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HETEROGENEOUS GAZE TRACKING SENSOR SYSTEMS, METHODS, AND DEVICES

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TECHNOLOGICAL FIELD

[0001] Examples of this disclosure relate generally to methods, apparatuses and computer program products for eye tracking and gaze pattern determinations using heterogeneous sensor systems.

BACKGROUND

[0002] Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, e.g., a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. AR, VR, MR, and hybrid reality devices often provide content through visual means, such as through a headset, e.g., glasses.

[0003] Many artificial reality devices utilize cameras to present information, render additive information and/or content on top of the physical world, and execute various AR operations and simulations. For example, an artificial reality device may display a hologram overlaid on top of a screen or display.

[0004] Eye tracking is a core component in AR/VR applications. Eye tracking methods traditionally use two same solutions for left and right eyes. For instance, many VR headsets use two similar cameras directed, respectively, to left and right eyes. However, these cameras operate separately and independently, and often have high power requirements. Although left and eye motions may be highly correlated, eye tracking techniques separately process each eye's information, and do not utilize correlation information and patterns that may be present. This may lead to redundant processing or increased latency that would not otherwise be necessary. Accordingly, improvements are needed for eye tracking and processing techniques to address the increasing power and processing requirements for artificial reality applications.

BRIEF SUMMARY

[0005] In meeting the described challenges, the present disclosure provides systems, methods, devices, and computer program products for eye tracking and gaze pattern determinations using heterogeneous sensor systems. Various aspects and examples may be usable on a range of artificial reality devices and applications, including but not limited to wearable devices, head-mounted systems, headsets, glasses, helmets, visors, gaming devices, and smart devices. In various aspects, a first sensor system may track movement of a first eye, and a second sensor system may track movement of a second eye. The second sensor system may apply a different tracking method than the first sensor system. A processor and a non-transitory memory including computer-executable instructions may correlate tracking information received from the first sensor and the second sensor to determine a gaze motion pattern. In various examples, the gaze motion pattern is a three-dimensional gaze motion pattern. The motion pattern may cause an associated visual display to project visual content responsive to the determined gaze pattern.

[0006] The tracking method may apply at least one of visual tracking via a camera, photosensor oculography (PSOG), finge tracking, real-time event-based tracking, indirect time of flight measurements, or range imaging. The first sensor system or the second sensing system may include at least one of: a range imaging camera, a photosensor, a finge sensor, or an event camera. Such sensors may be positioned outside a field of view of the first eye and the second eye. Various implementations may correlate tracking information by at least determining at least one of a convergence pattern or a divergence pattern based on tracked movement of the first eye and tracked movement of the second eye. As discussed herein, a machine learning module may be applied to assist in determining one or more of the tracked eye movements, or gaze motion patterns. Such machine learning models may be trained on data sets associating tracked eye movements and gaze motion patterns, determining eye movements, via reflected light, phase shifts, visual information, and the like.

[0007] In some examples, a third sensor system may track movement of the first eye, wherein the third sensor system applies a different tracking method than the first sensor system. In other examples, a fourth sensor system may track movement of the second eye, wherein the fourth sensor system applies a different tracking method than the second sensor system.

[0008] Additional advantages will be set forth in pan in the description which follows or may be learned by practice. The advantages will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The summary, as well as the following detailed description, is further understood when read in conjunction with the appended drawings. For the purpose of illustrating the disclosed subject matter, there are shown in the drawings exemplary embodiments of the disclosed subject matter; however, the disclosed subject matter is not limited to the specific methods, compositions, and devices disclosed. In addition, the drawings are not necessarily drawn to scale. In the drawings:

[0010] FIG. 1 illustrates an example heterogeneous eye tracking system, in accordance with various aspects discussed herein.

[0011] FIG. 2 illustrates another example of a heterogenous eye tracking system, in accordance with various aspects discussed herein.

[0012] FIG. 3 illustrates a flowchart for performing contextual analyses in accordance with various aspects discussed herein.

[0013] FIG. 4 illustrates a flowchart for heterogenous eye tracking, in accordance with various aspects discussed herein.

[0014] FIG. 5 illustrates a flowchart for tracking eye movements in accordance with various aspects discussed herein.

[0015] FIG. 6 illustrates an artificial reality system comprising a headset, in accordance with various aspects discussed herein.

[0016] FIG. 7 illustrates a block diagram of an example device in accordance with various aspects discussed herein.

[0017] FIG. 8 illustrates a block diagram of an example computing system in accordance with various aspects discussed herein.

[0018] FIG. 9 illustrates a machine learning and training model in accordance with various aspects discussed herein.

[0019] FIG. 10 illustrates a computing system in accordance with various aspects discussed herein.

[0020] The figures depict various examples for the purpose of illustration only. One skilled in the art will readily recognize from the following discussion that alternative examples of the structures and methods illustrated herein may be employed without departing from the principles described herein.

DETAILED DESCRIPTION

[0021] The present disclosure can be understood more readily by reference to the following detailed description taken in connection with the accompanying figures and examples, which form a part of this disclosure. It is to be understood that this disclosure is not limited to the specific devices, methods, applications, conditions, or parameters described and/or shown herein, and that the terminology used herein is for the purpose of describing particular embodiments by way of example only and is not intended to be limiting of the claimed subject matter.

[0022] Some examples of the present invention will now be described more fully hereinafter, with reference to the accompanying drawings, in which some, but not all examples of the invention are shown. Indeed, various examples of the invention may be embodied in many different forms and should not be construed as limited to the examples set forth herein. Like reference numerals refer to like elements throughout. As used herein, the terms “data,” “content,” “information,” and similar terms may be used interchangeably to refer to data capable of being transmitted, received, and/or stored in accordance with examples of the invention. Moreover, the term “exemplary”, as used herein, is not provided to convey any qualitative assessment, but instead merely to convey an illustration of an example. Thus, use of any such terms should not be taken to limit the spirit and scope of examples of the invention.

[0023] As defined herein a “computer-readable storage medium,” which refers to a non- transitory, physical, or tangible storage medium (e.g., volatile or non-volatile memory device), may be differentiated from a “computer-readable transmission medium,” which refers to an electromagnetic signal.

[0024] References in this description to “an example”, “one example”, or the like, may mean that the particular feature, function, or characteristic being described is included in at least one example of the present invention. Occurrences of such phrases in this specification do not necessarily all refer to the same example, nor are they necessarily mutually exclusive.

[0025] Also, as used in the specification including the appended claims, the singular forms “a,” “an,” and “the” include the plural, and reference to a particular numerical value includes at least that particular value, unless the context clearly dictates otherwise. The term “plurality”, as used herein, means more than one. When a range of values is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another embodiment. All ranges are inclusive and combinable. It is to be understood that the terminology used herein is for the purpose of describing particular aspects only, and is not intended to be limiting.

[0026] It is to be appreciated that certain features of the disclosed subject matter which are, for clarity, described herein in the context of separate embodiments, can also be provided in combination in a single embodiment. Conversely, various features of the disclosed subject matter that are, for brevity, described in the context of a single embodiment, can also be provided separately, or in any sub-combination. Further, any reference to values stated in ranges includes each and every value within that range. Any documents cited herein are incorporated herein by reference in their entireties for any and all purposes.

[0027] In various aspects, systems, and methods enable heterogenous eye tracking and processing techniques correlating eye movements. Left and right eye motions are highly correlated, and exhibit common motion patterns, including but not limited to convergence, divergence, and smooth pursuit. In these eye motions, the two eyes are highly correlated. Yet, the correlation information is not fully utilized in current eye tracking solutions.

[0028] Moreover, different types of sensors have different advantages and disadvantages, and may be used for eye tracking. For example, cameras, event sensors, fringe sensors, range tracking sensors, indirect time of flight (iTOF), time of flight (TOF) sensors, and photosensors, e.g., for photosensor oculography (PSOG) may be utilized to track eye motion. It is difficult for a single sensor or sensor type to achieve certain operational requirements and features, such as low power consumption, high speed, high accuracy, high precision, small size, low latency, and field of view (FOV) considerations. Such operational requirements and features are becoming increasingly important as applications, such as headsets, AR/VR devices, glasses become more advanced.

[0029] Accordingly, aspects of the present invention utilize two heterogenous sensors for the left and right eye separately. In other words, two different types of sensors are applied. In various aspects, a first sensor system may track movement of a first eye, and a second sensor system may track movement of a second eye. The two sensor systems may apply different tracking methods, as discussed herein. By leveraging the motion correlation information of two eyes, systems, methods, devices, and other applications may realize the advantages of two different sensors at the same time, while mitigating disadvantages.

[0030] FIG. 1 illustrates an example implementation of heterogenous eye tracking in accordance with embodiments discussed herein. FIG. 1 illustrates a plan view of an example system including system 100, on which various techniques may be applied. In examples, the system 100 may include an AR/VR glasses headset. It should be appreciated that the various sensors and techniques may be applied to a range of applications, including but not limited to other head-mounted devices, headsets, helmets, visors, gaming devices, smart devices, and other wearable technology.

[0031] Right eye 130a and left eye 130b may be positioned behind a lens system, e.g., right lens 105a and left lens 105b. The lens system may be configured to provide a visual display. A right eye sensor system 110a may capture a field of view 120a which includes the right eye 130a. A left eye sensor system 110b may capture a field of view 120b which includes the left eye 130b. In some instances, one or both sensor systems, e.g., 110a and 110b, may have a field of view which includes one or both eyes. In some examples, eye tracking information for one or both eyes, captured by a single sensor system may be used. In other examples, a sensor system may focus on a single eye, even if both eyes are within its field of view. Variations and combinations or sensor information and eye information may be adjusted based on a type of sensor desired information, and other application characteristics and factors, including but not limited to latency, power consumption, accuracy, and the like.

[0032] In various examples, the sensor systems may be positioned outside of a field of view of an eye, particularly, the eye which is being tracked by the sensor. As illustrated in FIG. 1, right eye sensor system 110a is positioned outside of the right eye field of view 140a, and left eye sensor system 110b is positioned outside of the left eye field of view 140b. Such positioning prevents obstruction, distraction, and other discomfort or annoyance which may arise with the sensor system being within an eye’s field of view. Such positioning further enables seamless operation, and in some cases, presentation of visual content on a lens system 105a, 105b.

[0033] The right eye sensor system 110a may track the right eye 130a using a first tracking method, and the left eye sensor system 110b may track the left eye 130b using a second tracking method different from the first sensor system. In various examples, the tracking may be visual tracking, for example, using a camera, photosensor oculography (PSOG), event-based tracking, which may occur in real-time, range imaging, and time of flight techniques, including indirect time of flight (iTOF) techniques, as further discussed herein.

[0034] The tracked eye movement information from both eyes may be processed via a computing system including a processor and non-transitory memory. The computing system and processing may occur locally, remotely, or both, with some processing operations happening locally and others remotely. Remote processing may occur over a network, via a cloud computing network as discussed herein, or via one or more servers, devices, and systems in remote network communication with the application 100.

[0035] The tracked eye movements from the left and right eye are correlated to determine a gaze motion pattern, which may be a three-dimensional gaze motion pattern. Correlating tracking information may include determining a convergence pattern or divergence pattern based on the tracked movement of both eyes. As discussed further, with respect to FIG. 3, such convergence and divergence patterns may indicate whether an eye is focusing on something near or far. Based on that contextual information, the gaze motion pattern may be determined to be a two-dimensional or three-dimensional gaze motion pattern.

[0036] In various examples, respective sensor systems determine a motion pattern based on the tracked eye movements. The two motion patterns, i.e., from each eye, may be combined to determine a gaze motion pattern, indicative of where the user is looking and focusing. Such motion pattern identification and gaze determinations may occur in real-time, and/or with very minimal (e.g., millisecond or less) latency. In certain AR/VR applications, such as gaming, or operation of smart glasses, such speeds may be crucial for a seamless and satisfying experience using the product. For example, a visual display may provide content, such as pictures, video, text, animations, etc., on a lens system (e.g., lens systems 105a, 105b). Such content may be shifted, selected, interacted with, or responsive to a gaze. Thus, fast and accurate eye tracking may be necessary to enable such interactions. Therefore, in some aspects, the determined gaze pattern, from the correlated eye tracking data, may cause a visual display to project visual content in response to the determined gaze pattern. The heterogeneous nature of the two sensor systems further enables such interactions and interactions with improved speed, power consumption, latency, and other characteristics, as discussed herein.

[0037] As one example, a camera may have a dense image information, thus being able to achieve high accuracy. However, such camera's power consumption may be very high. An iTOF sensor may achieve lower power consumption, but its accuracy may be low. Therefore, a camera may track one eye, and an iTOF sensor may track the other eye. Then, the information between the two eyes may be correlated, and the two measurements fused together to achieve a high accuracy measurement, with a lower overall power consumption than a two camera solution, and higher accuracy than a two iTOF sensor solution.

[0038] FIG. 2 illustrates another example of a heterogenous eye tracking system. The illustrated example may be applied to various systems, methods, applications, such as the system illustrated in FIG. 1. Furthermore, although only one eye is illustrated, a similar implementation may be applied to track a second eye, and the illustrated example is applicable to any or all aspects and examples discussed herein.

[0039] In FIG. 2, an eye may be looking towards a lens system 140. The lens system 140 may be a clear lens, e.g., on glasses, configured to provide visual content, e.g., on smart glasses, part of a gaming system, or other head-mounted device. A plurality of sensor systems may be associated with lens system 140, such as Sensor System A 210a and Sensor System B 210b. Sensor System A 210a may be a first type of sensor using a first tracking technique, while Sensor System B 210b may be a same or different type of sensor using a second tracking technique.

[0040] In applications where high accuracy may be desired or required, having a second sensor tracking eye movement may be beneficial. Such techniques may be applied to configurations, such as system 100 discussed in FIG. 1. The right eye and left eye may have one or more sensors tracking eye movements. In one example, both Sensor Systems A and B may be photosensors, executing PSOG techniques. In other examples, a right eye may have a plurality of sensors executing different tracking methods, and the left eye may have a plurality of sensors executing different tracking methods. The tracking methods between the left and right eye may be the same or different. Accordingly, the movements between the sensor systems, e.g., Sensor System A 210a and Sensor System B 210b, and between the two tracked eyes may be correlated to develop an accurate gaze motion pattern. Thus the heterogenous nature may be realized, both with respect to individual eyes, and between right and left eyes.

[0041] Example sensor and tracking method techniques 220 may include, but are not limited to, visual tracking, PSOG, event sensing, fringe sensing, range imaging, and time of flight techniques. Such techniques may utilize one or more of a range imaging camera, a photosensor, a fringe sensor, or an event camera.

[0042] Visual tracking techniques may utilize a camera to track movements of the eye over a period of time. In some examples, visual tracking techniques may follow a movement of a pupil over a period of time. Such movements may create a two-dimensional map estimating a direction and/or area towards which the user is looking. Such movements may, for example, indicate where on a lens system 140 or elsewhere that the eye 130 is looking at. Such information may further provide how long the eye is looking at an area. In some examples, the eye information may be combined with other contextual information, e.g., content provided on the lens system, etc., to determine a motion pattern. The eye's movement information and/or motion pattern may be correlated with other information, such as eye movement information and/or motion information with respect to a second eye, to determine a gaze motion pattern, as discussed herein.

[0043] In photosensor oculography (PSOG) techniques, one or more photosensors may be applied to determine an amount of reflected light when the eye moves. The photosensors may be infrared sensors, tracking movement based on an amount of reflected infrared light. In particular, a photosensor may track light reflection and/or intensity values over time. Variations in intensity values may be indicative of eye movement. The intensity values may be correlated to an eye position, for example, correlated to a coordinate system, to determine and track eye movement on a two-dimensional plane. In various techniques, one or more machine learning models may be applied, such as a neural network, to determine eye movement and position based on the tracked light reflection and intensity values. Such techniques may provide advantages such as high accuracy and precision, low latency, high spatial and temporal resolution, and significantly reduced power consumption, especially compared to traditional sensors, like cameras. Combined with one or more heterogeneous sensor techniques, PSOG may significantly improve eye tracking determinations.

[0044] In another example, a fringe sensor may be applied. In some aspects, a fringe sensor may be utilized alone or in combination with another sensor technique. For example, in FIG. 2, Sensory System A 210a may be a camera, and Sensor System B 210b may be a fringe sensor. The combination may realize improved accuracy compared to traditional camera systems. In fringe tracking techniques, measured distortions provide tracking information. A fringe sensor system may project an image on to an object, in this case, an eye, and a fringe sensor, such as a camera or other photodetector, may analyze the distortion on the object caused by the projected image. From the distortion, information about the eye, such as three-dimensional information may be identified. As applied to various aspects and implementations, a fringe sensor system may track information, e.g., three-dimensional information, about the eye, determine movement of the eye based on the received three-dimensional information over time, and based on the eye movement, determine a movement pattern, which may be correlated with a movement pattern of a second eye, to determine a gaze motion pattern. Similar to the other eye tracking techniques and sensor systems discussed herein, fringe sensor systems may utilize one or more machine learning models to determine, based on the received fringe information, three-dimensional eye information, movement information, motion patterns, and the like.

[0045] Event-based techniques may provide significant speed and power advantages for eye tracking, while enabling and improving real-time tracking of eye movements. In such techniques, variations in brightness/intensity levels correspond to “events.” When the variation, or difference between two values, reaches a certain threshold, it may be indicative of an eye movement. In various implementations, an event camera may be used. In other implementations, two cameras may be applied, and measured brightness/intensity levels between the two cameras may be compared, e.g., to determine a difference, and thereby determine whether an event has occurred. Event sensors, cameras, and the like may track a pupil 230, for example, and based on received brightness/intensity information of the pupil over time, its movement may be determined. Similar to other eye tracking techniques, event-based techniques may utilize one or more machine learning models to determine eye movement information, motion patterns, and the like, based on the received brightness/intensity information and differences.

[0046] Range imaging may utilize time of flight, interferometry, and/or triangulation techniques to estimate a distance from an object, then, based on the changes in the object’s distance over time, determine its position and movement. Such techniques may provide advantages including, but not limited to, high speed, resolution, precision, accuracy, and the ability to determine three-dimensional images.

[0047] Time of flight techniques may include direct time of flight (dTOF) and indirect time of flight (iTOF) techniques. A dTOF technique may determine a distance based on the amount of time it takes for a light pulse to be reflected back to the sensor. iTOF techniques may determine a distance from an object by emitting and collecting reflecting light, then comparing a phase shift between the emitted and reflected light. In iTOF, the emitted light pulses may be continuous light pulses, e.g., infrared light pulses, and may be modulated.

[0048] FIG. 3 illustrates an example three-dimensional gaze motion pattern, based on tracking and correlation techniques discussed herein. An eye 130 may be positioned at a distance 330 from a lens system 140 and looking towards a lens system. A sensor 110 may track an eye, and a second sensor may track another eye (not pictured). The sensor may be positioned outside of the eye’s field of view (see, e.g., Convergence Field of View 310, and Divergence Field of View 320). The gaze motion pattern 340 may be a three-dimensional motion pattern, and is indicative of the gaze focusing on a first area 350 located beyond the lens system, shifting to a second area 360, closer and in a different area beyond the lens system, and then focusing on an area on the lens system 370, such as a display or visual content on the display.

[0049] As discussed above, with respect to the various sensor systems and techniques, movement of an eye 130 may be tracked. Some techniques may be able to provide a two-dimensional and/or real time estimation as to a position or area towards which the eye is looking. However, correlation between two eyes, e.g., based on the tracked information from sensor systems, enables the determination of a gaze motion pattern 340, which may be a three-dimensional gaze motion pattern.

[0050] Tracked motion data from two eyes may provide convergence and divergence information, usable to generate a three-dimensional motion pattern. When a person changes their gaze to look at something closer, the eyes converge. Conversely, when a person shifts their gaze to look from a closer object to something farther away, the eyes diverge. In the illustrated example, the Convergence FOV 310 indicates the field of view when an eye is focusing on a nearby object, such as the lens system 140. Divergence FOV 320 indicates the field of view beyond the lens. When an eye is focusing on an object or area in the Divergence FOV 320, both eyes will diverge, compared to looking at something within the Convergence FOV 310. Thus, by correlating tracked movements from each eye, and the shifts that occur when eyes shift from a near to far view, or vice versa, a gaze depth may be determined. By tracking the gaze depth and position over time, a gaze motion pattern may be determined. If only one eye were tracked, depth may not be predicted with such accuracy.

[0051] FIG. 4 illustrates a flowchart for heterogenous eye tracking, in accordance with various aspects discussed herein. At block 410, a first sensor system may track movement of a first eye. At block 420, a second sensor system may track movement of a second eye, wherein the second sensor system may apply a different tracking method than the first tracking system. As discussed herein, a tracking method may apply at least one of visual tracking via a camera, photosensor oculography (PSOG), fringe tracking, real-time event-based tracking, indirect time of flight measurements, and/or range imaging. In various examples, the first sensor system or the second sensor system may comprise at least one of: a range imaging camera, a photosensor, a fringe sensor, or an event camera. In some examples, the first sensor system or the second sensor system may comprise an artificial reality system (e.g., artificial reality system 600 of FIG. 6).

[0052] In some examples, the first sensor system may utilize a camera (e.g., rear camera 618 of FIG. 6) to track movement of the first eye, and the second sensor system may utilize iTOF to track movement of the second eye. In another example, the first sensor system may utilize a camera to track movement of the first eye, and the second sensor system may utilize an event sensor to track movement of the second eye. In yet another example, the first sensor system may utilize a camera and a fringe sensor to track movement of the first eye, and the second sensor system may utilize PSOG to track movement of the second eye. It should be appreciated that any of a combination of sensors and/or techniques may be applied for respective sensor systems, in accordance with the heterogeneous tracking techniques discussed herein.

[0053] At block 430, tracking information received from the first sensor system may be correlated with tracking information from the second sensor system to determine a gaze motion pattern. Tracking information may include eye movements, eye movement over a period of time, eye position over a period of time, and/or the like. In various examples, correlating tracking information may include determining at least one of a convergence pattern or a divergence pattern based on tracked movement of the first eye and tracked movement of the second eye.

[0054] Various aspects, examples, and techniques discussed herein may utilize one or more machine learning models (e.g., machine learning model 910 of FIG. 9), such as neural networks, deep learning models, and other techniques such as object recognition, and/or the like, to assist in one or more of eye tracking determinations, correlation determinations, e.g., based on data from the first eye and second eye, convergence and divergence determinations, and/or the like. Such machine learning models may be trained on data sets associating tracked eye movements and/or gaze motion patterns, determining eye movements, via reflected light, phase shifts, visual information, and/or the like.

[0055] At block 440, visual content may be provided in response to the determined gaze pattern. As discussed herein, such techniques may optionally be implemented on systems, methods, and devices (e.g., artificial reality system 600 of FIG. 6), for example, those associated with wearable technology, such as a head-mounted device, headset, smart glasses, helmet, visor, gaming device, or other smart device. Other examples may include non-wearable applications, which may include one or more cameras and sensors positioned a distance away from a user and configured to track eye movements. For example, conferencing systems and/or video systems may utilize any or all of the techniques discussed herein to provide accurate actions and/or interactions that may rely on where a user is looking and/or other gaze patterns.

[0056] In some examples, a display associated with a system (e.g., the first sensor system, the second sensor system) may project visual content in response to the determined gaze pattern. For example, in a smart glasses application, a gaze pattern indicating a shift in the user's gaze from an area beyond the glasses to the lens may cause a projection, object, or other visual content to be projected onto the leas. Additionally, certain gazes may be indicative of an interaction with a smart device. Thus, accurate and efficient gaze pattern detection may be desirable. Lower power consumption, improved speed, reduced latency, and other benefits may be realized through the heterogeneous systems discussed herein. Such benefits are becoming more desirable and important as technologies improve, some applications/devices are becoming smaller, and real-time interactions may be crucial for user experience and satisfaction.

[0057] FIG. 5 illustrates a flowchart for tracking eye movements in accordance with various aspects discussed herein. At block 510, visual information may be received, wherein the visual information is indicative of eye movements. Such information may be received via one or more sensors, cameras, and techniques, as discussed herein. In some examples, the visual information, indicative of eye movements, may be received by a device (e.g., artificial reality system 600).

[0058] At block 520, one or more techniques may be applied to reduce latency, bandwidth, and/or power consumption. In some examples, the one or more techniques may be applied by a device (e.g., artificial reality system 600) to reduce latency, bandwidth, and/or power consumption. As described herein, applying a heterogeneous eye tracking technique, wherein eyes are tracked using different sensing techniques, and the eye movements are correlated, may provide significant benefits over traditional methods of using a single technique, without correlating movements from both eyes.

[0059] At block 530, eye movements may be visually tracked via a camera, photosensor, or other sensor system. In some examples, the eye movements may be visually tracked via a device (e.g., artificial reality system 600). Such techniques may utilize object recognition and/or other tracking techniques to analyze an eye's movement over time. In this, and any of the various techniques discussed herein, an eye's pupil may be tracked over time.

Changes in pupil position, size, and/or the like may provide useful information for eye tracking and gaze motion pattern determinations.

[0060] At block 540, a technique may determine an amount of reflected light in response to eye movements. In some examples, a device (e.g., artificial reality system 600) may determine the amount of reflected light in response to eye movements. Such techniques may utilize infrared light to determine eye movements. While infrared light may be useful so as to not disturb, be noticeable, or otherwise affect user experience, different wavelengths of light may be utilized as well.

[0061] At block 550, events associated with eye movement may be tracked. In some examples, the events associated with the eye movement may be tracked by a device (e.g., artificial reality system 600). As discussed herein, events may be determined by changes in brightness/intensity levels of received light. Pupil movements may also cause recognition of an event. Any of a plurality of techniques, event thresholds, and/or the like may be implemented in accordance with aspects discussed herein.

[0062] At block 560, a range imaging technique may be applied to track eye movements. In some examples, a range imaging technique implemented by a device (e.g., artificial reality system 600) may be applied to track eye movements. Such range imaging techniques may include one or more of iTOF, dTOF, triangulation, and/or the like.

[0063] Any combination of the above techniques may be utilized in accordance with heterogeneous eye tracking, correlation, and gaze motion pattern determinations discussed herein. Various combinations may be useful to achieve certain goals or thresholds related to one or more of latency, bandwidth, power consumption, accuracy, and/or resolution, among others.

[0064] FIG. 6 illustrates an example artificial reality system 600. The artificial reality system 600 can include a head-mounted display (HMD) 610 (e.g., glasses) comprising a frame 612, one or more displays 614, and a computing device 608 (also referred to herein as computing device 608). The displays 614 can be transparent or translucent, allowing a user wearing the HMD 610 to look through the displays 614 to see the real world and displaying visual artificial reality content to the user at the same time. The HMD 610 can include an audio device 606 (e.g., speaker/microphone 38 of FIG. 6) that can provide audio artificial reality content to users. The HMD 610 can include one or more cameras 616 which can capture images and videos of environments. The HMD 610 can include an eye tracking system to track the vergence movement of the user wearing the HMD 610. In one example embodiment, the camera 616 can be the eye tracking system. The HMD 610 can include a microphone of the audio device 606 to capture voice input from the user. The artificial reality system 600 can further include a controller 618 (e.g., processor 32 of FIG. 7) comprising a trackpad and one or more buttons. The controller can receive inputs from users and relay the inputs to the computing device 608. The controller can also provide haptic feedback to users. The computing device 608 can be connected to the HMD 610 and the controller through cables or wireless connections. The computing device 608 can control the HMD 610 and the controller to provide the augmented reality content to and receive inputs from one or more users. In some example embodiments, the controller 618 can be a standalone controller or integrated within the HMD 610. The computing device 608 can be a standalone host computer device, an on-board computer device integrated with the HMD 610, a mobile device, or any other hardware platform capable of providing artificial reality content to and receiving inputs from users. In some exemplary embodiments, HMD 610 can include an artificial reality system/virtual reality system (e.g., artificial reality system).

[0065] FIG. 7 illustrates a block diagram of an exemplary hardware/software architecture of a UE 30. As shown in FIG. 7, the UE 30 (also referred to herein as node 30) can include a processor 32, non-removable memory 44, removable memory 46, a speaker/microphone 38, a keypad 40, a display, touchpad, and/or indicators 42, a power source 48, a global positioning system (GPS) chipset 50, and other peripherals 52. The UE 30 can also include a camera 54. In an exemplary embodiment, the camera 54 is a smart camera configured to sense images appearing within one or more bounding boxes. The UE 30 can also include communication circuitry, such as a transceiver 34 and a transmit/receive element 36. It will be appreciated the UE 30 can include any sub-combination of the foregoing elements while remaining consistent with an embodiment.

[0066] The processor 32 can be a special purpose processor, a digital signal processor (DSP), a plurality of microprocessors, one or more microprocessors in association with a DSP core, a controller, a microcontroller, Application Specific Integrated Circuits (ASICs), Field Programmable Gate Array (FPGAs) circuits, any other type of integrated circuit (IC), a state machine, and the like. In general, the processor 32 can execute computer-executable instructions stored in the memory (e.g., non-removable memory 44 and/or memory 46) of the node 30 in order to perform the various required functions of the node. For example, the processor 32 can perform signal coding, data processing, power control, input/output processing, and/or any other functionality that enables the node 30 to operate in a wireless or wired environment. The processor 32 can run application-layer programs (e.g., browsers) and/or radio access-layer (RAN) programs and/or other communications programs. The processor 32 can also perform security operations such as authentication, security key agreement, and/or cryptographic operations, such as at the access-layer and/or application layer, for example.

[0067] The processor 32 is coupled to its communication circuitry (e.g., transceiver 34 and transmit/receive element 36). The processor 32, through the execution of computer executable instructions, can control the communication circuitry in order to cause the node 30 to communicate with other nodes via the network to which it is connected.

[0068] The transmit/receive element 36 can be configured to transmit signals to, or receive signals from, other nodes or networking equipment. For example, in an embodiment, the transmit/receive element 36 can be an antenna configured to transmit and/or receive radio frequency (RF) signals. The transmit/receive element 36 can support various networks and air interfaces, such as wireless local area network (WLAN), wireless personal area network (WPAN), cellular, and the like. In yet another embodiment, the transmit/receive element 36 can be configured to transmit and receive both RF and light signals. It will be appreciated that the transmit/receive element 36 can be configured to transmit and/or receive any combination of wireless or wired signals.

[0069] The transceiver 34 can be configured to modulate the signals that are to be transmitted by the transmit/receive element 36 and to demodulate the signals that are received by the transmit/receive element 36. As noted above, the node 30 can have multi-mode capabilities. Thus, the transceiver 34 can include multiple transceivers for enabling the node 30 to communicate via multiple radio access technologies (RATs), such as universal terrestrial radio access (UTRA) and Institute of Electrical and Electronics Engineers (IEEE 802.11), for example.

[0070] The processor 32 can access information from, and store data in, any type of suitable memory, such as the non-removable memory 44 and/or the removable memory 46. For example, the processor 32 can store session context in its memory, as described above. The non-removable memory 44 can include RAM, ROM, a hard disk, or any other type of memory storage device. The removable memory 46 can include a subscriber identity module (SIM) card, a memory stick, a secure digital (SD) memory card, and the like. In other embodiments, the processor 32 can access information from, and store data in, memory that is not physically located on the node 30, such as on a server or a home computer.

[0071] The processor 32 can receive power from the power source 48, and can be configured to distribute and/or control the power to the other components in the node 30. The power source 48 can be any suitable device for powering the node 30. For example, the power source 48 can include one or more dry cell batteries (e.g., nickel-cadmium (NiCd), nickel-zinc (NiZn), nickel metal hydride (NiMH), lithium-ion (Li-ion), etc.), solar cells, fuel cells, and the like.

[0072] The processor 32 can also be coupled to the GPS chipset 50, which can be configured to provide location information (e.g., longitude and latitude) regarding the current location of the node 30. It will be appreciated that the node 30 can acquire location information by way of any suitable location-determination method while remaining consistent with an exemplary embodiment.

[0073] FIG. 8 is a block diagram of a computing system 800 which can also be used to implement components of the system or be part of the UE 30. The computing system 800 can comprise a computer or server and can be controlled primarily by computer readable instructions, which can be in the form of software, wherever, or by whatever means such software is stored or accessed. Such computer readable instructions can be executed within a processor, such as central processing unit (CPU) 91, to cause computing system 800 to operate. In many workstations, servers, and personal computers, central processing unit 91 can be implemented by a single-chip CPU called a microprocessor. In other machines, the central processing unit 91 can comprise multiple processors. Coprocessor 81 can be an optional processor, distinct from main CPU 91, that performs additional functions or assists CPU 91.

[0074] In operation, CPU 91 fetches, decodes, and executes instructions, and transfers information to and from other resources via the computer's main data-transfer path, system bus 80. Such a system bus connects the components in computing system 800 and defines the medium for data exchange. System bus 80 typically includes data lines for sending data, address lines for sending addresses, and control lines for sending interrupts, and for operating the system bus. An example of such a system bus 80 is the Peripheral Component Interconnect (PCI) bus.

[0075] Memories coupled to system bus 80 include RAM 82 and ROM 93. Such memories can include circuitry that allows information to be stored and retrieved. ROMs 93 generally contain stored data that cannot easily be modified. Data stored in RAM 82 can be read or changed by CPU 91 or other hardware devices. Access to RAM 82 and/or ROM 93 can be controlled by memory controller 92. Memory controller 92 can provide an address translation function that translates virtual addresses into physical addresses as instructions are executed. Memory controller 92 can also provide a memory protection function that isolates processes within the system and isolates system processes from user processes. Thus, a program running in a first mode can access only memory mapped by its own process virtual address space; it cannot access memory within another process's virtual address space unless memory sharing between the processes has been set up.

[0076] In addition, computing system 800 can contain peripherals controller 83 responsible for communicating instructions from CPU 91 to peripherals, such as printer 94, keyboard 84, mouse 95, and disk drive 85.

[0077] Display 86, which is controlled by display controller 96, is used to display visual output generated by computing system 800. Such visual output can include text, graphics, animated graphics, and video. Display 86 can be implemented with a cathode-ray tube (CRT)-based video display, a liquid-crystal display (LCD)-based flat-panel display, gas plasma-based flat-panel display, or a touch-panel. Display controller 96 includes electronic components required to generate a video signal that is sent to display 86.

[0078] Further, computing system 800 can contain communication circuitry, such as for example a network adaptor 97, that can be used to connect computing system 800 to an external communications network, such as network 12 of FIG. 7, to enable the computing system 800 to communicate with other nodes (e.g., UE 30) of the network.

[0079] FIG. 9 illustrates a framework 900 employed by a software application (e.g., an algorithm) for evaluating attributes of a gesture. The framework 900 can be hosted remotely. Alternatively, the framework 900 can reside within the UE 30 shown in FIG. 7 and/or be processed by the computing system 800 shown in FIG. 8. The machine learning model 910 is operably coupled to the stored training data 920 in a database.

[0080] In an exemplary embodiment, the training data 920 can include attributes of thousands of objects. For example, the object can include eye positions and movements, pupil sizes, eye positions associated with various positions and the like. Attributes can include, but are not limited to the size, shape, orientation, position of the object, i.e., eye, gaze, etc. The training data 920 employed by the machine learning model 910 can be fixed or updated periodically. Alternatively, the training data 920 can be updated in real-time based upon the evaluations performed by the machine learning model 910 in a non-training mode. This is illustrated by the double-sided arrow connecting the machine learning model 910 and stored training data 920.

[0081] In operation, the machine learning model 910 can evaluate attributes of images/videos obtained by hardware (e.g., of the AR device 120, UE 30, etc.). For example, the camera 124 of AR device 120 and/or camera 54 of the UE 30 shown in FIG. 7 senses and captures an image/video, such as, for example approaching or departing objects, object interactions, hang gestures, and/or other objects, appearing in or around a bounding box of a software application. The attributes of the captured image (e.g., captured image of an object or person are then compared with respective attributes of stored training data 920 (e.g., prestored objects). The likelihood of similarity between each of the obtained attributes (e.g., of the captured image of an object(s)) and the stored training data 920 (e.g., prestored objects) is given a confidence score. In one exemplary embodiment, if the confidence score exceeds a predetermined threshold, the attribute is included in an image description that is ultimately communicated to the user via a user interface of a computing device (e.g., UE 30, computing device). In another exemplary embodiment, the description can include a certain number of attributes which exceed a predetermined threshold to share with the user. The sensitivity of sharing more or less attributes can be customized based upon the needs of the particular user.

[0082] FIG. 10 illustrates an example computer system 1000. In exemplary embodiments, one or more computer systems 1000 perform one or more steps of one or more methods described or illustrated herein. In particular embodiments, one or more computer systems 1000 provide functionality described or illustrated herein. In exemplary embodiments, software running on one or more computer systems 1000 performs one or more steps of one or more methods described or illustrated herein or provides functionality described or illustrated herein. Exemplary embodiments include one or more portions of one or more computer systems 1000. Herein, a reference to a computer system can encompass a computing device, and vice versa, where appropriate. Moreover, a reference to a computer system can encompass one or more computer systems, where appropriate.

[0083] This disclosure contemplates any suitable number of computer systems 1000. This disclosure contemplates computer system 1000 taking any suitable physical form. As example and not by way of limitation, computer system 1000 can be an embedded computer system, a system-on-chip (SOC), a single-board computer system (SBC) (such as, for example, a computer-on-module (COM) or system-on-module (SOM)), a desktop computer system, a laptop or notebook computer system, an interactive kiosk, a mainframe, a mesh of computer systems, a mobile telephone, a personal digital assistant (PDA), a server, a tablet computer system, or a combination of two or more of these. Where appropriate, computer system 1000 can include one or more computer systems 1000; be unitary or distributed; span multiple locations; span multiple machines; span multiple data centers; or reside in a cloud, which can include one or more cloud components in one or more networks. Where appropriate, one or more computer systems 1000 can perform without substantial spatial or temporal limitations, one or more steps of one or more methods described or illustrated herein. As an example, and not by way of limitation, one or more computer systems 1000 can perform in real time or in batch mode one or more steps of one or more methods described or illustrated herein. One or more computer systems 1000 can perform at different times or at different locations one or more steps of one or more methods described or illustrated herein, where appropriate.

[0084] In exemplary embodiments, computer system 1000 includes a processor 1002, memory 1004, storage 1006, an input/output (I/O) interface 1008, a communication interface 1010, and a bus 1012. Although this disclosure describes and illustrates a particular computer system having a particular number of particular components in a particular arrangement, this disclosure contemplates any suitable computer system having any suitable number of any suitable components in any suitable arrangement.

[0085] In exemplary embodiments, processor 1002 includes hardware for executing instructions, such as those making up a computer program. As an example and not by way of limitation, to execute instructions, processor 1002 can retrieve (or fetch) the instructions from an internal register, an internal cache, memory 1004, or storage 1006; decode and execute them; and then write one or more results to an internal register, an internal cache, memory 1004, or storage 1006. In particular embodiments, processor 1002 can include one or more internal caches for data, instructions, or addresses. This disclosure contemplates processor 1002, including any suitable number of any suitable internal caches, where appropriate. As an example and not by way of limitation, processor 1002 can include one or more instruction caches, one or more data caches, and one or more translation lookaside buffers (TLBs). Instructions in the instruction caches can be copies of instructions in memory 1004 or storage 1006, and the instruction caches can speed up retrieval of those instructions by processor 1002. Data in the data caches can be copies of data in memory 1004 or storage 1006 for instructions executing at processor 1002 to operate on; the results of previous instructions executed at processor 1002 for access by subsequent instructions executing at processor 1002 or for writing to memory 1004 or storage 1006; or other suitable data. The data caches can speed up read or write operations by processor 1002. The TLBs can speed up virtual-address translation for processor 1002. In particular embodiments, processor 1002 can include one or more internal registers for data, instructions, or addresses. This disclosure contemplates processor 1002 including any suitable number of any suitable internal registers, where appropriate. Where appropriate, processor 1002 can include one or more arithmetic logic units (ALUs); be a multi-core processor; or include one or more processors 1002. Although this disclosure describes and illustrates a particular processor, this disclosure contemplates any suitable processor.

[0086] In exemplary embodiments, memory 1004 includes main memory for storing instructions for processor 1002 to execute or data for processor 1002 to operate on. As an example, and not by way of limitation, computer system 1000 can load instructions from storage 1006 or another source (such as, for example, another computer system 1000) to memory 1004. Processor 1002 can then load the instructions from memory 1004 to an internal register or internal cache. To execute the instructions, processor 1002 can retrieve the instructions from the internal register or internal cache and decode them. During or after execution of the instructions, processor 1002 can write one or more results (which can be intermediate or final results) to the internal register or internal cache. Processor 1002 can then write one or more of those results to memory 1004. In particular embodiments, processor 1002 executes only instructions in one or more internal registers or internal caches or in memory 1004 (as opposed to storage 1006 or elsewhere) and operates only on data in one or more internal registers or internal caches or in memory 1004 (as opposed to storage 1006 or elsewhere). One or more memory buses (which can each include an address bus and a data bus) can couple processor 1002 to memory 1004. Bus 1012 can include one or more memory buses, as described below. In exemplary embodiments, one or more memory management units (MMUs) reside between processor 1002 and memory 1004 and facilitate accesses to memory 1004 requested by processor 1002. In particular embodiments, memory 1004 includes random access memory (RAM). This RAM can be volatile memory, where appropriate. Where appropriate, this RAM can be dynamic RAM (DRAM) or static RAM (SRAM). Moreover, where appropriate, this RAM can be single-ported or multi-ported RAM. This disclosure contemplates any suitable RAM. Memory 1004 can include one or more memories 1004, where appropriate. Although this disclosure describes and illustrates particular memory, this disclosure contemplates any suitable memory.

[0087] In exemplary embodiments, storage 1006 includes mass storage for data or instructions. As an example, and not by way of limitation, storage 1006 can include a hard disk drive (HDD), a floppy disk drive, flash memory, an optical disc, a magneto-optical disc, magnetic tape, or a Universal Serial Bus (USB) drive, or a combination of two or more of these. Storage 1006 can include removable or non-removable (or fixed) media, where appropriate. Storage 1006 can be internal or external to computer system 1000, where appropriate. In exemplary embodiments, storage 1006 is non-volatile, solid-state memory. In particular embodiments, storage 1006 includes read-only memory (ROM). Where appropriate, this ROM can be mask-programmed ROM, programmable ROM (PROM), erasable PROM (EPROM), electrically erasable PROM (EEPROM), electrically alterable ROM (EAROM), or flash memory or a combination of two or more of these. This disclosure contemplates mass storage 1006 taking any suitable physical form. Storage 1006 can include one or more storage control units facilitating communication between processor 1002 and storage 1006, where appropriate. Where appropriate, storage 1006 can include one or more storages 1006. Although this disclosure describes and illustrates particular storage, this disclosure contemplates any suitable storage.

[0088] In exemplary embodiments, I/O interface 1008 includes hardware, software, or both, providing one or more interfaces for communication between computer system 1000 and one or more I/O devices. Computer system 1000 can include one or more of these I/O devices, where appropriate. One or more of these I/O devices can enable communication between a person and computer system 1000. As an example and not by way of limitation, an I/O device can include a keyboard, keypad, microphone, monitor, mouse, printer, scanner, speaker, still camera, stylus, tablet, touch screen, trackball, video camera, another suitable I/O device or a combination of two or more of these. An I/O device can include one or more sensors. This disclosure contemplates any suitable I/O devices and any suitable I/O interfaces 1008 for them. Where appropriate, I/O interface 1008 can include one or more device or software drivers, enabling processor 1002 to drive one or more of these I/O devices. I/O interface 1008 can include one, or more I/O interfaces 1008, where appropriate. Although this disclosure describes and illustrates a particular I/O interface, this disclosure contemplates any suitable I/O interface.

[0089] In exemplary embodiments, communication interface 1010 includes hardware, software, or both providing one or more interfaces for communication (such as, for example, packet-based communication) between computer system 1000 and one or more other computer systems 1000 or one or more networks. As an example and not by way of limitation, communication interface 1010 can include a network interface controller (NIC) or network adapter for communicating with an Ethernet or other wire-based network or a wireless NIC (WNIC) or wireless adapter for communicating with a wireless network, such as a WI-FI network. This disclosure contemplates any suitable network and any suitable communication interface 1010 for it. As an example, and not by way of limitation, computer system 1000 can communicate with an ad hoc network, a personal area network (PAN), a local area network (LAN), a wide area network (WAN), a metropolitan area network (MAN), or one or more portions of the Internet, or a combination of two or more of these. One or more portions of one or more of these networks can be wired or wireless. As an example, computer system 1000 can communicate with a wireless PAN (WPAN) (such as, for example, a BLUETOOTH WPAN), a WI-FI network, a WI-MAX network, a cellular telephone network (such as, for example, a Global System for Mobile Communications (GSM) network), or other suitable wireless network or a combination of two or more of these. Computer system 1000 can include any suitable communication interface 1010 for any of these networks, where appropriate. Communication interface 1010 can include one or more communication interfaces 1010, where appropriate. Although this disclosure describes and illustrates a particular communication interface, this disclosure contemplates any suitable communication interface.

[0090] In particular embodiments, bus 1012 includes hardware, software, or both coupling components of computer system 1000 to each other. As an example and not by way of limitation, bus 1012 can include an Accelerated Graphics Port (AGP) or other graphics bus, an Enhanced Industry Standard Architecture (EISA) bus, a front-side bus (FSB), a HYPERTRANSPORT (HT) interconnect, an Industry Standard Architecture (ISA) bus, an INFINIBAND interconnect, a low-pin-count (LPC) bus, a memory bus, a Micro Channel Architecture (MCA) bus, a Peripheral Component Interconnect (PCI) bus, a PCI-Express (PCIe) bus, a serial advanced technology attachment (SATA) bus, a Video Electronics Standards Association local (VLB) bus, or another suitable bus or a combination of two or more of these. Bus 1012 can include one or more buses 1012, where appropriate. Although this disclosure describes and illustrates a particular bus, this disclosure contemplates any suitable bus or interconnect.

[0091] Herein, a computer-readable non-transitory storage medium or media can include one or more semiconductor-based or other integrated circuits (ICs) (such, as for example, field-programmable gate arrays (FPGAs) or application-specific ICs (ASICs)), hard disk drives (HDDs), hybrid hard drives (HHDs), optical discs, optical disc drives (ODDs), magneto-optical discs, magneto-optical drives, floppy diskettes, floppy disk drives (FDDs), magnetic tapes, solid-state drives (SSDs), RAM-drives, SECURE DIGITAL cards or drives, any other suitable computer-readable non-transitory storage media, computer readable medium or any suitable combination of two or more of these, where appropriate. A computer-readable non-transitory storage medium can be volatile, non-volatile, or a combination of volatile and non-volatile, where appropriate.

[0092] Herein, “or” is inclusive and not exclusive, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A or B” means “A, B, or both,” unless expressly indicated otherwise or indicated otherwise by context. Moreover, “and” is both joint and several, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A and B” means “A and B, jointly or severally,” unless expressly indicated otherwise or indicated otherwise by context.

[0093] The scope of this disclosure encompasses all changes, substitutions, variations, alterations, and modifications to the example embodiments described or illustrated herein that a person having ordinary skill in the art would comprehend. The scope of this disclosure is not limited to the example embodiments described or illustrated herein. Moreover, although this disclosure describes and illustrates respective embodiments herein as including particular components, elements, feature, functions, operations, or steps, any of these embodiments can include any combination or permutation of any of the components, elements, features, functions, operations, or steps described or illustrated anywhere herein that a person having ordinary skill in the art would comprehend. Furthermore, reference in the appended claims to an apparatus or system or a component of an apparatus or system being adapted to, arranged to, capable of, configured to, enabled to, operable to, or operative to perform a particular function encompasses that apparatus, system, component, whether or not it or that particular function is activated, turned on, or unlocked, as long as that apparatus, system, or component is so adapted, arranged, capable, configured, enabled, operable, or operative. Additionally, although this disclosure describes or illustrates particular embodiments as providing particular advantages, particular embodiments can provide none, some, or all of these advantages.

What is Claimed:

1. A system for heterogeneous eye tracking, comprising:

a first sensor system tracking movement of a first eye;

a second sensor system tracking movement of a second eye, wherein the second sensor system applies a different tracking method than the first sensor system; and

a processor and a non-transitory memory including computer-executable instructions, which when executed, cause the processor to at least:

correlate tracking information received from the first sensor system and the second sensor system to determine a gaze motion pattern.

2. The system of claim 1, wherein the tracking method of at least one sensor system applies at least one of visual tracking via a camera, photosensor oculography (PSOG), fringe tracking, real-time event-based tracking, indirect time of flight measurements, or range imaging.

3. The system of claim 1, wherein correlating tracking information comprises determining at least one of a convergence pattern or a divergence pattern based on tracked movement of the first eye and tracked movement of the second eye.

4. The system of claim 1, wherein the gaze motion pattern is a three-dimensional gaze motion pattern.

5. The system of claim 1, further comprising applying a machine learning module trained on data sets associating tracked eye movements and gaze motion patterns to determine the gaze motion pattern.

6. The system of claim 1, further comprising a third sensor system to track movement of the first eye, wherein the third sensor system applies a different tracking method than the first sensor system.

7. The system of claim 1, further comprising a fourth sensor system to track movement of the second eye, wherein the fourth sensor system applies a different tracking method than the second sensor system.

8. The system of claim 1, wherein the first sensor system or the second sensing system comprises at least one of: a range imaging camera, a photosensor, a fringe sensor, or an event camera.

9. The system of claim 1, wherein the first sensor system and the second sensor system are mounted on a head-mounted device.

10. The system of claim 9, wherein the head-mounted device is at least one of a headset, glasses, helmet, visor, gaming device, or a smart device.

11. The system of claim 9, wherein the head-mounted device comprises a display projecting visual content responsive to the determined gaze motion pattern.

12. A method for heterogeneous eye tracking, comprising:

tracking movement of a first eye using a first sensor system;

tracking movement of a second eye using a second sensor system, wherein the second sensor system applies a different tracking method than different than the first sensor system; and

correlate tracking information received from the first sensor system and the second sensor system to determine a gaze motion pattern.

13. The method of claim 12, wherein the gaze motion pattern is a three-dimensional gaze motion pattern.

14. The method of claim 12, wherein the tracking method of at least one sensory system applies at least one of visual tracking via a camera, photosensor oculography (PSOG), fringe tracking, real-time event-based tracking, indirect time of flight measurements, or range imaging.

15. The method of claim 12, wherein the first sensor system and second sensor system are positioned outside of a field of view of the first eye and the second eye.

16. A non-transitory, computer readable medium including computer-executable instructions, which when executed by a processor, cause a computing device to at least:

track movement of a first eye using a first sensor system;

track movement of a second eye using a second sensor system, wherein the second sensor system applies a different tracking method than different than the first sensor system; and

correlate tracking information received from the first sensor system and the second sensor system to determine a gaze motion pattern.

17. The non-transitory, computer readable medium of claim 16, wherein correlating tracking information comprises determining at least one of a convergence pattern or a divergence pattern based on tracked movement of the first eye and tracked movement of the second eye, and wherein the gaze motion pattern is a three-dimensional gaze motion pattern.

18. The non-transitory, computer readable medium of claim 16, wherein the tracking method of at least one sensor system applies at least one of visual tracking via a camera, photosensor oculography (PSOG), fringe tracking, real-time event-based tracking, indirect time of flight measurements, or range imaging.

19. The non-transitory, computer readable medium of claim 16, wherein the first sensor system or the second sensing system comprises at least one of: a range imaging camera, a photosensor, a fringe sensor, or an event camera.

20. The non-transitory, computer readable medium of claim 16, wherein the first sensor system and the second sensor system are mounted on a head-mounted device comprising a display configured to provide visual content responsive to the determined gaze pattern.

ABSTRACT

Systems, methods, devices, and computer program products are provided for eye tracking and gaze pattern determinations using heterogeneous sensor systems. A first sensor system may track movement of a first eye, and a second sensor system may track movement of a second eye, wherein the second sensor system applies a different tracking method than the first sensor system. Tracking information received from the first sensor and the second sensor may be correlated to determine a gaze motion pattern, such as a three-dimensional motion pattern. The heterogeneous nature of the sensors enables realization of numerous advantages, including but not limited to reduced power consumption and latency, and improved accuracy and resolution.

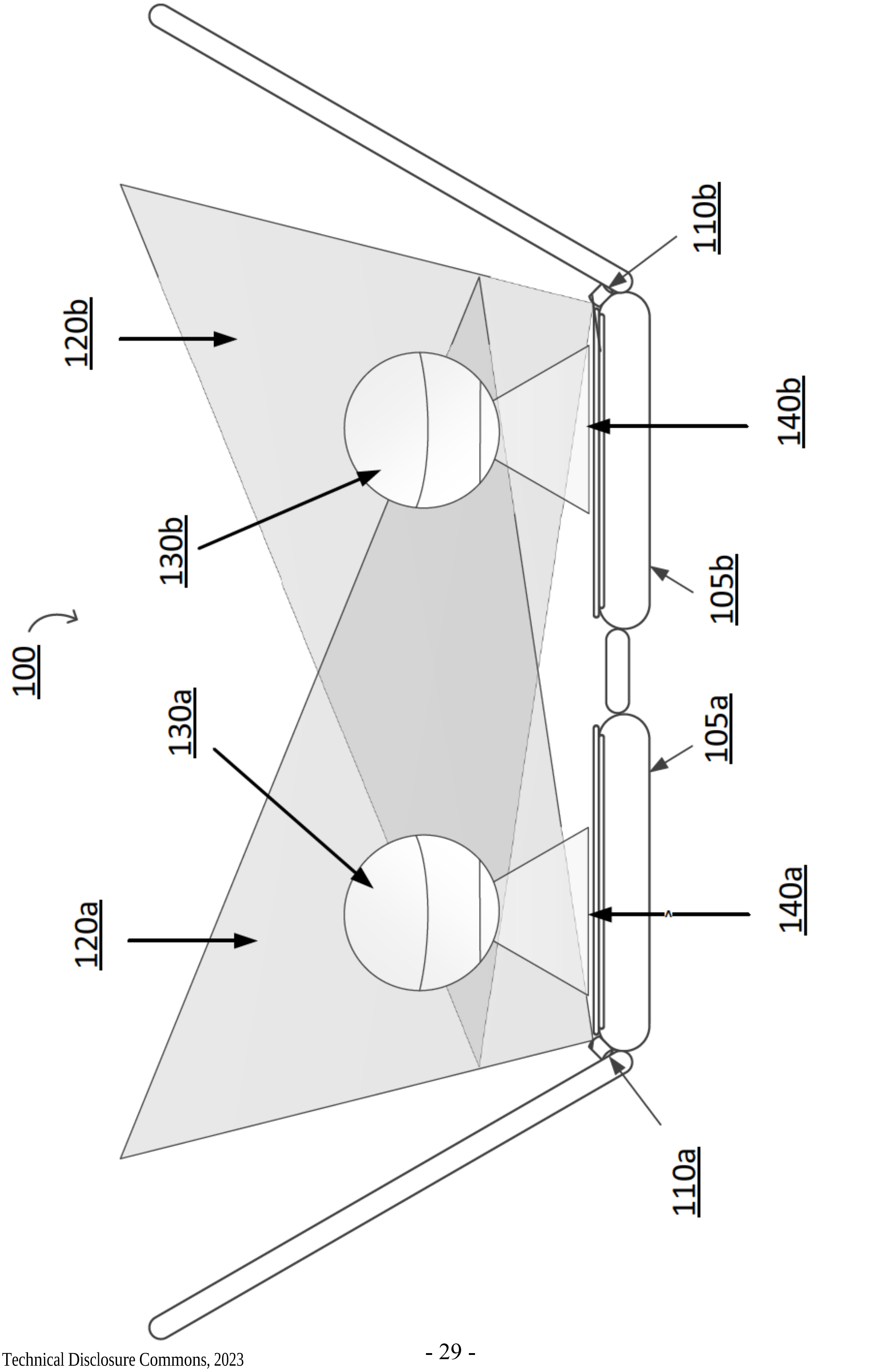

FIG. 1

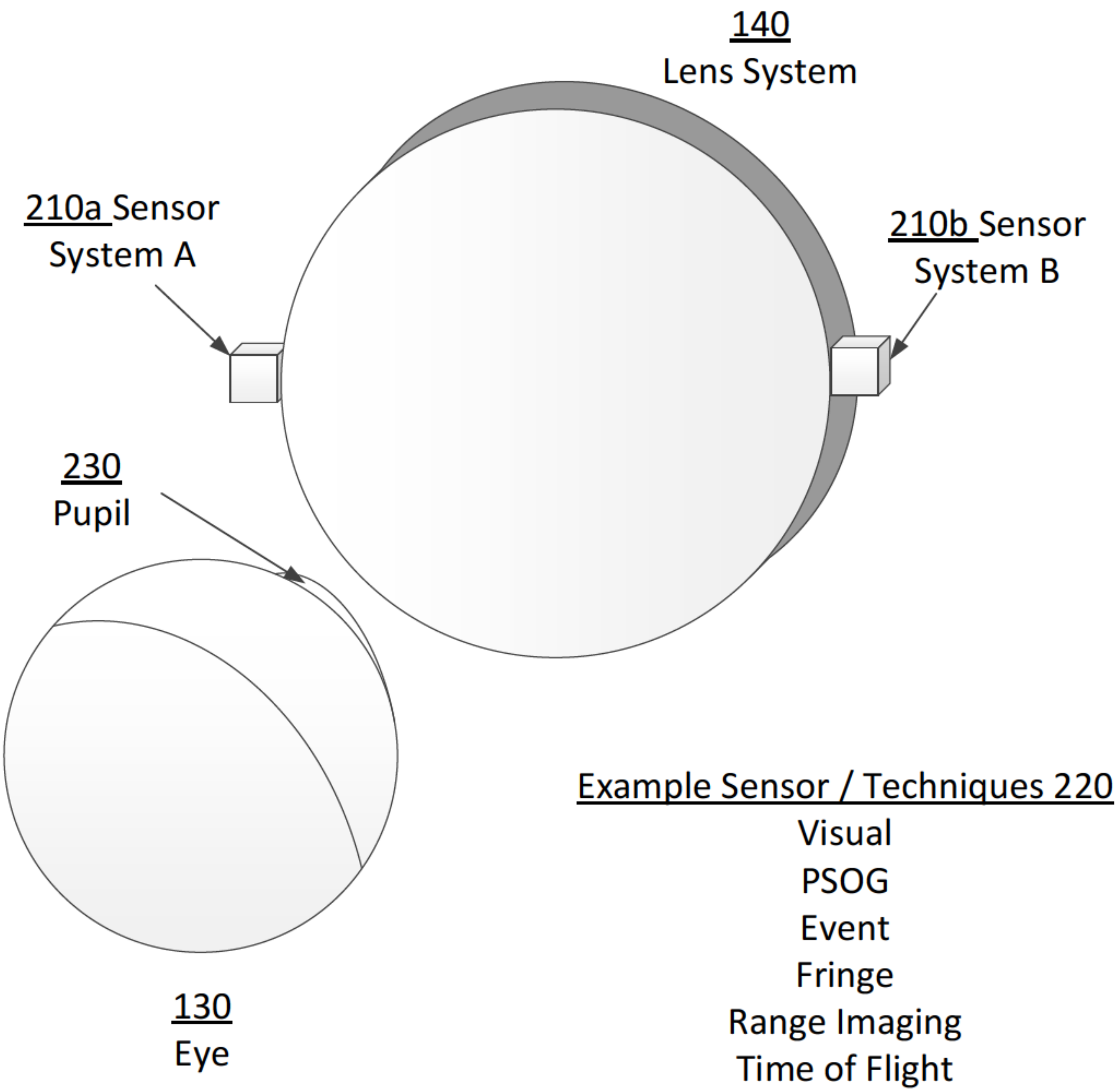
140
Lens System
210a Sensor System A
210b Sensor System B
230
Pupil
130
Eye
Example Sensor / Techniques 220
Visual
PSOG
Event
Fringe
Range Imaging
Time of Flight

FIG. 2

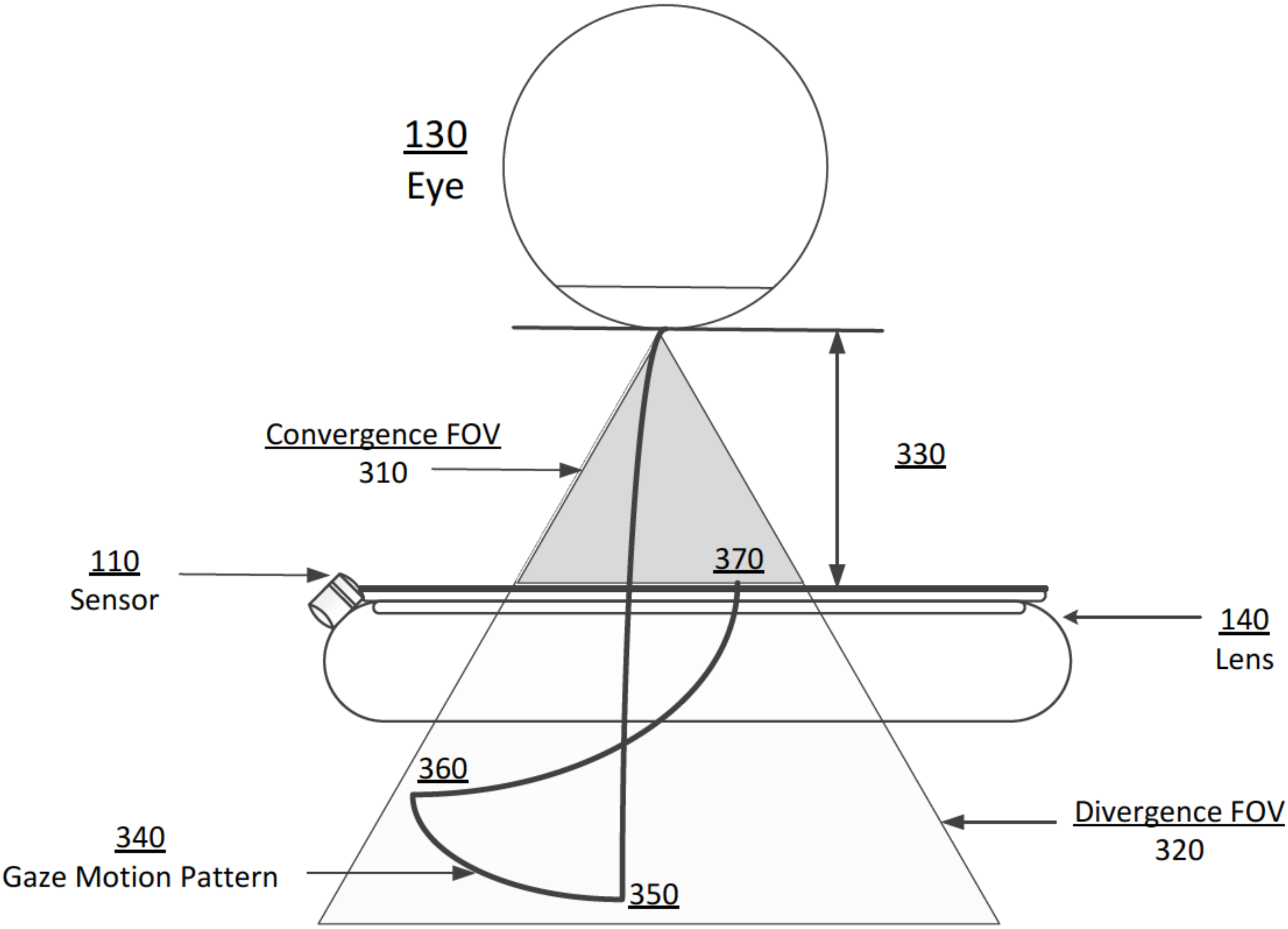
130
Eye
Convergence FOV
310
330
110
Sensor
370
140
Lens
360
340
Gaze Motion Pattern
Divergence FOV
320
350

FIG. 3

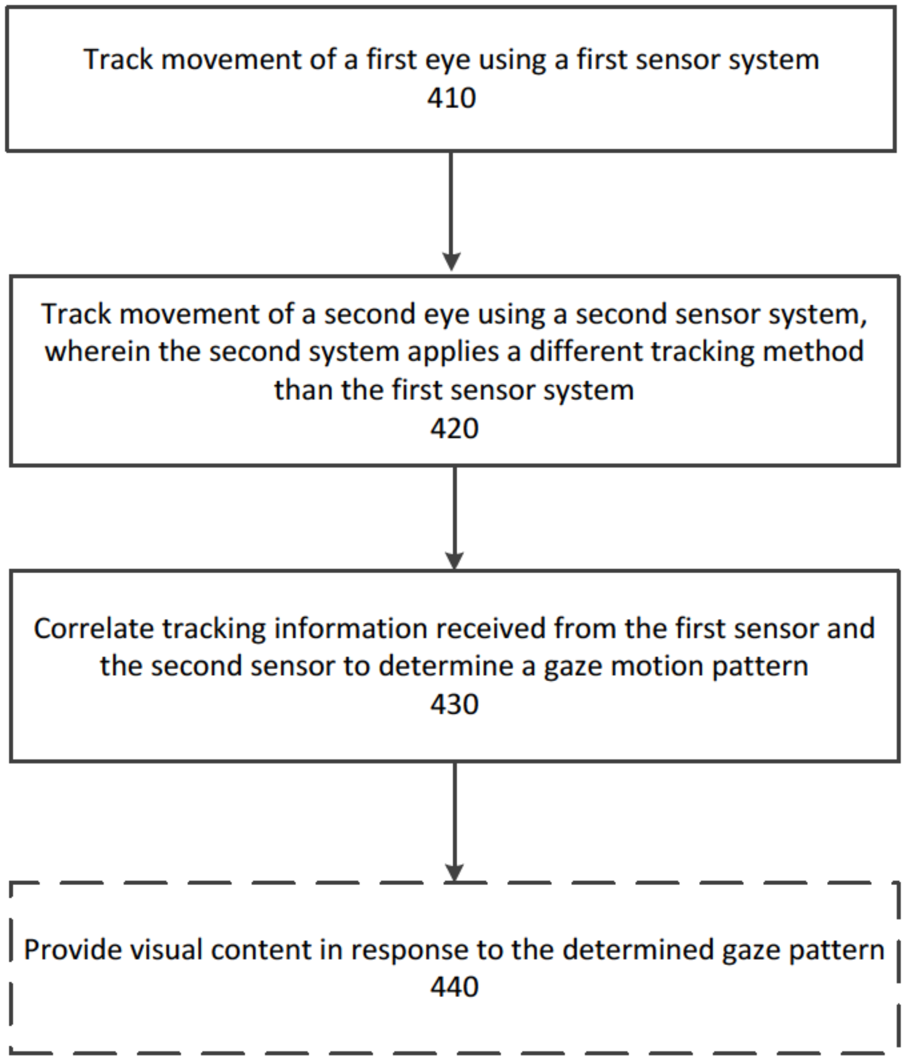
Track movement of a first eye using a first sensor system
410
Track movement of a second eye using a second sensor system, wherein the second system applies a different tracking method than the first sensor system
420
Correlate tracking information received from the first sensor and the second sensor to determine a gaze motion pattern
430
Provide visual content in response to the determined gaze pattern
440

FIG. 4

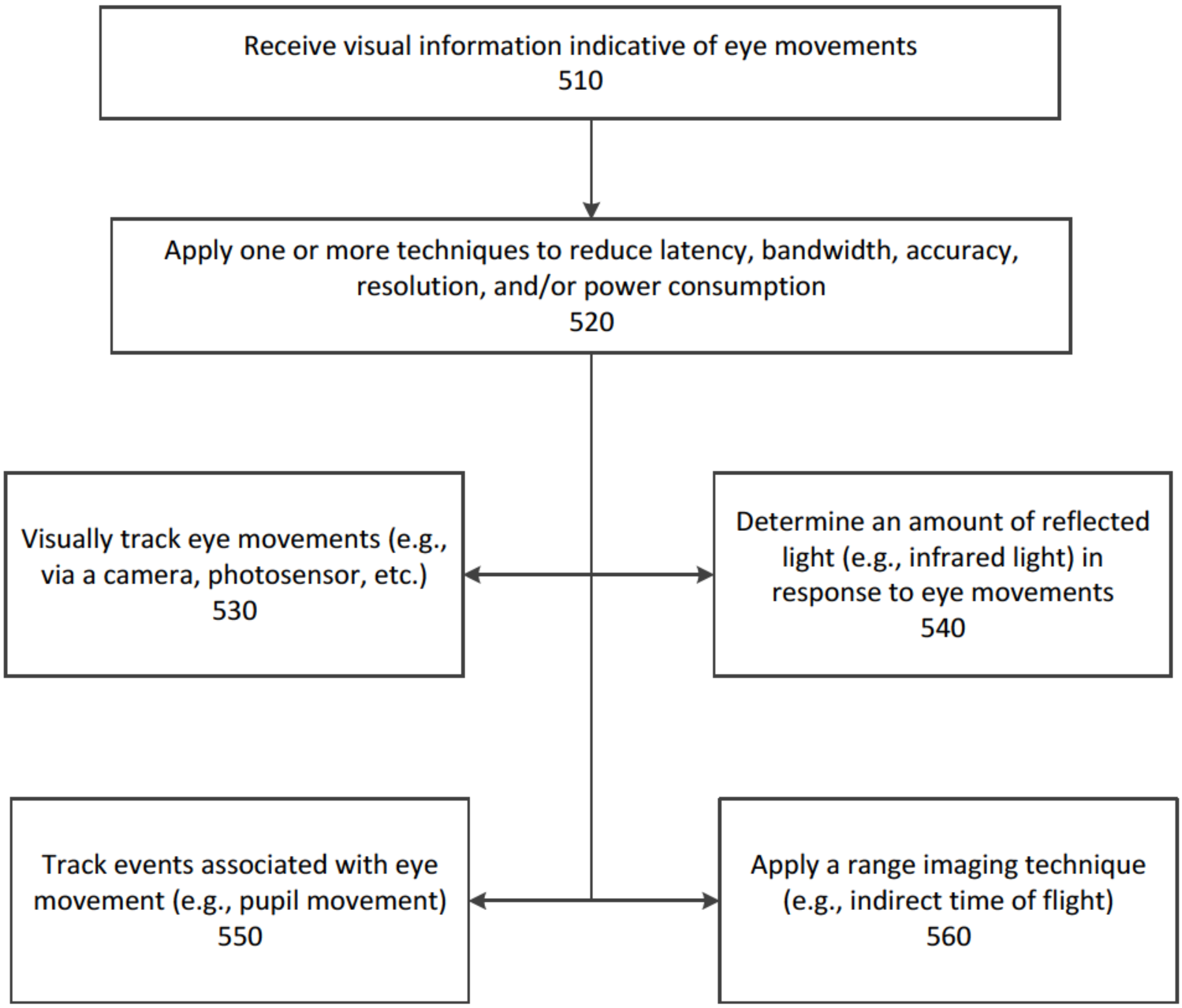
Receive visual information indicative of eye movements
510
Apply one or more techniques to reduce latency, bandwidth, accuracy, resolution, and/or power consumption
520
Visually track eye movements (e.g., via a camera, photosensor, etc.)
530
Determine an amount of reflected light (e.g., infrared light) in response to eye movements
540
Track events associated with eye movement (e.g., pupil movement)
550
Apply a range imaging technique (e.g., indirect time of flight)
560

FIG. 5

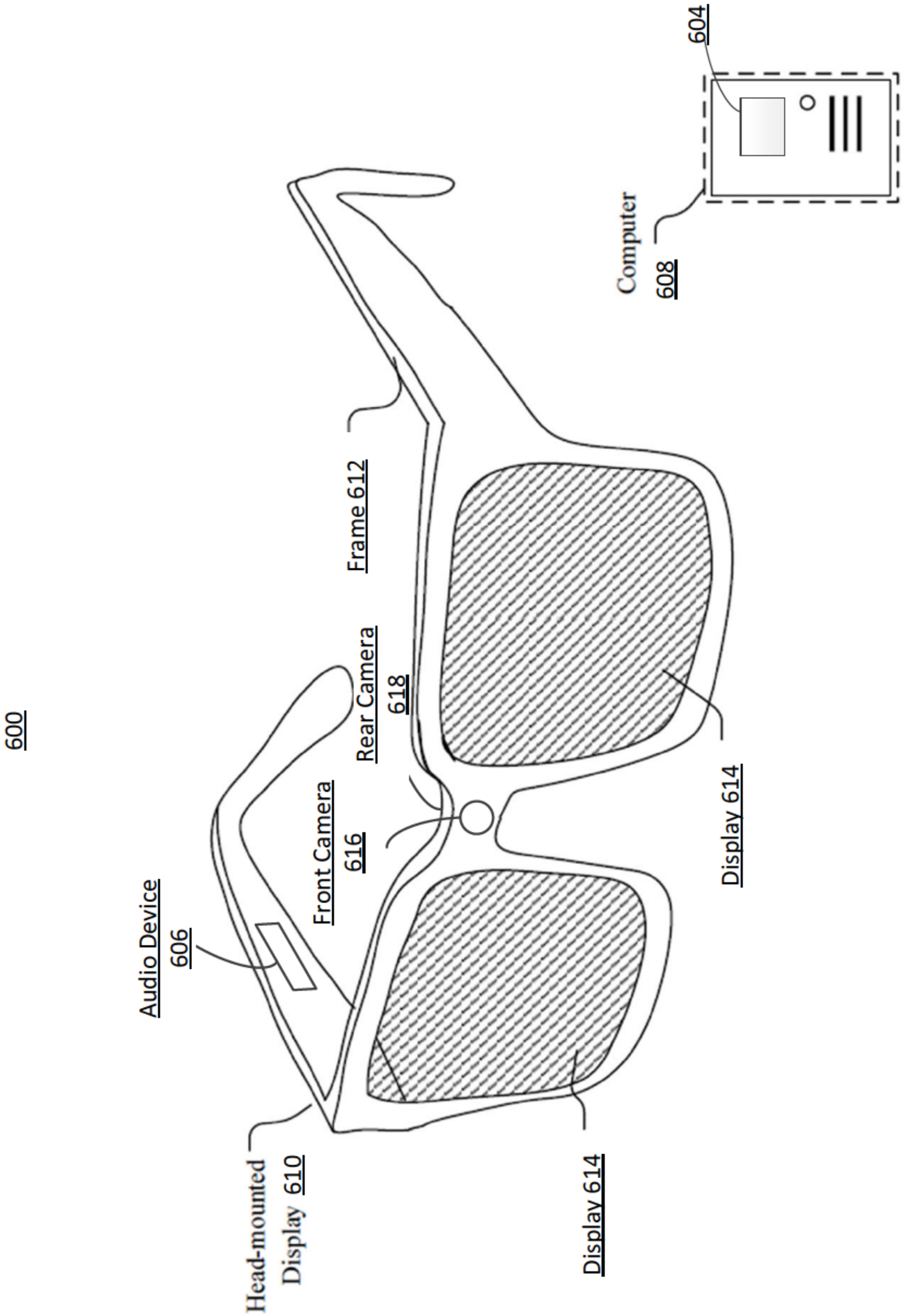
600
Computer
608
604
Frame 612
Rear Camera
618
Front Camera
616
Audio Device
606
Display 614
Display 614
Head-mounted
Display 610

FIG. 6

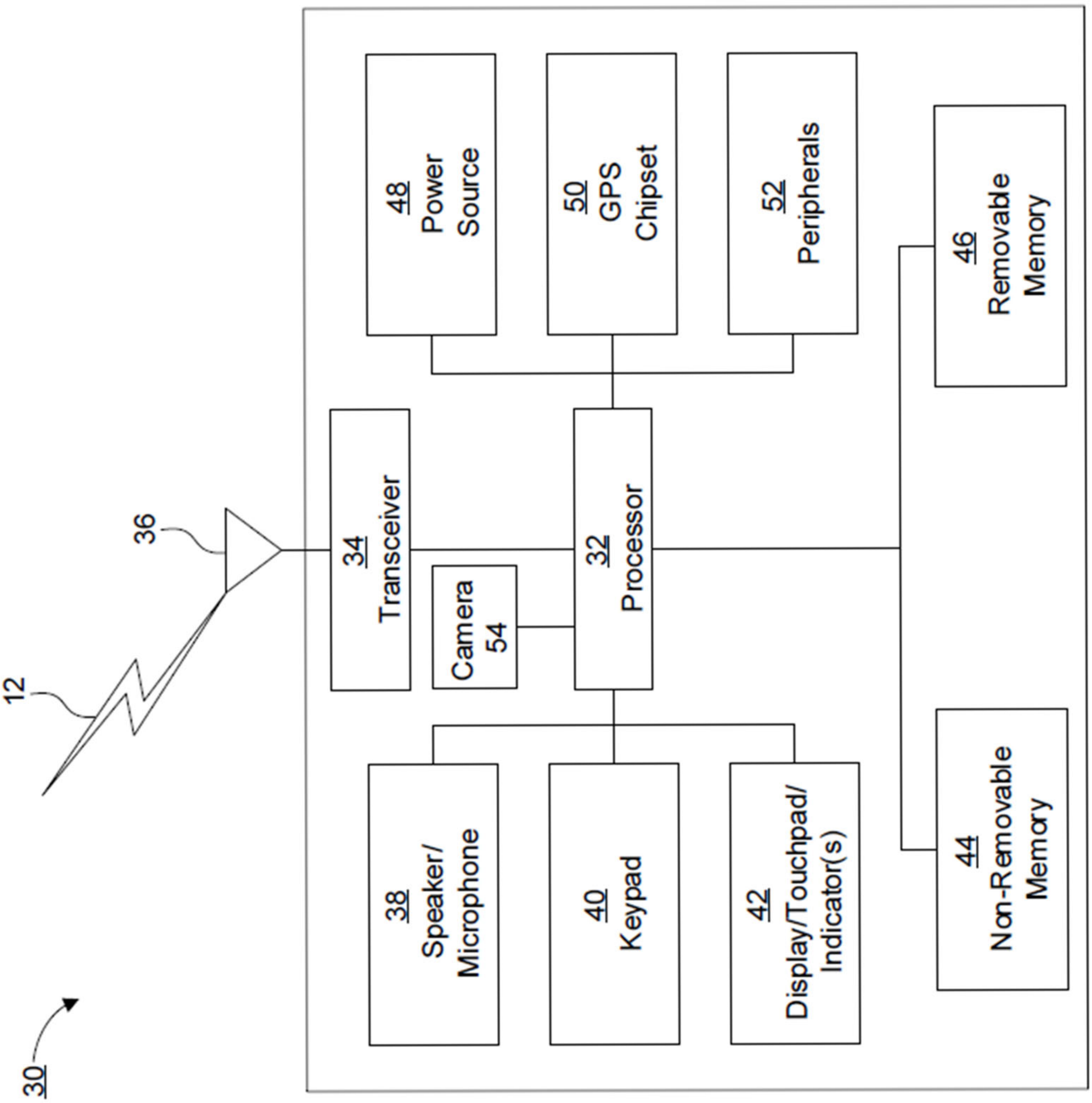
30
12
36
34
Transceiver
Camera
54
32
Processor
48
Power
Source
50
GPS
Chipset
52
Peripherals
46
Removable
Memory
38
Speaker/
Microphone
40
Keypad
42
Display/Touchpad/
Indicator(s)
44
Non-Removable
Memory

FIG. 7

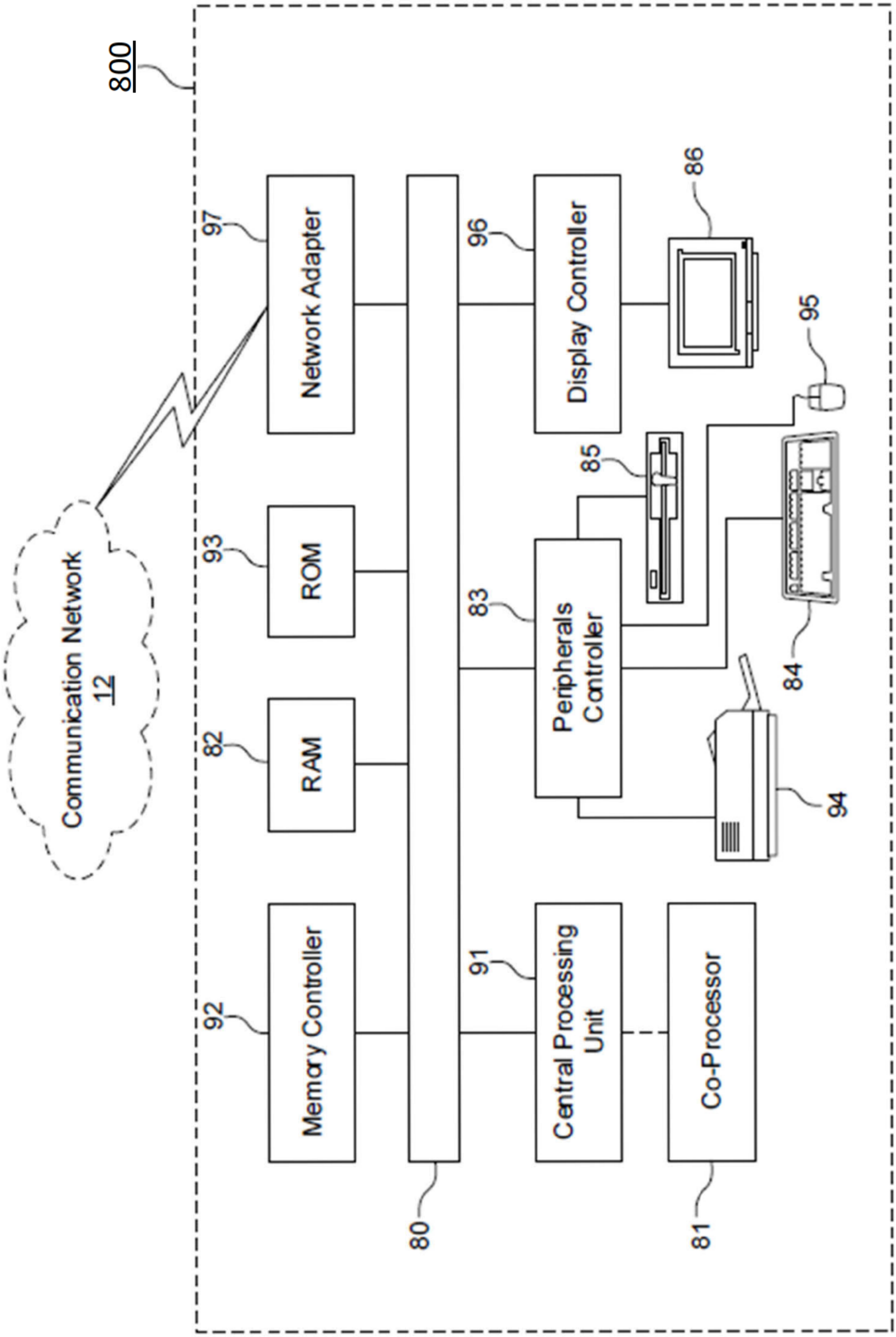
800
Communication Network
12
97
Network Adapter
93
ROM
82
RAM
92
Memory Controller
96
Display Controller
86
95
85
83
Peripherals Controller
84
94
91
Central Processing Unit
Co-Processor
80
81

FIG. 8

900

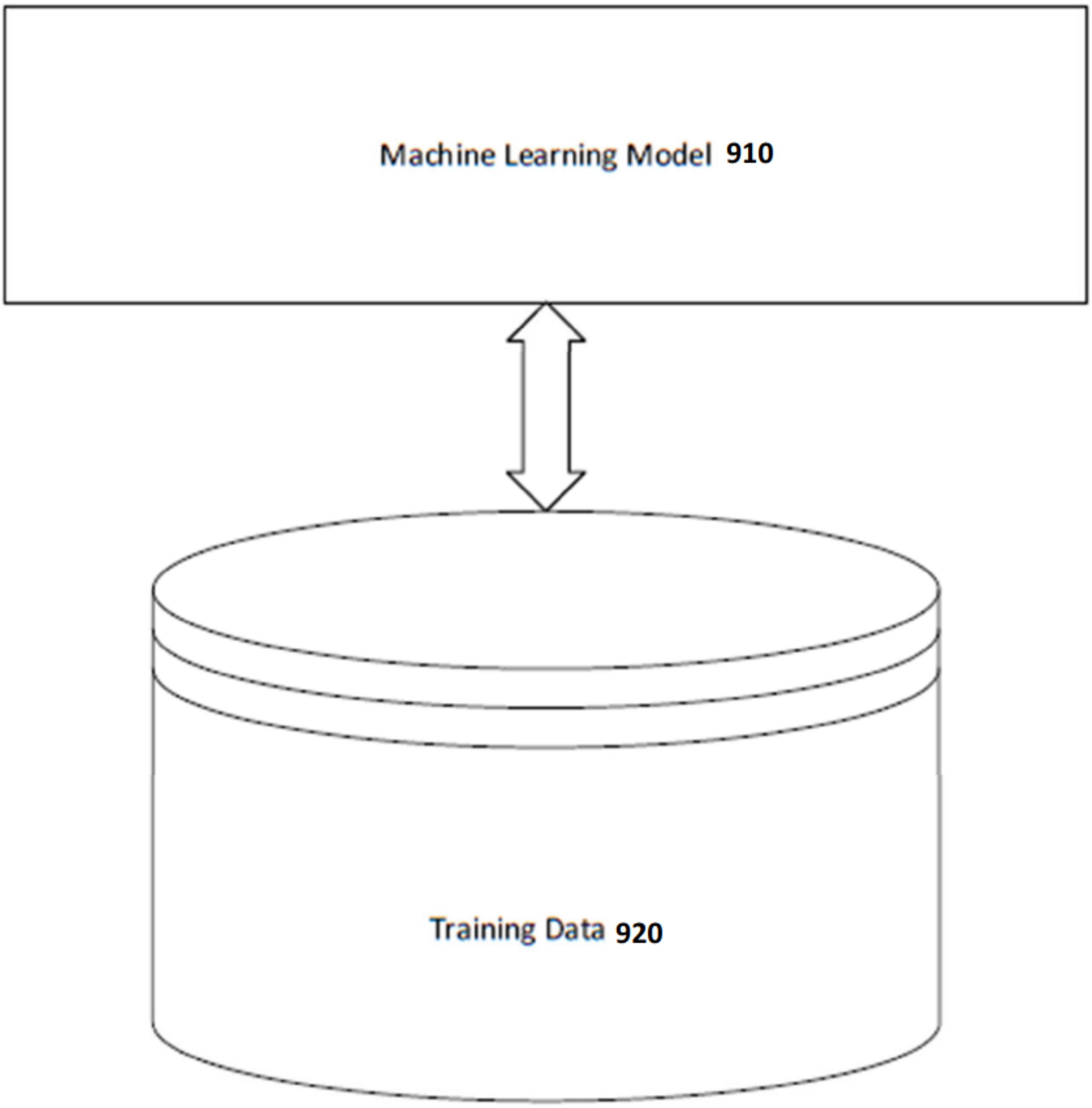

FIG. 9

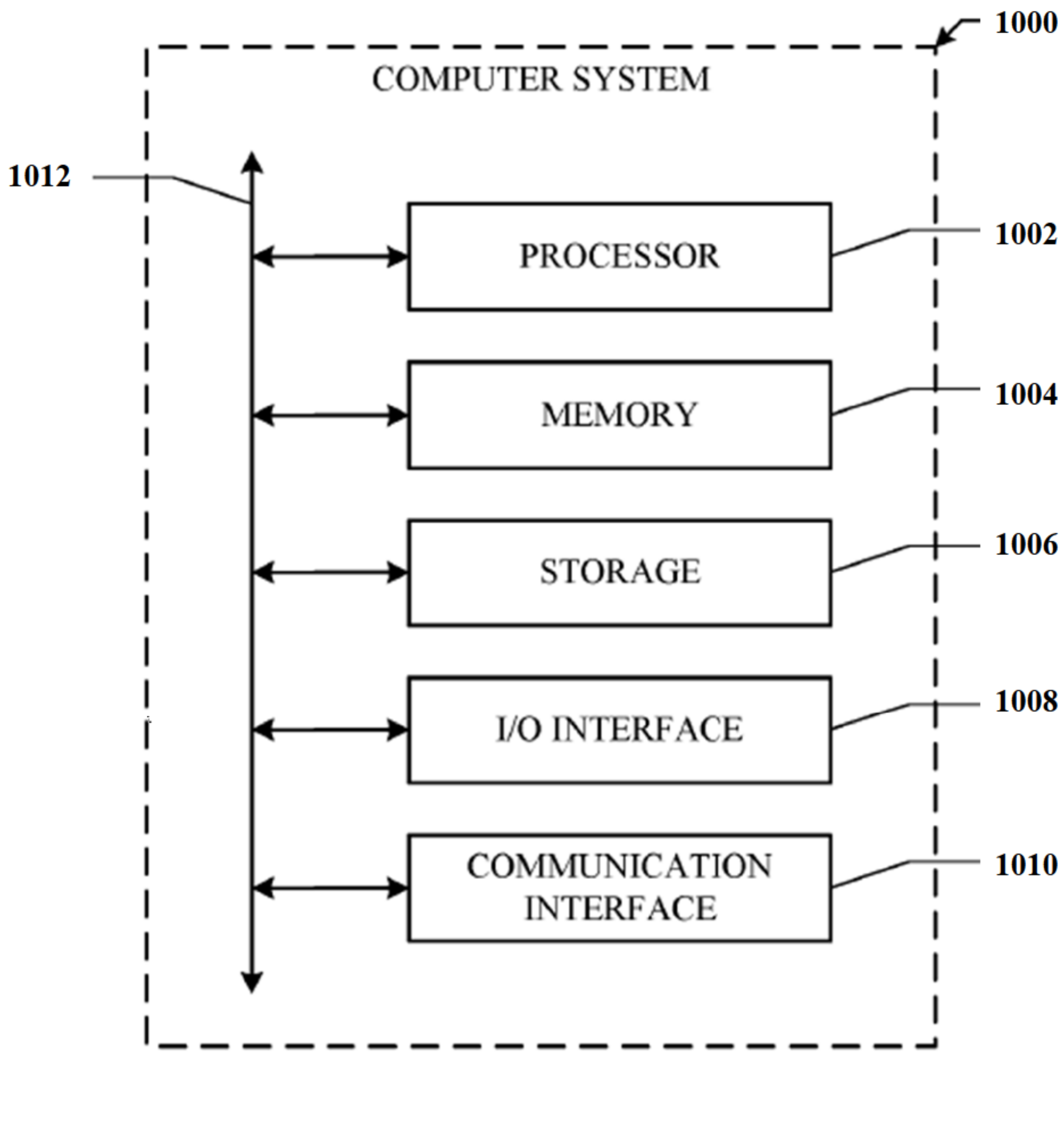
1000
COMPUTER SYSTEM
1012
PROCESSOR
1002
MEMORY
1004
STORAGE
1006
I/O INTERFACE
1008
COMMUNICATION INTERFACE
1010

FIG. 10