual camera **1002**.

In the ray tracing process, for each respective pixel **1030***a* of the target screen **1090**, a ray can be launched from the virtual camera **1002** to a corresponding point **1030***a'* on the viewing frustum **1010** of the virtual camera **1002**, using the UV-XY mapping. The color data estimated by tracing the ray is then assigned to the respective pixel **1030***a* on the target screen **1090**. The rendered image can be projected onto a display screen corresponding to the target screen **1090**, again using the UV-XY mapping. Thus, by rendering directly in the native image space of the target screen **1090**, over-rendering (e.g., rendering in unused pixels, rendering at a higher pixel resolution than needed, and the like) can be avoided. Also, certain intermediate steps, such as resampling during projection, can be eliminated. Therefore, a final image with desired pixel resolution can be rendered in less time, fewer steps, and without resampling loss.

To achieve a higher quality image with less noise (e.g., a smoother image), multiple rays per pixel can be sampled. The color data estimated for the multiple rays sampled for a given pixel can be averaged (or by other statistical means) to obtain the color data for the given pixel. In some embodiments, the spatial dimension of a given pixel (e.g., the solid angle subtended by the given pixel with respect to the virtual camera) can be determined; then N samples can be randomly chosen in that spatial dimension.

The rendering techniques described above can also be useful for rendering images to be displayed on background screens (e.g., LED background screens) used in live-action shoots. For example, ray tracing can be performed directly for the pixels of a large LED screen, based on a hero camera's point view.

FIG. **12** shows a simplified flowchart illustrating a method **1200** of rendering an image for a display screen by ray tracing according to some embodiments.

The method **1200** includes, at **1210**, receiving information of a virtual camera. The information of the virtual camera can include a camera position and a camera orientation. The information of the virtual camera can define a virtual screen perpendicular to an optical axis of the virtual camera.

The method **1200** further includes, at **1220**, receiving information of a target screen. The information of the target screen can include a target screen position and a target screen orientation. The target screen can define a plurality of pixels. For example, the pixels can be defined according to a desired pixel resolution. The information of the target screen can also include the geometry of the target screen. For example, the target screen can be substantially flat or can be curved. Points on the target screen may be defined in a UV coordinate system. Thus, each respective pixel can correspond to a respective UV coordinate on the target screen.

The method **1200** further includes, at **1230**, performing the following for each respective pixel of the plurality of pixels of the target screen. At **1232**, a respective XY coordinate of a corresponding point on the virtual screen is determined based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate. For example, the respective XY coordinate can be determined using a UV-XY mapping. At **1234**, one or more rays are traced from the virtual camera through the corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene. At **1236**, a respective color value for the respective pixel is estimated based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

According to the method **1200** illustrated in the flowchart of FIG. **12**, ray tracing is performed directly for the pixels in the native image space of the target screen. This rendering technique can be advantageous for rendering images to be projected or displayed on non-standard display screens, for example in 3D rides and immersive environments used in virtual content production. It can eliminate certain intermediate steps (e.g., resampling from the virtual screen to the display screen, stitching together multiple sections of the display screen, and the like), save rendering cycles, eliminate wasteful renderings on unused pixels, and prevent generational losses.

It should be appreciated that the specific steps illustrated in FIG. **12** provide a particular method of rendering an image for a display screen by ray tracing according to some embodiments. Other sequences of steps can also be performed according to alternative embodiments. For example, alternative embodiments of the present invention can perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. **12** can include multiple sub-steps that can be performed in various sequences as appropriate to the individual step. Furthermore, additional steps can be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

FIG. **13** shows a schematic diagram of an example of a computer system **1300**. The computer system **1300** is exemplary only and one having skill in the art will recognize that variations and modifications are possible. The system **1300** can be used for the operations described in association with the processes of FIG. **12**.

The system **1300** includes a processor **1310**, a memory **1320**, a storage device **1330**, and an input/output device **1340**. Each of the components **1310**, **1320**, **1330**, and **1340** are interconnected using a system bus **1350**. The processor **1310** is capable of processing instructions for execution within the system **1300**. In one implementation, the processor **1310** is a single-threaded processor. In another implementation, the processor **1310** is a multi-threaded processor. The processor **1310** is capable of processing instructions stored in the memory **1320** or on the storage device **1330** to perform the steps of processes according to the present invention.

The memory **1320** stores information within the system **1300** and can be associated with various characteristics and implementations. For example, the memory **1320** can include various types of computer-readable medium such as volatile memory, a non-volatile memory and other types of memory technology, individually or in combination.

The storage device **1330** is capable of providing mass storage for the system **1300**. In one implementation, the storage device **1330** is a computer-readable medium. In various different implementations, the storage device **1330** can be a floppy disk device, a hard disk device, an optical disk device, or a tape device.

The input/output device **1340** provides input/output operations for the system **1300**. In one implementation, the input/output device **1340** includes a keyboard, pointing device, touchscreen display, and/or the like. In another implementation, the input/output device **1340** includes a display unit for displaying graphical user interfaces.

The features described can be implemented in digital electronic circuitry, or in computer hardware, firmware, software, or in combinations of them. The apparatus can be implemented in a computer program product tangibly embodied in an information carrier, e.g., in a machine-readable storage device, for execution by a programmable processor; and method steps can be performed by a programmable processor executing a program of instructions to perform functions of the described implementations by operating on input data and generating output. The described features can be implemented advantageously in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program is a set of instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment.

Suitable processors for the execution of a program of instructions include, by way of example, both general and special purpose microprocessors, and the sole processor or one of multiple processors of any kind of computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for executing instructions and one or more memories for storing instructions and data. Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files; such devices include magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

To provide for interaction with a user, the features can be implemented on a computer having a display device such as a CRT (cathode ray tube), LCD (liquid crystal display), LED (light emitting diode) monitor for displaying information to the user and a keyboard and a pointing device such as a mouse or a trackball by which the user can provide input to the computer.

The features can be implemented in a computer system that includes a back-end component, such as a data server, or that includes a middleware component, such as an application server or an Internet server, or that includes a front-end component, such as a client computer having a graphical user interface or an Internet browser, or any combination of them. The components of the system can be connected by any form or medium of digital data communication such as a communication network. Examples of communication networks include, e.g., a LAN, a WAN, and the computers and networks forming the Internet.

The computer system **1300** can include clients and servers. A client and server are generally remote from each other and typically interact through a network, such as the described one. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other. Although a few implementations have been described in detail above, other modifications are possible.

It is understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and scope of the appended claims.

What is claimed is:

1. A method of rendering an image of a scene on a curved surface of a target screen by ray tracing, the method comprising:

receiving information for a camera, including a camera position and a camera orientation defining a virtual screen perpendicular to an optical axis of the camera;

receiving information of the target screen, including a target screen position and a target screen orientation, wherein points on the target screen are defined in a UV coordinate system and the target screen defines a plurality of pixels with each pixel in the plurality of pixels corresponding to a respective UV coordinate on the target screen; and

rendering the image on the curved surface of the target screen by performing ray tracing for the plurality of pixels of the target screen to simulate lighting of the scene by tracing a path of light from a virtual camera through a two-dimensional viewing plane out into a three-dimensional scene and back to light sources for the scene, wherein performing ray tracing comprises sighting down one or more rays per pixel of the target screen by, for each respective pixel of the target screen having a respective UV coordinate:

(i) determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate;

(ii) tracing one or more rays from the camera through the pixel of the target screen towards a corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and

(iii) estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays.

2. The method of claim **1**, wherein a normal of the target screen forms a non-zero angle with respect to the optical axis of the camera.

3. The method of claim **1**, wherein the target screen is curved.

4. The method of claim **3**, wherein a normal of the target screen at a center of the target screen forms a non-zero angle with respect to the optical axis of the camera.

5. The method of claim **1**, wherein the target screen partially fills a smallest viewing frustum of the camera that encompasses an entirety of the target screen.

6. The method of claim **1**, wherein the target screen encompasses a field of view of the camera that is greater than 90 degrees.

7. The method of claim **1** wherein the target screen is part of an immersive content production system.

8. The method of claim **7** wherein the immersive content production system comprises a performance area that is at least partially surrounded by one or more curved light emitting diode display walls and a display ceiling that display a virtual environment and the target screen is on one or more of the light emitting diode display walls.

9. The method of claim **1** wherein estimating a respective color value for the respective pixel comprises averaging color value for the respective pixel.

10. The method of claim **9** wherein an angle to the camera from the target screen changes over time as the camera moves.

11. A computer product comprising a non-transitory computer readable medium storing a plurality of instructions that when executed control a computer system to render an image of a scene on a curved surface of a target screen by ray tracing, the instructions comprising:

receiving information for a camera, including a camera position and a camera orientation defining a virtual screen perpendicular to an optical axis of the camera;

receiving information of the target screen, including a target screen position and a target screen orientation, wherein points on the target screen are defined in a UV coordinate system and the target screen defines a plurality of pixels each pixel in the plurality of pixels corresponding to a respective UV coordinate on the target screen;

rendering the image on the curved surface of the target screen by performing ray tracing for the plurality of pixels of the target screen to simulate lighting of the scene by tracing a path of light from a virtual camera through a two-dimensional viewing plane out into a three-dimensional scene and back to light sources for the scene, wherein performing ray tracing comprises sighting down one or more rays per pixel of the target screen by, for each respective pixel of the target screen having a respective UV coordinate of the plurality of pixels of the target screen:

(i) determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate;

(ii) tracing one or more rays from the camera through the pixel of the target screen towards a corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and

(iii) estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the one or more rays by averaging color value data for the respective pixel.

12. The computer product of claim **11**, wherein a normal of the target screen forms a non-zero angle with respect to the optical axis of the camera.

13. The computer product of claim **11**, wherein the target screen is curved.

14. The computer product of claim **13**, wherein a normal of the target screen at a center of the target screen forms a non-zero angle with respect to the optical axis of the camera.

15. The computer product of claim **11**, wherein the target screen partially fills a smallest viewing frustum of the camera that encompasses an entirety of the target screen.

16. The computer product of claim **11**, wherein the target screen encompasses a field of view of the camera that is greater than 90 degrees.

17. A computer system comprising:

one or more processors; and

a non-transitory computer readable medium storing a plurality of instructions that when executed control the one or more processors to render an image of a scene by ray tracing for an immersive content production system the instructions comprising:

receiving information for a camera of the immersive content production system having a performance area that is at least partially surrounded by one or more curved light emitting diode display walls and a display ceiling that display virtual environment content, including a camera position and a camera orientation defining a virtual screen perpendicular to an optical axis of the camera;

receiving information of a target screen on the one or more curved light emitting diode display walls, including a target screen position and a target screen orientation, the target screen defining a plurality of pixels, each respective pixel corresponding to a respective UV coordinate on the target screen;

rendering the image by performing ray tracing for the plurality of pixels of the target screen to simulate

lighting of the scene by tracing a path of light from a virtual camera through a two-dimensional viewing plane out into a three-dimensional scene and back to light sources for the scene, wherein performing ray tracing comprises sighting down one or more rays per pixel of the target screen by, for each respective pixel of the target screen having a respective UV coordinate of the plurality of pixels of the target screen:

(i) determining a respective XY coordinate of a corresponding point on the virtual screen based on the camera position, the camera orientation, the target screen position, the target screen orientation, and the respective UV coordinate;

(ii) tracing one or more rays from the camera through the pixel of the target screen towards a corresponding point on the virtual screen at the respective XY coordinate toward a virtual scene; and

(iii) estimating a respective color value for the respective pixel based on incoming light from virtual objects in the virtual scene that intersect the multiple rays by averaging color value data for the respective pixel, wherein an angle of the camera to the target screen changes over time as the camera moves.

18. The computer system of claim **17**, wherein a normal of the target screen forms a non-zero angle with respect to the optical axis of the camera.

19. The computer system of claim **17**, wherein the target screen is curved.

20. The computer system of claim **19**, wherein a normal of the target screen at a center of the target screen forms a non-zero angle with respect to the optical axis of the camera.

21. The computer system of claim **17**, wherein the target screen partially fills a smallest viewing frustum of the camera that encompasses an entirety of the target screen.

22. The computer system of claim **17**, wherein the target screen encompasses a field of view of the camera that is greater than 90 degrees.

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