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United States Patent Application Publication	20250264723
Kind Code	A1
Publication Date	August 21, 2025
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STACKED WAVEGUIDES FOR UNIFORM PUPIL REPLICATION AND EYEBOX EXPANSION

Abstract

Disclosed herein are pupil expanders for pupil replication in near-eye display systems. In some examples, a pupil expander includes a waveguide and a variable reflectivity transflective mirror, where display light propagating in the waveguide is transmitted through a plurality of regions of the variable reflectivity transflective mirror to form a plurality of replicas of the pupil along one direction. Two such pupil expanders can be used to replicate the pupil in two directions. In some examples, a pupil expander includes a waveguide, an output coupler formed on or in the waveguide, and two or more transflective mirrors in the waveguide and parallel to a surface the waveguide for improving the pupil replication density and light intensity uniformity of the eyebox.

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Family ID: **1000008434904**

Appl. No.: **19/033090**

Filed: **January 21, 2025**

Foreign Application Priority Data

GR	20240100120	Feb. 16, 2024

Publication Classification

Int. Cl.: **G02B27/01** (20060101); **G02B27/00** (20060101)

U.S. Cl.:

CPC **G02B27/0172** (20130101); **G02B27/0081** (20130101); **G02B27/0093** (20130101); G02B2027/011 (20130101); G02B2027/0178 (20130101)

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to Greek Patent Application No. 20240100120, filed Feb. 16, 2024, entitled "STACKED WAVEGUIDES FOR UNIFORM PUPIL REPLICATION AND EYEBOX EXPANSION," which is assigned to the assignee hereof and is hereby incorporated by reference in its entirety.

BACKGROUND

[0002] An artificial reality system, such as a head-mounted display (HMD) or heads-up display (HUD) system, generally includes a near-eye display (e.g., in the form of a headset or a pair of glasses) configured to present content to a user via an electronic or optic display within, for example, about 10 to 20 mm in front of the user's eyes. The near-eye display may display virtual objects or combine images of real objects with virtual objects, as in virtual reality (VR), augmented reality (AR), or mixed reality (MR) applications. For example, in an AR system, a user may view both images of virtual objects (e.g., computer-generated images (CGIs)), and the surrounding environment by, for example, seeing through transparent display glasses or lenses (often referred to as optical see-through) or viewing displayed images of the surrounding environment captured by a camera (often referred to as video see-through).

[0003] A near-eye display may include an optical system configured to form an image of a computer-generated image on an image plane. The optical system of the near-eye display may relay the image generated by an image source (e.g., a display panel) to create a virtual image that appears to be away from the image source and further than just a few centimeters away from the user's eyes. For example, the optical system may collimate the light from the image source or otherwise convert spatial information of the displayed virtual objects into angular information to create a virtual image that may appear to be far away. The optical system may also magnify the image source to make the image appear larger than the actual size of the image source. It is generally desirable that the near-eye display has a small size, a low weight, a large field of view, a large eyebox, a high efficiency, and a low cost.

SUMMARY

[0004] This disclosure relates generally to near-eye display systems. More specifically, disclosed herein are pupil expanders for pupil replication in near-eye display systems. Various inventive embodiments are described herein, including devices, components, systems, modules, assemblies, subsystems, and the like.

[0005] According to certain embodiments, a pupil expander of a near-eye display may include a waveguide transparent to display light and configured to guide the display light along a first direction, and a partial reflective mirror on a first surface of the waveguide. The partial reflective mirror may be parallel to the first direction and may be characterized by different reflectivity at a plurality of regions along the first direction. Each region of the plurality of regions of the partial reflective mirror may be configured to partially reflect incident light and partially transmit the incident light through the region of the plurality of regions of the partial reflective mirror.

[0006] According to certain embodiments, a near-eye display may include a first pupil expander and a second pupil expander. The first pupil expander may extend in a first direction and may include a first waveguide transparent to display light and configured to guide the display light along the first direction, and a first partial reflective mirror on a first surface of the first waveguide. The first partial reflective mirror may be parallel to the first direction and may be characterized by different reflectivity at a first plurality of regions along the first direction. Each region of the first plurality of regions of the first partial reflective mirror may be configured to partially reflect incident light and partially transmit the incident light through the region of the first plurality of regions of the first partial reflective mirror. The second pupil expander may be configured to split the display light transmitted from each region of the first plurality of regions of the first partial reflective mirror at a second plurality of regions along a second direction that is different from the first direction.

[0007] This summary is neither intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings, and each claim. The foregoing, together with other features and examples, will be described in more detail below in the following specification, claims, and accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Illustrative embodiments are described in detail below with reference to the following figures.

[0009] FIG. **1** is a simplified block diagram of an example of an artificial reality system environment including a near-eye display according to certain embodiments.

[0010] FIG. **2** is a perspective view of an example of a near-eye display in the form of a head-mounted display (HMD) device for implementing some of the examples disclosed herein.

[0011] FIG. **3** is a perspective view of an example of a near-eye display in the form of a pair of glasses for implementing some of the examples disclosed herein.

[0012] FIG. **4** illustrates an example of an optical see-through augmented reality system including a waveguide display according to certain embodiments.

[0013] FIG. **5** illustrates an example of an optical see-through augmented reality system including a waveguide display for exit pupil expansion according to certain embodiments.

[0014] FIG. **6**A illustrates an example of an optical see-through augmented reality system including a waveguide display and surface-relief gratings for exit pupil expansion according to certain embodiments.

[0015] FIG. **6**B illustrates an example of an eyebox including a two-dimensional array of replicated exit pupils.

[0016] FIGS. **7**A-**7**C show that the pupil replication density may depend on the thickness of the waveguide.

[0017] FIG. **7**D illustrates an example of a waveguide including an embedded beam splitter (e.g., partial reflector) in the waveguide.

[0018] FIG. **8**A illustrates an example of a waveguide display including one or more groups of reflective and/or transflective mirrors for two-dimensional pupil expansion according to certain embodiments.

[0019] FIG. **8**B illustrates an example of an eyebox including a two-dimensional array of replicated exit pupils.

[0020] FIGS. **9**A-**9**C illustrate examples of a pupil expander in the form of a geometrical waveguide that includes a set of transflective mirrors within the geometrical waveguide.

[0021] FIG. **10**A illustrates an example of a geometrical waveguide display.
[0022] FIG. **10**B illustrates an example of pupil replication in the geometrical waveguide display of FIG. **10**A.
[0023] FIG. **10**C illustrates an example of a geometrical waveguide display including an embedded partial reflector parallel to a surface of the geometrical waveguide display.
[0024] FIG. **10**D illustrates an example of pupil replication in the geometrical waveguide display of FIG. **10**C.
[0025] FIG. **11**A illustrates an example of a geometrical waveguide display including two or more embedded partial reflectors parallel to a surface of the geometrical waveguide display according to certain embodiments.
[0026] FIG. **11**B illustrates an example of pupil replication in the geometrical waveguide display of FIG. **11**A.
[0027] FIG. **12**A illustrates an example of simulation of pupil replication by a single waveguide.
[0028] FIG. **12**B illustrates an example of the simulation result showing pupils replicated by the single waveguide.
[0029] FIG. **13**A illustrates an example of simulation of pupil replication by a stacked waveguide including embedded transflective mirrors parallel to a surface of the stacked waveguide according to certain embodiments.
[0030] FIG. **13**B illustrates an example of the simulation result showing pupils replicated by the stacked waveguide including embedded transflective mirrors parallel to a surface of the stacked waveguide according to certain embodiments.
[0031] FIG. **14** illustrates an example of a geometrical waveguide for one-dimensional pupil replication.
[0032] FIG. **15**A illustrates an example of a pupil expander including a variable reflectivity transflective mirror on a surface of a waveguide for one-dimensional pupil replication according to certain embodiments.
[0033] FIG. **15**B illustrates another example of a pupil expander including a variable reflectivity transflective mirror on a surface of a waveguide for one-dimensional pupil replication according to certain embodiments.
[0034] FIG. **16**A illustrates an example of a waveguide display including two one-dimensional pupil expanders for two-dimensional pupil replication according to certain embodiments.
[0035] FIG. **16**B illustrates another example of a waveguide display including two one-dimensional pupil expanders for two-dimensional pupil replication according to certain embodiments.
[0036] FIG. **17** illustrates another example of a waveguide display including two one-dimensional pupil expanders for two-dimensional pupil replication according to certain embodiments.
[0037] FIG. **18** is a simplified block diagram of an electronic system of an example of a near-eye display for implementing some of the examples disclosed herein.
[0038] The figures depict embodiments of the present disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated may be employed without departing from the principles, or benefits touted, of this disclosure.
[0039] In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

DETAILED DESCRIPTION

[0040] This disclosure relates generally to near-eye display systems. More specifically, disclosed herein are pupil expanders for pupil replication in near-eye display systems. Various inventive embodiments are described herein, including devices, components, systems, modules, assemblies, subsystems, and the like.

[0041] An optical see-through near-eye display system for augmented reality or mixed reality applications generally includes an image source (e.g., a micro-display), an optical combiner, and an eyepiece. The optical combiner may include, for example, a flat beam splitter, a curved or freeform surface with a beam-splitting coating, a diffractive (e.g., holographic) waveguide, or a geometrical waveguide. Optical combiners made of flat beam splitters or freeform surfaces may have high image quality but may have large sizes. Waveguide displays using, for example, diffractive couplers (e.g., volume Bragg gratings or surface-relief gratings) or transflective mirrors, can be made thin and compact. In waveguide displays, multiple waveguides and/or couplers may be used to replicate the exit pupil, thereby increasing the size of the eyebox so that the user's eyes may be able to view the displayed image even if the user's eyes move within a large area. In some waveguide displays, a 50/50 reflective layer parallel to the waveguide surface may be used to duplicate and mix the pupils, thereby improving the pupil replication density and uniformity in the eyebox. The 50/50 reflective layer may generate a second guided mode within the waveguide, thereby creating a set of exit pupils, in addition to the set of exit pupils replicated from a first guided mode within the waveguide. The set of exit pupils created from the second guided mode may partially overlap with the set of exit pupils created from the first guided mode in the eyebox, and thus the light intensity in the eyebox may not be uniform.

[0042] According to certain embodiments, two or more partial reflective mirrors may be used in a waveguide, where the two or more mirrors may be parallel to a surface of the waveguide, and may, in some embodiments, equally spaced in a thickness direction of the waveguide. The two or more partial reflective mirrors may significantly increase the light intensity uniformity of the eyebox, without increasing the number of facets or changing the size of the input (entrance) pupil. The waveguide may be, for example, a grating waveguide that include a grating coupler (e.g., a surface-relief grating or a holographic grating) for pupil replication, or a geometrical waveguide including an array of transflective mirrors for pupil replication.

[0043] According to certain embodiments, a one-dimensional pupil expander may include a waveguide transparent to display light and configured to guide the display light along a first direction, a partial reflective mirror on a first surface of the waveguide, and a reflector on a second surface of the waveguide opposing the first surface. The partial reflective mirror may be parallel to the first direction and may be characterized by different reflectivity at a plurality of regions along the first direction. Each region of the plurality of regions of the partial reflective mirror may be configured to partially reflect incident light towards the reflector and partially transmit the incident light through the region of the plurality of regions of the partial reflective mirror. The reflector may be configured to reflect the light reflected by a region of the plurality of regions of the partial reflective mirror towards another region of the plurality of regions of the partial reflective mirror. The reflector may include, for example, a mirror or an interface between the waveguide and air that is configured to cause total internal reflection. In some embodiments, two such one-dimensional pupil expanders may be used in a near-eye display system to replicate the pupil in two directions to form a 2-D array of pupils.

[0044] In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of examples of the disclosure. However, it will be apparent that various examples may be practiced without these specific details. For example, devices, systems, structures, assemblies, methods, and other components may be shown as components in block diagram form in order not to obscure the examples in unnecessary detail. In other instances, well-known devices, processes, systems, structures, and techniques may be shown without necessary detail in order to avoid obscuring the examples. The figures and description are not intended to be restrictive. The terms and expressions that have been employed in this disclosure are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof. The word “example” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment or design described herein as “example” is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0045] FIG. **1** is a simplified block diagram of an example of an artificial reality system environment **100** including a near-eye display **120** in accordance with certain embodiments. Artificial reality system environment **100** shown in FIG. **1** may include near-eye display **120**, an optional external imaging device **150**, and an optional input/output interface **140**, each of which may be coupled to an optional console **110**. While FIG. **1** shows an example of artificial reality system environment **100** including one near-eye display **120**, one external imaging device **150**, and one input/output interface **140**, any number of these components may be included in artificial reality system environment **100**, or any of the components may be omitted. For example, there may be multiple near-eye displays **120** monitored by one or more external imaging devices **150** in communication with console **110**. In some configurations, artificial reality system environment **100** may not include external imaging device **150**, optional input/output interface **140**, and optional console **110**. In alternative configurations, different or additional components may be included in artificial reality system environment **100**.

[0046] Near-eye display **120** may be a head-mounted display that presents content to a user. Examples of content presented by near-eye display **120** include one or more of images, videos, audio, or any combination thereof. In some embodiments, audio may be presented via an external device (e.g., speakers and/or headphones) that receives audio information from near-eye display **120**, console **110**, or both, and presents audio data based on the audio information. Near-eye display **120** may include one or more rigid bodies, which may be rigidly or non-rigidly coupled to each other. A rigid coupling between rigid bodies may cause the coupled rigid bodies to act as a single rigid entity. A non-rigid coupling between rigid bodies may allow the rigid bodies to move relative to each other. In various embodiments, near-eye display **120** may be implemented in any suitable form-factor, including a pair of glasses. Some embodiments of near-eye display **120** are further described below with respect to FIGS. **2** and **3**. Additionally, in various embodiments, the functionality described herein may be used in a headset that combines images of an environment external to near-eye display **120** and artificial reality content (e.g., computer-generated images). Therefore, near-eye display **120** may augment images of a physical, real-world environment external to near-eye display **120** with generated content (e.g., images, video, sound, etc.) to present an augmented reality to a user.

[0047] In various embodiments, near-eye display **120** may include one or more of display electronics **122**, display optics **124**, and an eye-tracking unit **130**. In some embodiments, near-eye display **120** may also include one or more locators **126**, one or more position sensors **128**, and an inertial measurement unit (IMU) **132**. Near-eye display **120** may omit any of eye-tracking unit **130**, locators **126**, position sensors **128**, and IMU **132**, or include additional elements in various embodiments. Additionally, in some embodiments, near-eye display **120** may include elements combining the function of various elements described in conjunction with FIG. **1**.

[0048] Display electronics **122** may display or facilitate the display of images to the user according to data received from, for example, console **110**. In various embodiments, display electronics **122** may include one or more display panels, such as a liquid crystal display (LCD), an organic light emitting diode (OLED) display, an inorganic light emitting diode (ILED) display, a micro light emitting diode (μLED) display, an active-matrix OLED display (AMOLED), a transparent OLED display (TOLED), or some other display. For example, in one implementation of near-eye display **120**, display electronics **122** may include a front TOLED panel, a rear display panel, and an optical component (e.g., an attenuator, polarizer, or diffractive or spectral film) between the front and rear display panels. Display electronics **122** may include pixels to emit light of a predominant color such as red, green, blue, white, or yellow. In some implementations, display electronics **122** may display a three-dimensional (3D) image through stereoscopic effects produced by two-dimensional panels to create a subjective perception of image depth. For example, display electronics **122** may include a left display and a right display positioned in front of a user's left eye and right eye, respectively. The left and right displays may present copies of an image shifted horizontally relative to each other to create a stereoscopic effect (i.e., a perception of image depth by a user viewing the image).

[0049] In certain embodiments, display optics **124** may display image content optically (e.g., using optical waveguides and couplers) or magnify image light received from display electronics **122**, correct optical errors associated with the image light, and present the corrected image light to a user of near-eye display **120**. In various embodiments, display optics **124** may include one or more optical elements, such as, for example, a substrate, optical waveguides, an aperture, a Fresnel lens, a convex lens, a concave lens, a filter, input/output couplers, or any other suitable optical elements that may affect image light emitted from display electronics **122**. Display optics **124** may include a combination of different optical elements as well as mechanical couplings to maintain relative spacing and orientation of the optical elements in the combination. One or more optical elements in display optics **124** may have an optical coating, such as an antireflective coating, a reflective coating, a filtering coating, or a combination of different optical coatings.

[0050] Magnification of the image light by display optics **124** may allow display electronics **122** to be physically smaller, weigh less, and consume less power than larger displays. Additionally, magnification may increase a field of view of the displayed content. The amount of magnification of image light by display optics **124** may be changed by adjusting, adding, or removing optical elements from display optics **124**. In some embodiments, display optics **124** may project displayed images to one or more image planes that may be further away from the user's eyes than near-eye display **120**.

[0051] Display optics **124** may also be designed to correct one or more types of optical errors, such as two-dimensional optical errors, three-dimensional optical errors, or any combination thereof. Two-dimensional errors may include optical aberrations that occur in two dimensions. Example types of two-dimensional errors may include barrel distortion, pincushion distortion, longitudinal chromatic aberration, and transverse chromatic aberration. Three-dimensional errors may include optical errors that occur in three dimensions. Example types of three-dimensional errors may include spherical aberration, comatic aberration, field curvature, and astigmatism.

[0052] Locators **126** may be objects located in specific positions on near-eye display **120** relative to one another and relative to a reference point on near-eye display **120**. In some implementations, console **110** may identify locators **126** in images captured by external imaging device **150** to determine the artificial reality headset's position, orientation, or both. A locator **126** may be a light-emitting diode (LED), a corner cube reflector, a reflective marker, a type of light source that contrasts with an environment in which near-eye display **120** operates, or any combination thereof. In embodiments where locators **126** are active components (e.g., LEDs or other types of light emitting devices), locators **126** may emit light in the visible band (e.g., about 380 nm to 750 nm), in the infrared (IR) band (e.g., about 750 nm to 1 mm), in the ultraviolet band (e.g., about 12 nm to about 380 nm), in another portion of the electromagnetic spectrum, or in any combination of portions of the electromagnetic spectrum.

[0053] External imaging device **150** may include one or more cameras, one or more video cameras, any other device capable of capturing images including one or more of locators **126**, or any combination thereof. Additionally, external imaging device **150** may include one or more filters (e.g., to increase signal to noise ratio). External imaging device **150** may be configured to detect light emitted or reflected from locators **126** in a field of view of external imaging device **150**. In embodiments where locators **126** include passive elements (e.g., retroreflectors), external imaging device **150** may include a light source that illuminates some or all of locators **126**, which may retro-reflect the light to the light source in external imaging device **150**. Slow calibration data may be communicated from external imaging device **150** to console **110**, and external imaging device **150** may receive one or more calibration parameters from console **110** to adjust one or more imaging parameters (e.g., focal length, focus, frame rate, sensor temperature, shutter speed, aperture, etc.).

[0054] Position sensors **128** may generate one or more measurement signals in response to motion of near-eye display **120**. Examples of position sensors **128** may include accelerometers, gyroscopes, magnetometers, other motion-detecting or error-correcting sensors, or any combination thereof. For example, in some embodiments, position sensors **128** may include multiple accelerometers to measure translational motion (e.g., forward/back, up/down, or left/right) and multiple gyroscopes to measure rotational motion (e.g., pitch, yaw, or roll). In some embodiments, various position sensors may be oriented orthogonally to each other.

[0055] IMU **132** may be an electronic device that generates fast calibration data based on measurement signals received from one or more of position sensors **128**. Position sensors **128** may be located external to IMU **132**, internal to IMU **132**, or any combination thereof. Based on the one or more measurement signals from one or more position sensors **128**, IMU **132** may generate fast calibration data indicating an estimated position of near-eye display **120** relative to an initial position of near-eye display **120**. For example, IMU **132** may integrate measurement signals received from accelerometers over time to estimate a velocity vector and integrate the velocity vector over time to determine an estimated position of a reference point on near-eye display **120**. Alternatively, IMU **132** may provide the sampled measurement signals to console **110**, which may determine the fast calibration data. While the reference point may generally be defined as a point in space, in various embodiments, the reference point may also be defined as a point within near-eye display **120** (e.g., a center of IMU **132**).

[0056] Eye-tracking unit **130** may include one or more eye-tracking systems. Eye tracking may refer to determining an eye's position, including orientation and location of the eye, relative to near-eye display **120**. An eye-tracking system may include an imaging system to image one or more eyes and may optionally include a light emitter, which may generate light that is directed to an eye such that light reflected by the eye may be captured by the imaging system. For example, eye-tracking unit **130** may include a non-coherent or coherent light source (e.g., a laser diode) emitting light in the visible spectrum or infrared spectrum, and a camera capturing the light reflected by the user's eye. As another example, eye-tracking unit **130** may capture reflected radio waves emitted by a miniature radar unit. Eye-tracking unit **130** may use low-power light emitters that emit light at frequencies and intensities that would not injure the eye or cause physical discomfort. Eye-tracking unit **130** may be arranged to increase contrast in images of an eye captured by eye-tracking unit **130** while reducing the overall power consumed by eye-tracking unit **130** (e.g., reducing power consumed by a light emitter and an imaging system included in eye-tracking unit **130**). For example, in some implementations, eye-tracking unit **130** may consume less than 120 milliwatts of power.

[0057] Near-eye display **120** may use the orientation of the eye to, e.g., determine an inter-pupillary distance (IPD) of the user, determine gaze direction, introduce depth cues (e.g., blur image outside of the user's main line of sight), collect heuristics on the user interaction in the VR media (e.g., time spent on any particular subject, object, or frame as a function of exposed stimuli), some other functions that are based in part on the orientation of at least one of the user's eyes, or any combination thereof. Because the orientation may be determined for both eyes of the user, eye-tracking unit **130** may be able to determine where the user is looking. For example, determining a direction of a user's gaze may include determining a point of convergence based on the determined orientations of the user's left and right eyes. A point of convergence may be the point where the two foveal axes of the user's eyes intersect. The direction of the user's gaze may be the direction of a line passing through the point of convergence and the mid-point between the pupils of the user's eyes.

[0058] Input/output interface **140** may be a device that allows a user to send action requests to console **110**. An action request may be a request to perform a particular action. For example, an action request may be to start or to end an application or to perform a particular action within the application. Input/output interface **140** may include one or more input devices. Example input devices may include a keyboard, a mouse, a game controller, a glove, a button, a touch screen, or any other suitable device for receiving action requests and communicating the received action requests to console **110**. An action request received by the input/output interface **140** may be communicated to console **110**, which may perform an action corresponding to the requested action. In some embodiments, input/output interface **140** may provide haptic feedback to the user in accordance with instructions received from console **110**. For example, input/output interface **140** may provide haptic feedback when an action request is received, or when console **110** has performed a requested action and communicates instructions to input/output interface **140**. In some embodiments, external imaging device **150** may be used to track input/output interface **140**, such as tracking the location or position of a controller (which may include, for example, an IR light source) or a hand of the user to determine the motion of the user. In some embodiments, near-eye display **120** may include one or more imaging devices to track input/output interface **140**, such as tracking the location or position of a controller or a hand of the user to determine the motion of the user.

[0059] Console **110** may provide content to near-eye display **120** for presentation to the user in accordance with information received from one or more of external imaging device **150**, near-eye display **120**, and input/output interface **140**. In the example shown in FIG. **1**, console **110** may include an application store **112**, a headset tracking subsystem **114**, an artificial reality engine **116**, and an eye-tracking subsystem **118**. Some embodiments of console **110** may include different or additional devices or subsystems than those described in conjunction with FIG. **1**. Functions further described below may be distributed among components of console **110** in a different manner than is described here.

[0060] In some embodiments, console **110** may include a processor and a non-transitory computer-readable storage medium storing instructions executable by the processor. The processor may include multiple processing units executing instructions in parallel. The non-transitory computer-readable storage medium may be any memory, such as a hard disk drive, a removable memory, or a solid-state drive (e.g., flash memory or dynamic random access memory (DRAM)). In various embodiments, the devices or subsystems of console **110** described in conjunction with FIG. **1** may be encoded as instructions in the non-transitory computer-readable storage medium that, when executed by the processor, cause the processor to perform the functions further described below.

[0061] Application store **112** may store one or more applications for execution by console **110**. An application may include a group of instructions that, when executed by a processor, generates content for presentation to the user. Content generated by an application may be in response to inputs received from the user via movement of the user's eyes or inputs received from the input/output interface **140**. Examples of the applications may include gaming applications, conferencing applications, video playback application, or other suitable applications.

[0062] Headset tracking subsystem **114** may track movements of near-eye display **120** using slow calibration information from external imaging device **150**. For example, headset tracking subsystem **114** may determine positions of a reference point of near-eye display **120** using observed locators from the slow calibration information and a model of near-eye display **120**. Headset tracking subsystem **114** may also determine positions of a reference point of near-eye display **120** using position information from the fast calibration information. Additionally, in some embodiments, headset tracking subsystem **114** may use portions of the fast calibration information, the slow calibration information, or any combination thereof, to predict a future location of near-eye display **120**. Headset tracking subsystem **114** may provide the estimated or predicted future position of near-eye display **120** to artificial reality engine **116**.

[0063] Artificial reality engine **116** may execute applications within artificial reality system environment **100** and receive position information of near-eye display **120**, acceleration information of near-eye display **120**, velocity information of near-eye display **120**, predicted future positions of near-eye display **120**, or any combination thereof from headset tracking subsystem **114**. Artificial reality engine **116** may also receive estimated eye position and orientation information from eye-tracking subsystem **118**. Based on the received information, artificial reality engine **116** may determine content to provide to near-eye display **120** for presentation to the user. For example, if the received information indicates that the user has looked to the left, artificial reality engine **116** may generate content for near-eye display **120** that mirrors the user's eye movement in a virtual environment. Additionally, artificial reality engine **116** may perform an action within an application executing on console **110** in response to an action request received from input/output interface **140**, and provide feedback to the user indicating that the action has been performed. The feedback may be visual or audible feedback via near-eye display **120** or haptic feedback via input/output interface **140**.

[0064] Eye-tracking subsystem **118** may receive eye-tracking data from eye-tracking unit **130** and determine the position of the user's eye based on the eye tracking data. The position of the eye may include an eye's orientation, location, or both relative to near-eye display **120** or any element thereof. Because the eye's axes of rotation change as a function of the eye's location in its socket, determining the eye's location in its socket may allow eye-tracking subsystem **118** to more accurately determine the eye's orientation.

[0065] FIG. **2** is a perspective view of an example of a near-eye display in the form of an HMD device **200** for implementing some of the examples disclosed herein. HMD device **200** may be a part of, e.g., a VR system, an AR system, an MR system, or any combination thereof. HMD device **200** may include a body **220** and a head strap **230**. FIG. **2** shows a bottom side **223**, a front side **225**, and a left side **227** of body **220** in the perspective view. Head strap **230** may have an adjustable or extendible length. There may be a sufficient space between body **220** and head strap **230** of HMD device **200** for allowing a user to mount HMD device **200** onto the user's head. In various embodiments, HMD device **200** may include additional, fewer, or different components. For example, in some embodiments, HMD device **200** may include eyeglass temples and temple tips as shown in, for example, FIG. **3** below, rather than head strap **230**.

[0066] HMD device **200** may present to a user media including virtual and/or augmented views of a physical, real-world environment with computer-generated elements. Examples of the media presented by HMD device **200** may include images (e.g., two-dimensional (2D) or three-dimensional (3D) images), videos (e.g., 2D or 3D videos), audio, or any combination thereof. The images and videos may be presented to each eye of the user by one or more display assemblies (not shown in FIG. **2**) enclosed in body **220** of HMD device **200**. In various embodiments, the one or more display assemblies may include a single electronic display panel or multiple electronic display panels (e.g., one display panel for each eye of the user). Examples of the electronic display panel(s) may include, for example, an LCD, an OLED display, an ILED display, a μLED display, an AMOLED, a TOLED, some other display, or any combination thereof. HMD device **200** may include two eyebox regions.

[0067] In some implementations, HMD device **200** may include various sensors (not shown), such as depth sensors, motion sensors, position sensors, and eye tracking sensors. Some of these sensors may use a structured light pattern for sensing. In some implementations, HMD device **200** may include an input/output interface for communicating with a console. In some implementations, HMD device **200** may include a virtual reality engine (not shown) that can execute applications within HMD device **200** and receive depth information, position information, acceleration information, velocity information, predicted future positions, or any combination thereof of HMD device **200** from the various sensors. In some implementations, the information received by the virtual reality engine may be used for producing a signal (e.g., display instructions) to the one or more display assemblies. In some implementations, HMD device **200** may include locators (not shown, such as locators **126**) located in fixed positions on body **220** relative to one another and relative to a reference point. Each of the locators may emit light that is detectable by an external imaging device.

[0068] FIG. **3** is a perspective view of an example of a near-eye display **300** in the form of a pair of glasses for implementing some of the examples disclosed herein. Near-eye display **300** may be a specific implementation of near-eye display **120** of FIG. **1**, and may be configured to operate as a virtual reality display, an augmented reality display, and/or a mixed reality display. Near-eye display **300** may include a frame **305** and a display **310**. Display **310** may be configured to present content to a user. In some embodiments, display **310** may include display electronics and/or display optics. For example, as described above with respect to near-eye display **120** of FIG. **1**, display **310** may include an LCD display panel, an LED display panel, or an optical display panel (e.g., a waveguide display assembly).

[0069] Near-eye display **300** may further include various sensors **350***a*, **350***b*, **350***c*, **350***d*, and **350***e* on or within frame **305**. In some embodiments, sensors **350***a*-**350***e* may include one or more depth sensors, motion sensors, position sensors, inertial sensors, or ambient light sensors. In some embodiments, sensors **350***a*-**350***e* may include one or more image sensors configured to generate image data representing different fields of views in different directions. In some embodiments, sensors **350***a*-**350***e* may be used as input devices to control or influence the displayed content of near-eye display **300**, and/or to provide an interactive VR/AR/MR experience to a user of near-eye display **300**. In some embodiments, sensors **350***a*-**350***e* may also be used for stereoscopic imaging.

[0070] In some embodiments, near-eye display **300** may further include one or more illuminators **330** to project light into the physical environment. The projected light may be associated with different frequency bands (e.g., visible light, infra-red light, ultra-violet light, etc.), and may serve various purposes. For example, illuminator(s) **330** may project light in a dark environment (or in an environment with low intensity of infra-red light, ultra-violet light, etc.) to assist sensors **350***a*-**350***e* in capturing images of different objects within the dark environment. In some embodiments, illuminator(s) **330** may be used to project certain light patterns onto the objects within the environment. In some embodiments, illuminator(s) **330** may be used as locators, such as locators **126** described above with respect to FIG. **1**.

[0071] In some embodiments, near-eye display **300** may also include a high-resolution camera **340**. High-resolution camera **340** may capture images of the physical environment in the field of view. The captured images may be processed, for example, by a virtual reality engine (e.g., artificial reality engine **116** of FIG. **1**) to add virtual objects to the captured images or modify physical objects in the captured images, and the processed images may be displayed to the user by display **310** for AR or MR applications.

[0072] FIG. **4** illustrates an example of an optical see-through augmented reality system **400** including a waveguide display according to certain embodiments. Augmented reality system **400** may include a projector **410** and a combiner **415**. Projector **410** may include a light source or image source **412** and projector optics **414**. In some embodiments, light source or image source **412** may include one or more micro-LED devices described above. In some embodiments, image source **412** may include a plurality of pixels that displays virtual objects, such as an LCD display panel or an LED display panel. In some embodiments, image source **412** may include a light source that generates coherent or partially coherent light. For example, image source **412** may include a laser diode, a vertical cavity surface emitting laser, an LED, and/or a micro-LED described above. In some embodiments, image source **412** may include a plurality of light sources (e.g., an array of micro-LEDs described above), each emitting a monochromatic image light corresponding to a primary color (e.g., red, green, or blue). In some embodiments, image source **412** may include three two-dimensional arrays of micro-LEDs, where each two-dimensional array of micro-LEDs may include micro-LEDs configured to emit light of a primary color (e.g., red, green, or blue). In some embodiments, image source **412** may include an optical pattern generator, such as a spatial light modulator.

[0073] Projector optics **414** may include one or more optical components that can condition the light from image source **412**, such as expanding, collimating, scanning, or projecting light from image source **412** to combiner **415**. The one or more optical components may include, for example, one or more lenses, liquid lenses, mirrors, apertures, and/or gratings. For example, in some embodiments, image source **412** may include one or more one-dimensional arrays or elongated two-dimensional arrays of micro-LEDs, and projector optics **414** may include one or more one-dimensional scanners (e.g., micro-mirrors or prisms) configured to scan the one-dimensional arrays or elongated two-dimensional arrays of micro-LEDs to generate image frames. In some embodiments, projector optics **414** may include a liquid lens (e.g., a liquid crystal lens) with a plurality of electrodes that allows scanning of the light from image source **412**.

[0074] Combiner **415** may include an input coupler **430** for coupling light from projector **410** into a substrate **420** of combiner **415**. Input coupler **430** may include a volume holographic grating, a diffractive optical element (DOE) (e.g., a surface-relief grating), a slanted surface of substrate **420**, or a refractive coupler (e.g., a wedge or a prism). For example, input coupler **430** may include a reflective volume Bragg grating or a transmissive volume Bragg grating. Input coupler **430** may have a coupling efficiency of greater than 30%, 50%, 75%, 90%, or higher for visible light. Light coupled into substrate **420** may propagate within substrate **420** through, for example, total internal reflection (TIR). Substrate **420** may be in the form of a lens of a pair of eyeglasses. Substrate **420** may have a flat or a curved surface, and may include one or more types of dielectric materials, such as glass, quartz, plastic, polymer, poly(methyl methacrylate) (PMMA), crystal, or ceramic. A thickness of the substrate may range from, for example, less than about 1 mm to about 12 mm or more. Substrate **420** may be transparent to visible light.

[0075] Substrate **420** may include or may be coupled to a plurality of output couplers **440**, each configured to extract at least a portion of the light guided by and propagating within substrate **420** from substrate **420**, and direct extracted light **460** to an eyebox **495** where an eye **490** of the user of augmented reality system **400** may be located when augmented reality system **400** is in use. The plurality of output couplers **440** may replicate the exit pupil to increase the size of eyebox **495** such that the displayed image is visible in a larger area. As input coupler **430**, output couplers **440** may include grating couplers (e.g., volume holographic gratings or surface-relief gratings), other diffraction optical elements, prisms, etc. For example, output couplers **440** may include reflective volume Bragg gratings or transmissive volume Bragg gratings. Output couplers **440** may have different coupling (e.g., diffraction) efficiencies at different locations. Substrate **420** may also allow light **450** from the environment in front of combiner **415** to pass through with little or no loss. Output couplers **440** may also allow light **450** to pass through with little loss. For example, in some implementations, output couplers **440** may have a very low diffraction efficiency for light **450** such that light **450** may be refracted or otherwise pass through output couplers **440** with little loss, and thus may have a higher intensity than extracted light **460**. In some implementations, output couplers **440** may have a high diffraction efficiency for light **450** and may diffract light **450** in certain desired directions (i.e., diffraction angles) with little loss. As a result, the user may be able to view combined images of the environment in front of combiner **415** and images of virtual objects projected by projector **410**.

[0076] In some embodiments, projector **410**, input coupler **430**, and output coupler **440** may be on any side of substrate **420**. Input coupler **430** and output coupler **440** may be reflective gratings (also referred to as reflective gratings) or transmissive gratings (also referred to as transmissive gratings) to couple display light into or out of substrate **420**.

[0077] FIG. **5** illustrates an example of an optical see-through augmented reality system **500** including a waveguide display for exit pupil expansion according to certain embodiments. Augmented reality system **500** may be similar to augmented reality system **500**, and may include the waveguide display and a projector that may include a light source or image source **510** and projector optics **520**. The waveguide display may include a substrate **530**, an input coupler **540**, and a plurality of output couplers **550** as described above with respect to augmented reality system **500**. While FIG. **5** only shows the propagation of light from a single field of view, FIG. **5** shows the propagation of light from multiple fields of view.

[0078] FIG. **5** shows that the exit pupil is replicated by output couplers **550** to form an aggregated exit pupil or eyebox, where different regions in a field of view (e.g., different pixels on image source **510**) may be associated with different respective propagation directions towards the eyebox, and light from a same field of view (e.g., a same pixel on image source **510**) may have a same propagation direction for the different individual exit pupils. Thus, a single image of image source **510** may be formed by the user's eye located anywhere in the eyebox, where light from different individual exit pupils and propagating in the same direction may be from a same pixel on image source **510** and may be focused onto a same location on the retina of the user's eye. In other words, the user's eye may convert angular information in the eyebox or exit pupil (e.g., corresponding to a Fourier plane) to spatial information in images form on the retina. FIG. **5** shows that the image of the image source is visible by the user's eye even if the user's eye moves to different locations in the eyebox.

[0079] As described above, in a waveguide-based near-eye display system, light of projected images may be coupled into a waveguide (e.g., a transparent substrate), propagate within the waveguide through total internal reflection, and be coupled out of the waveguide at multiple locations to replicate the exit pupil and expand the eyebox. Multiple waveguides and/or multiple couplers (e.g., gratings or transflective mirrors) may be used to replicate the exit pupil in two dimensions to fill a large eyebox (e.g., 40×40 mm.sup.2 or larger) with a 2D array of pupils (e.g., 2×2 mm.sup.2), thereby expanding the eyebox such that the user's eyes can view the displayed image even if the user's eyes move within a large area. For example, two or more gratings may be used to expand the display light in two dimensions or along two axes. The two gratings may have different grating parameters, such that one grating may be used to replicate the exit pupil in one direction and the other grating may be used to replicate the exit pupil in another direction.

[0080] As also described above, in optical see-through near-eye display system for augmented reality or mixed reality applications generally includes an image source (e.g., a micro-display), an optical combiner, and an eyepiece. The optical combiner may include, for example, a flat beam splitter, a curved or freeform surface with a beam-splitting coating, a diffractive (e.g., holographic) waveguide, or a geometrical waveguide. Optical combiners made of flat beam splitters or freeform surfaces may have high image quality but may have large sizes. Waveguide displays using, for example, diffractive couplers (e.g., volume Bragg gratings or surface-relief gratings) or transflective mirrors, can be made thin and compact. In waveguide displays, multiple waveguides and/or couplers may be used to replicate the exit pupil, thereby increasing the size of the eyebox, such that the user's eyes may be able to view the displayed image even if the user's eyes move within a large area.

[0081] In a waveguide-based near-eye display system, display light of projected images may be coupled into a waveguide, propagate within the waveguide, and be coupled out of the waveguide at different locations to replicate exit pupils and expand the eyebox. In some implementations of the waveguide-based near eye display system, display light of the projected images may be coupled into or out of a waveguide (e.g., a substrate) using, for example, refractive optical elements (e.g., prisms), diffractive optical elements (e.g., gratings), or partial reflectors (e.g., transflective mirrors). The display light coupled into the waveguide may propagate within the waveguide through total internal reflection at surfaces of the waveguide, and may, for example, be partially diffracted by gratings or reflected by partial reflectors when the display light propagating within the waveguide. The undiffracted or unreflected portion of the display light may continue to propagate within the waveguide through total internal reflection and may be partially diffracted or reflected when the display light reaches another grating or partial reflector. In a waveguide-based near-eye display system for augmented reality applications, light from the surrounding environment may also pass through at least a see-through region of the waveguide display (e.g., a transparent substrate) and reach the eyebox and the user's eyes.

[0082] FIG. **6**A illustrates an example of an optical see-through augmented reality system including a waveguide display **600** and surface-relief gratings for exit pupil expansion according to certain embodiments. Waveguide display **600** may include a substrate **610** (e.g., a waveguide), which may be similar to substrate **420** or **530**. Substrate **610** may be transparent to visible light and may include, for example, a glass, quartz, plastic, polymer, PMMA, ceramic, Si.sub.3N.sub.4, SiC, or crystal substrate. Substrate **610** may be a flat substrate or a curved substrate. Substrate **610** may include two opposing broadside surfaces that include a first surface **612** and a second surface **614**, and multiple sidewalls surfaces **616** that may be perpendicular to the broadside surfaces. Display light may be coupled into substrate **610** by an input coupler **620**, and may be reflected by first surface **612** and second surface **614** through total internal reflection, such that the display light may propagate within substrate **610**. Input coupler **620** may include a grating, a refractive coupler (e.g., a wedge or a prism), or a reflective coupler (e.g., a reflective surface having a slant angle with respect to substrate **610**). For example, in one embodiment, input coupler **620** may include a prism that may couple display light of different colors into substrate **610** at a same refraction angle. In another example, input coupler **620** may include a grating coupler that may diffract light of different colors into substrate **610** at different directions. Input coupler **620** may have a coupling efficiency of greater than 10%, 20%, 30%, 50%, 75%, 90%, or higher for visible light.

[0083] Waveguide display **600** may also include a first output grating **630** and a second output grating **640** positioned on one or two surfaces (e.g., first surface **612** and second surface **614**) of substrate **610** for expanding incident display light beam in two dimensions in order to fill an eyebox with the display light. First output grating **630** may be configured to expand at least a portion of the display light beam along one direction, such as approximately in the x direction. Display light coupled into substrate **610** may propagate in a direction shown by a line **632**. While the display light propagates within substrate **610** along a direction shown by line **632**, a portion of the display light may be diffracted by a region of first output grating **630** towards second output grating **640** as shown by a line **634** each time the display light propagating within substrate **610** reaches first output grating **630**. Second output grating **640** may then expand the display light from first output grating **630** in a different direction (e.g., approximately in the y direction) by diffracting a portion of the display light from an exit region **650** to the eyebox each time the display light propagating within substrate **610** reaches second output grating **640**.

[0084] FIG. **6**B illustrates an example of an eyebox including a two-dimensional array of replicated exit pupils. FIG. **6**B shows that a single input pupil **605** may be replicated by first output grating **630** and second output grating **640** to form an aggregated exit pupil **660** that includes a two-dimensional array of individual exit pupils **662**. For example, the exit pupil may be replicated in approximately the x direction by first output grating **630** and in approximately the y direction by second output grating **640**. As described above, output light from individual exit pupils **662** and propagating in a same direction may be focused onto a same location in the retina of the user's eye. Thus, a single image may be formed by the user's eye from the output light in the two-dimensional array of individual exit pupils **662**.

[0085] FIGS. **7**A-**7**C show that the pupil replication density may depend on the thickness of the waveguide. In the examples shown in FIGS. **7**A-**7**C, grating couplers **712**, **722**, and **732** (e.g., surface-relief gratings, holographic gratings, polarization volume holograms, etc.) may be used to couple portions of the guided light out of waveguides **710**, **720**, and **730**, respectively, at a plurality of locations along one direction (e.g., the x direction), thereby replicating the pupils in one direction. As illustrated, for an input beam with the same beam size w, a thin waveguide **710** may replicate the light beam at a high density in at least the light propagation direction (e.g., x direction), a waveguide **720** with a higher thickness (in the z direction) may replicate the light beam at a lower pupil replication density, and a waveguide **730** with an even higher thickness y (in the z direction) may replicate the light beam at a much lower pupil replication density.

[0086] FIG. **7**D shows an example of a waveguide including an embedded beam splitter (e.g., a 50/50 reflector) in the waveguide to increase the pupil replication density. In the example shown in FIG. **7**D, a grating coupler **742** may be used to couple portions of the guided light out of a waveguide **740** at a plurality of locations along one direction (e.g., the x direction), thereby replicating the pupils in one direction. FIG. **7**D shows that for a waveguide **740** with a thickness t, when a beam splitter **744** is positioned in the middle (in the thickness direction such as z direction) of waveguide **740**, waveguide **740** may replicate the light beam at a higher pupil replication density for an input light beam with a beam width w, such as about two times of the pupil replication density in waveguide **730**.

[0087] FIG. **8**A illustrates an example of a waveguide display **800** including one or more groups of reflective and/or transflective mirrors for two-dimensional pupil expansion according to certain embodiments. Waveguide display **800** may be similar to waveguide display **600**, but may use reflective or transflective mirrors (rather than refractive or diffractive optical components) to replace input coupler **620**, first output grating **630**, and second output grating **640**. In the example illustrated in FIG. **8**A, waveguide display **800** may include an input coupler **810** that may include one or more reflective and/or transflective mirrors and may be referred to as the input mirror. The input mirror may be used to couple display light into a waveguide **802** such that the display light may propagate within waveguide **802** through total internal reflection. In some embodiments, input coupler **810** may be a prism or a grating.

[0088] Waveguide display **800** may include a middle mirror **820** that may include a group of reflective and/or transflective mirrors having the same orientation. One or more reflective and/or transflective mirrors of middle mirror **820** may be used to direct display light from input coupler **810** towards other reflective and/or transflective mirrors of middle mirror **820**, which may replicate the pupil in a first dimension (e.g., approximately the x direction) by reflecting portions of the display light at multiple locations along the first dimension as shown in FIG. **8**A. For example, a first mirror and a last mirror (e.g., in x direction) in middle mirror **820** may be reflective mirrors with reflectivity close to 100%, and mirrors between the first mirror and the last mirror in middle mirror **820** may be transflective mirrors that have reflectivity less than 100% and are partially transmissive.

[0089] In some embodiments, middle mirror **820** may include a first middle mirror **822** and a second middle mirror **824**. First middle mirror **822** may include one or more reflective and/or transflective mirrors that may direct display light from input coupler **810** towards second middle mirror **824**. For example, the first mirror (e.g., in x direction) in first middle mirror **822** may be a reflective mirror with reflectivity close to 100% and other mirrors in first middle mirror **822** may be transflective mirrors that are partially transmissive. Second middle mirror **824** may include a plurality of reflective and/or transflective mirrors and may expand the pupil in a first dimension (e.g., approximately the x direction) by reflecting portions of the display light at multiple locations along the first dimension as shown in FIG. **8**A. In one example, the last mirror (e.g., in x direction) in second middle mirror **824** may be a reflective mirror with reflectivity close to 100%, and other mirrors in second middle mirror **824** may be transflective mirrors that are partially transmissive.

[0090] Waveguide display **800** may also include an output mirror **830**, which may include a plurality of reflective and/or transflective mirrors. As described above with respect to FIG. **6**A and **6**B and shown in FIG. **8**A, the transflective mirrors in output mirror **830** may reflect, at multiple locations along a second dimension (e.g., approximately the y direction), portions of the display light from each location of the multiple locations of middle mirror **820** to the eyebox to replicate the exit pupil in the second dimension. Therefore, middle mirror **820** and output mirror **830** may replicate the pupil in two-dimensions to fill the eyebox. In one example, the last mirror (e.g., in −y direction) in output mirror **830** may be a reflective mirror with reflectivity close to 100%, and other mirrors in output mirror **830** may be transflective mirrors that are partially transmissive.

[0091] FIG. **8**B illustrates an example of an eyebox including a two-dimensional array of replicated exit pupils. FIG. **8**B shows that a single input pupil may be replicated by middle mirror **820** and output mirror **830** to form an aggregated exit pupil **860** that includes a two-dimensional array of individual exit pupils **862**. For example, the exit pupil may be replicated in approximately the x direction by middle mirror **820** and in approximately the y direction by output mirror **830**. As described above, output light from individual exit pupils **862** and propagating in a same direction may be focused onto a same location in the retina of the user's eye. Thus, a single image may be formed by the user's eye from the output light in the two-dimensional array of individual exit pupils **862**.

[0092] FIG. **9**A illustrates an example of a pupil expander in the form of a geometrical waveguide **910** that includes a set of transflective mirrors **912** within geometrical waveguide **910**. In the illustrated example, the angle between transflective mirrors **912** and broadside surfaces (e.g., x-y planes) of geometrical waveguide **910** may be large, and thus the diameter D**1** of the reflected beam (measured in the x direction) may be small. As such, the modulation transfer function (MTF) of the pupil expander may be low, and the resolution and/or the contrast of the images displayed to the user's eye may be low. In addition, as shown in FIG. **9**A, due to the small size of each replicated pupil, there may be gaps between the replicated pupils. As such, the pupil replication density may be low, and the replicated pupils may not fill the eyebox. Therefore, the image uniformity in the eyebox may be low.

[0093] FIG. **9**B illustrates another example of a pupil expander in the form of a geometrical waveguide **920** that includes a set of transflective mirrors **922** within geometrical waveguide **920**. In the illustrated example, the angle between transflective mirrors **922** and the out-coupling surface of geometrical waveguide **920** may be small, and thus the diameter D**2** of the reflected beam (measured in the x direction) may be large. As such, the MTF of the pupil expander may be higher, the resolution and/or the contrast of the images displayed to the user's eye may be better, and the replicated pupils may more uniformly fill the eyebox.

[0094] FIG. **9**C illustrates an example of a pupil expander in the form of a geometrical waveguide **930** that includes a set of transflective mirrors **932** within geometrical waveguide **930**. In the illustrated example, the angle between transflective mirrors **932** and the out-coupling surface of geometrical waveguide **930** may be large. But the thickness (in z direction) may be much higher than that of geometrical waveguide **910**. As such, the diameter D**3** of the reflected beam (measured in the x direction) may be large. Therefore, the MTF of the pupil expander may be higher, the resolution and/or the contrast of the images displayed to the user's eye may be better, and the replicated pupils may more uniformly fill the eyebox. However, increasing the thickness of the geometrical waveguide as shown in FIG. **9**C may significantly increase the size and weight of the waveguide display.

[0095] FIG. **10**A illustrates an example of a geometrical waveguide display **1010** including transflective mirrors **1012** slanted with respect to surfaces of geometrical waveguide display **1010**. As described above, each transflective mirror **1012** may reflect a portion of the incident light out of geometrical waveguide display **1010** and may allow a portion of the incident light to pass though. Thus, transflective mirrors **1012** at different locations of the geometrical waveguide may couple portions of the light propagating in geometrical waveguide display **1020** out of geometrical waveguide display **1020** at different locations, thereby replicating the pupils in the eyebox. Even though only one geometrical waveguide is shown in FIG. **10**A, geometrical waveguide display **1010** may include two geometrical waveguides configured to replicate the pupil in two directions to form a 2-D array of exit pupils.

[0096] As described above, in order to generate replicated exit pupils with more uniform light intensity, transflective mirrors **1012** at different locations may need to have different reflectivity.

For example, the reflectivity of transflective mirrors **1012** may need to gradually increase along the light propagation direction, where the transflective mirror closest to the input coupler may have the lowest reflectivity, while the last transflective mirror on the optical path may have a reflectivity close to about 100%.

[0097] FIG. **10**B illustrates an example of pupil replication in the geometrical waveguide display **1010** of FIG. **10**A. As shown in FIG. **10**B, in geometrical waveguide display **1010**, there may be gaps between the replicated pupils in the eyebox. Therefore, the replicated pupils may not fill the eyebox and the light intensity in the eyebox may not be uniform.

[0098] FIG. **10**C illustrates an example of a geometrical waveguide display **1020** including an embedded partial reflector **1024** parallel to a surface of the geometrical waveguide display. As geometrical waveguide display **1010**, geometrical waveguide display **1020** may include transflective mirrors **1022** slanted with respect to surfaces of geometrical waveguide display **1020**. Geometrical waveguide display **1020** may also include partial reflector **1024** that may partially reflect the guided light (e.g., with a reflectivity about 50%). Geometrical waveguide display **1020** may be formed by bonding two substrates together, where partial reflector **1024** may be formed on a surface of one of the two substrates before bonding.

[0099] As illustrated in FIG. **10**C, light propagating within geometrical waveguide display **1020** may be split by partial reflector **1024** while propagating from one surface of geometrical waveguide display **1020** to an opposing surface of geometrical waveguide display **1020**. One portion of the light may be reflected by partial reflector **1024** back to a surface of geometrical waveguide display **1020** and then reflected at the surface by total internal reflection. The other portion of the light may be transmitted through partial reflector **1024** towards an opposing surface and then reflected by the opposing surface of geometrical waveguide display **1020**. In this way, light propagating within geometrical waveguide display **1020** may reach transflective mirrors **1022** more frequently, and thus the pupil may be replicated more frequently and densely to more uniformly fill the eyebox. Even though only one geometrical waveguide is shown in FIG. **10**C, geometrical waveguide display **1020** may include two geometrical waveguides configured to replicate the pupil in two directions to form a 2-D array of exit pupils.

[0100] FIG. **10**D illustrates an example of pupil replication in the geometrical waveguide display **1020** of FIG. **10**C. As shown in FIG. **10**D, in geometrical waveguide display **1020**, the replicated pupils may fill the eyebox more densely, and the light intensity in the eyebox may be more uniform than the example shown in FIG. **10**B. However, as shown in FIG. **10**D, the replicated exit pupils may partially overlap in some regions, where the regions with overlapped pupils may have higher light intensity than other regions, and thus the light intensity in the eyebox may still not be uniform.

[0101] According to certain embodiments, two or more partial reflective mirrors may be used in a waveguide, where the two or more mirrors may be parallel to a surface of the waveguide, and may, in some embodiments, equally spaced in a thickness direction of the waveguide. The two or more partial reflective mirrors may significantly increase the light intensity uniformity of the eyebox, without increasing the number of facets or changing the size of the input (entrance) pupil. The waveguide may be, for example, a grating waveguide that include a grating coupler (e.g., a surface-relief grating or a holographic grating) for pupil replication, or a geometrical waveguide including an array of transflective mirrors for pupil replication.

[0102] FIG. **11**A illustrates an example of a geometrical waveguide display **1100** including two or more embedded partial reflectors **1120** parallel to a surface of a geometrical waveguide **1110** according to certain embodiments. Geometrical waveguide **1110** may include transflective mirrors **1112** at a slant angle with respect to surfaces of geometrical waveguide **1110**. Geometrical waveguide **1110** may also include two or more partial reflectors **1120** that may partially reflect the guided light (e.g., with a reflectivity about 50%). The two or more partial reflectors **1120** may be parallel to a surface of geometrical waveguide **1110**, and may be evenly or unevenly distributed within geometrical waveguide **1110** in the thickness direction (e.g., z direction). Geometrical

waveguide **1110** may be formed by bonding three substrates together, where each partial reflector **1120** may be formed on a surface of a substrate of the three substrates before bonding.
[0103] As illustrated in FIG. **11**A, light propagating within geometrical waveguide **1110** may be split by partial reflectors **1120** while propagating from one surface of geometrical waveguide **1110** to an opposing surface of geometrical waveguide **1110**, where one portion of the light may be reflected by a partial reflector **1120** back towards a surface of geometrical waveguide **1110**, while the other portion of the light may be transmitted through partial reflector **1120** towards the opposing surface of geometrical waveguide **1110**. In this way, light propagating within geometrical waveguide **1110** may reach transflective mirrors **1112** more frequently, and thus the pupils may be replicated more frequently and densely to fill the eyebox. The replicated pupils may overlap and mix in the eyebox, such that the light intensity in the eyebox may be more uniform. Even though only one geometrical waveguide **1110** is shown in FIG. **11**A, geometrical waveguide display **1100** may include two geometrical waveguides configured to replicate the pupil in two directions to form a 2-D array of exit pupils.
[0104] FIG. **11**B illustrates an example of pupil replication in geometrical waveguide display **1100** of FIG. **11**A. As illustrated, the replicated pupils may fill the eyebox even more densely, and the replicated pupils may overlap throughout the eyebox and mix together to achieve more uniform light intensity in the eyebox.
[0105] In some embodiments, a surface-relief grating, a holographic grating, a polarization volume hologram, or an array of micro-mirrors formed at a surface of the first waveguide, may be used instead of transflective mirrors **1112** to couple the light out of a waveguide at a plurality of locations.
[0106] FIG. **12**A illustrates an example of simulating the pupil replication by a single waveguide using, for example, ray tracing. FIG. **12**B illustrates an example of the simulation result showing pupils replicated by the single waveguide, where the pupil replication density may be low.
[0107] FIG. **13**A illustrates an example of simulating the pupil replication by a stacked waveguide including embedded transflective mirrors parallel to a surface of the waveguide according to certain embodiments. FIG. **13**B illustrates an example of the simulation result showing pupils replicated by the stacked waveguide including embedded transflective mirrors parallel to a surface of the waveguide according to certain embodiments, where the pupil replication density may be higher.
[0108] FIG. **14** illustrates an example of a geometrical waveguide **1400** for one-dimensional pupil replication according to certain embodiments. Geometrical waveguide **1400** may include a waveguide **1410** and transflective mirrors **1412** (partial reflectors) in waveguide **1410**. Each transflective mirror **1412** may split the incident light by partially reflecting the incident light and partially transmitting the incident light such that a portion of the incident light may continue to propagate within the waveguide to be split by other transflective mirrors. Each transflective mirror **1412** may include, for example, a plurality of dielectric coating layers, one or more metal coating layers, or a combination of dielectric coating layers and metal coating layers.
[0109] For example, a transflective mirror may include a plurality of dielectric coating layers coated on a substrate, where the plurality of dielectric coating layers may include two or more different transparent dielectric materials having different refractive indices. The number of dielectric coating layers, and the refractive index and the thickness of each dielectric coating layer may be selected to achieve the desired performance, such as the desired reflectivity (reflection efficiency) and polarization performance. A plurality of substrates with a plurality of transflective mirrors formed thereon may be stacked and bonded (e.g., glued) together using, for example, optically clear adhesives. The bonded stack may be cut at a certain angle to form a geometrical waveguide including a plurality of transflective mirrors embedded therein. Different transflective mirrors in the plurality of transflective mirrors may have different reflectivity efficiencies. For example, the reflectivity of a first transflective mirror that may receive the in-coupled display light

before a second transflective mirror may have a lower reflectivity than the second transflective mirror, such that the portion of the display light reflected by the first transflective mirror may have a similar intensity as the portion of the display light reflected by the second transflective mirror.

[0110] As illustrated, an input beam **1420** may be split by a first transflective mirror of the array of transflective mirrors, where a fraction of input beam **1420** may be reflected and the other portion of input beam **1420** may be transmitted to reach a second transflective mirror of the array of transflective mirrors. The second transflective mirror and other transflective mirrors may split the incident light beam in a similar manner until the light beam reaches the last transflective mirror in the array of transflective mirrors. The last transflective mirror in the array of transflective mirrors may have a reflectivity about 100% to reflect all incident light. In this way, the input (or entrance) pupil may be replicated along one dimension (e.g., x or y direction in the illustrated example) by an array of transflective mirrors.

[0111] In geometrical waveguides such as geometrical waveguides **910**, **920**, **930**, **1110**, and **1400** described above, an array of transflective mirrors **1412** embedded in a waveguide is generally used to replicate or expand the pupil in one dimension. As described above, fabricating geometrical waveguides with embedded transflective mirrors may be a complicate and costly process.

[0112] According to certain embodiments, a one-dimensional pupil expander may include a waveguide transparent to display light and configured to guide the display light along a first direction, a partial reflective mirror on a first surface of the waveguide, and a reflector on a second surface of the waveguide opposing the first surface. The partial reflective mirror may be parallel to the first direction and may be characterized by different reflectivity at a plurality of regions along the first direction. Each region of the plurality of regions of the partial reflective mirror may be configured to partially reflect incident light towards the reflector and partially transmit the incident light through the region of the plurality of regions of the partial reflective mirror to create of replica of the pupil. The reflector may be configured to reflect the light reflected by a region of the plurality of regions of the partial reflective mirror towards another region of the plurality of regions of the partial reflective mirror. In this way, a plurality of replicas of the pupil may be created by the plurality of regions of the partial reflective mirror. The reflector may include, for example, a mirror (with a reflective close to 100%) or an interface between the waveguide and air that may be configured to cause total internal reflection. In some embodiments, two such one-dimensional pupil expanders may be used in a near-eye display system to replicate the pupil in two directions to form a 2-D array of pupils.

[0113] FIG. **15**A illustrates an example of a pupil expander **1502** including a variable reflectivity transflective mirror on a surface of a waveguide for one-dimensional pupil replication according to certain embodiments. In the illustrated example, pupil expander **1502** may include a waveguide **1540** (e.g., a bar or a rod), and a variable reflectivity transflective mirror **1550** at an interface between waveguide **1540** and a medium **1530** (e.g., a substrate or air). Variable reflectivity transflective mirror **1550** may be formed on a surface of waveguide **1540** or medium **1530**.

[0114] As illustrated, an input beam **1522** may be coupled into waveguide **1540** (e.g., by a prism **1542**). Input beam **1522** may be partially reflected by a first region of transflective mirror **1550** and partially transmitted by the first region of transflective mirror **1550** into medium **1530**. The reflected portion of the input beam may be reflected by a surface of waveguide **1540** opposing transflective mirror **1550**, for example, through total internal reflection (or by an optional mirror **1552** that has a reflectivity close to 100% if the total internal reflection condition is not met), towards a second region of transflective mirror **1550**. The second region of transflective mirror **1550** may split the incident light by reflecting a portion of the incident light and transmitting a fraction of the incident light into medium **1530**, where the reflected portion may be reflected back towards a third region of transflective mirror **1550** by a surface of waveguide **1540** opposing transflective mirror **1550** (or by mirror **1552**). In this way, the light coupled into waveguide **1540** may be guided by transflective mirror **1550** and a surface of waveguide **1540** (or mirror **1552**) to propagate within waveguide **1540**, where portions of the light beam may be transmitted by transflective mirror **1550** into medium **1530** each time the light beam is incident on transflective mirror **1550**, thereby replicating the input pupil in one dimension (e.g., the y direction). The period of the pupil replicas may depend on the size and orientation of the waveguide **1540**. To achieve more uniform light intensity among the replicated pupils, the reflectivity of transflective mirror **1550** may gradually decrease (or the transmissivity of transflective mirror **1550** may gradually increase) in the direction of light propagation in waveguide **1540**, such that the transmissivity of transflective mirror **1550** is lower when the incident light has a higher intensity, and is higher when the incident light has a lower intensity. In some implementations, transflective mirror **1550** may have different reflectivity in different regions. In some implementations, the reflectivity of transflective mirror **1550** may vary (e.g., increase or decrease) continuously along at least one direction (e.g., when each region having a uniform reflectivity is small).

[0115] In the example shown in FIG. **15**A, if input beam **1522** includes a linear array of replicated pupils (e.g., replicated along the x direction), pupil expander **1502** may further replicate the pupils along another direction (e.g., the y direction), such that output beams of pupil expander **1502** may include a two-dimensional array of pupils replicated along both x and y directions. The linear array of replicated pupils may be generated by another pupil expander disclosed herein, such as another pupil expander **1502**.

[0116] FIG. **15**B illustrates another example of a pupil expander **1504** including a variable reflectivity transflective mirror on a surface of a waveguide for one-dimensional pupil replication according to certain embodiments. In the illustrated example, pupil expander **1504** may include a waveguide **1560**, and a variable reflectivity transflective mirror **1570** at an interface between waveguide **1560** and a medium **1580** (e.g., a substrate or air). Variable reflectivity transflective mirror **1570** may be formed on a surface of waveguide **1560** or medium **1580**.

[0117] As illustrated, an input beam **1524** may be coupled into waveguide **1560** (e.g., by a refractive, diffractive, or reflective coupler). Input beam **1524** may be partially reflected by a first region of transflective mirror **1570** and partially transmitted by the first region of transflective mirror **1570** into medium **1580**. The reflected portion of the input beam may be reflected by a surface of waveguide **1560** opposing transflective mirror **1570**, for example, through total internal reflection (or by an optional mirror **1562** that has a reflectivity close to 100% if the total internal reflection condition is not met), towards a second region of transflective mirror **1570**. The second region of transflective mirror **1570** may split the incident light by reflecting a portion of the incident light and transmitting a fraction of the incident light into medium **1580**, where the reflected portion may be reflected back towards a third region of transflective mirror **1570** by a surface of waveguide **1560** opposing transflective mirror **1570** (or by mirror **1562**). In this way, the light coupled into waveguide **1560** may be guided by transflective mirror **1570** and a surface of waveguide **1560** (or mirror **1562**) to propagate within waveguide **1560**, where portions of the light beam may be transmitted by transflective mirror **1570** into medium **1580** each time the light beam is incident on transflective mirror **1570**, thereby replicating the input pupil in one dimension (e.g., the y direction). The period of the pupil replicas may depend on the size and orientation of the waveguide **1560**. To achieve more uniform light intensity among the replicated pupils, the reflectivity of transflective mirror **1570** may gradually decrease (or the transmissivity of transflective mirror **1570** may gradually increase) in the direction of light propagation in waveguide **1560**, such that the transmissivity of transflective mirror **1570** is lower when the incident light has a higher intensity, and is higher when the incident light has a lower intensity. In some implementations, transflective mirror **1570** may have different reflectivity in different regions. In some implementations, the reflectivity of transflective mirror **1570** may vary (e.g., increase or decrease) continuously along at least one direction (e.g., when each region having a uniform reflectivity is small).

[0118] In the example shown in FIG. **15**B, if input beam **1524** includes a linear array of replicated pupils (e.g., replicated along the x direction), pupil expander **1504** may further replicate the pupils along another direction (e.g., the y direction), such that output beams of pupil expander **1504** may include a two-dimensional array of pupils replicated along both x and y directions. The linear array of replicated pupils may be generated by another pupil expander disclosed herein, such as another pupil expander **1502** or **1504**.

[0119] As described above, in some embodiments, one or more transflective mirrors **1572** that are parallel to a surface of waveguide **1540** or **1560** may be embedded in waveguide **1540** or **1560** to increase the pupil replication density.

[0120] FIG. **16**A illustrates an example of a waveguide display **1600** including two one-dimensional pupil expanders **1610** and **1620** for two-dimensional pupil replication according to certain embodiments. Each of pupil expanders **1610** and **1620** may be similar to pupil expander **1502** or pupil expander **1504**. Pupil expander **1610** may include a waveguide, a variable reflectivity transflective mirror **1612** (e.g., similar to variable reflectivity transflective mirror **1550**) on a surface of the waveguide, and an optional reflector **1614** (e.g., similar to mirror **1552**) on an opposing surface of the waveguide. Pupil expander **1610** may replicate the pupil through a plurality of regions of variable reflectivity transflective mirror **1612** along approximately the x direction, as described above with respect to, for example, FIGS. **15**A and **15**B. Light coupled out of pupil expander **1610** may be coupled into pupil expander **1620** through a coupler **1624**, which may be a grating, a prism, or a mirror. Pupil expander **1620** may include a waveguide, a variable reflectivity transflective mirror **1622** (e.g., similar to variable reflectivity transflective mirror **1550**) or a grating coupler on a surface of the waveguide, and an optional reflector **1626** (e.g., similar to mirror **1552**) on an opposing surface of the waveguide. Pupil expander **1620** may replicate the pupil through a plurality of regions of variable reflectivity transflective mirror **1622** along approximately the y direction, as described above with respect to, for example, FIGS. **15**A and **15**B. Thus, pupil expanders **1610** and **1620** may replicate the pupil along the x and y directions, respectively, to create a two-dimensional array of pupils.

[0121] FIG. **16**B illustrates another example of a waveguide display **1605** including two one-dimensional pupil expanders **1630** and **1640** for two-dimensional pupil replication according to certain embodiments. Each of pupil expanders **1630** and **1640** may be similar to pupil expander **1502** or pupil expander **1504**. Pupil expander **1630** may include a waveguide, a variable reflectivity transflective mirror **1632** (e.g., similar to variable reflectivity transflective mirror **1550**) on a surface of the waveguide, and an optional reflector **1634** (e.g., similar to mirror **1552**) on an opposing surface of the waveguide. Pupil expander **1630** may replicate the pupil through a plurality of regions of variable reflectivity transflective mirror **1632** along approximately the x direction, as described above with respect to, for example, FIGS. **15**A and **15**B. Light coupled out of pupil expander **1630** may be coupled into pupil expander **1640** through a slanted edge of the waveguide of pupil expander **1640**. Pupil expander **1640** may include a waveguide, a variable reflectivity transflective mirror **1642** (e.g., similar to variable reflectivity transflective mirror **1550**) or a grating coupler on a surface of the waveguide, and an optional reflector **1644** (e.g., similar to mirror **1552**) on an opposing surface of the waveguide. Pupil expander **1640** may replicate the pupil through a plurality of regions of variable reflectivity transflective mirror **1642** along approximately the y direction, as described above with respect to, for example, FIGS. **15**A and **15**B. Thus, pupil expanders **1630** and **1640** may replicate the pupil along the x and y directions, respectively, to create a two-dimensional array of pupils.

[0122] FIG. **17** illustrates another example of a waveguide display **1700** including two one-dimensional pupil expanders **1710** and **1730** for two-dimensional pupil replication according to certain embodiments. Pupil expanders **1710** and **1730** may be similar to pupil expander **1502** or **1504** described above. In the illustrated example, pupil expander **1710** may include a variable reflectivity transflective mirror **1720** on one surface, and an optional reflector **1722** on an opposing surface, as described above with respect to FIG. **15**A or **15**B. Pupil expander **1710** may have a bar shape and may replicate an input pupil **1712** along one direction (e.g., the y direction) to generate a linear array of pupil. In the illustrated example, pupil expander **1730** may include a variable reflectivity transflective mirror **1740** on one surface, and an optional reflector **1750** on an opposing surface, as described above with respect to FIG. **15**A or **15**B. Pupil expander **1730** may have a larger area and may replicate the linear array of pupil from pupil expander **1710** along another direction (e.g., the x direction).

[0123] In some embodiments, a two-dimensional pupil expander may include a plurality of one-dimensional pupil expanders similar to pupil expander **1502** or **1504**. The plurality of one-dimensional pupil expanders may have different thicknesses, and may replicate the pupils with different densities.

[0124] Embodiments of the invention may include or be implemented in conjunction with an artificial reality system. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, for example, a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, and any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., perform activities in) an artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a head-mounted display (HMD) connected to a host computer system, a standalone HMD, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

[0125] FIG. **18** is a simplified block diagram of an example electronic system **1800** of an example near-eye display (e.g., HMD device) for implementing some of the examples disclosed herein. Electronic system **1800** may be used as the electronic system of an HMD device or other near-eye displays described above. In this example, electronic system **1800** may include one or more processor(s) **1810** and a memory **1820**. Processor(s) **1810** may be configured to execute instructions for performing operations at a number of components, and can be, for example, a general-purpose processor or microprocessor suitable for implementation within a portable electronic device. Processor(s) **1810** may be communicatively coupled with a plurality of components within electronic system **1800**. To realize this communicative coupling, processor(s) **1810** may communicate with the other illustrated components across a bus **1840**. Bus **1840** may be any subsystem adapted to transfer data within electronic system **1800**. Bus **1840** may include a plurality of computer buses and additional circuitry to transfer data.

[0126] Memory **1820** may be coupled to processor(s) **1810**. In some embodiments, memory **1820** may offer both short-term and long-term storage and may be divided into several units. Memory **1820** may be volatile, such as static random access memory (SRAM) and/or dynamic random access memory (DRAM) and/or non-volatile, such as read-only memory (ROM), flash memory, and the like. Furthermore, memory **1820** may include removable storage devices, such as secure digital (SD) cards. Memory **1820** may provide storage of computer-readable instructions, data structures, program code, and other data for electronic system **1800**. In some embodiments, memory **1820** may be distributed into different hardware subsystems. A set of instructions and/or code might be stored on memory **1820**. The instructions might take the form of executable code that may be executable by electronic system **1800**, and/or might take the form of source and/or installable code, which, upon compilation and/or installation on electronic system **1800** (e.g., using any of a variety of generally available compilers, installation programs, compression/decompression utilities, etc.), may take the form of executable code.

[0127] In some embodiments, memory **1820** may store a plurality of applications **1822** through **1824**, which may include any number of applications. Examples of applications may include gaming applications, conferencing applications, video playback applications, or other suitable applications. The applications may include a depth sensing function or eye tracking function. Applications **1822-1824** may include particular instructions to be executed by processor(s) **1810**. In some embodiments, certain applications or parts of applications **1822-1824** may be executable by other hardware subsystems **1880**. In certain embodiments, memory **1820** may additionally include secure memory, which may include additional security controls to prevent copying or other unauthorized access to secure information.

[0128] In some embodiments, memory **1820** may include an operating system **1825** loaded therein. Operating system **1825** may be operable to initiate the execution of the instructions provided by applications **1822-1824** and/or manage other hardware subsystems **1880** as well as interfaces with a wireless communication subsystem **1830** which may include one or more wireless transceivers. Operating system **1825** may be adapted to perform other operations across the components of electronic system **1800** including threading, resource management, data storage control and other similar functionality.

[0129] Wireless communication subsystem **1830** may include, for example, an infrared communication device, a wireless communication device and/or chipset (such as a Bluetooth® device, an IEEE 802.11 device, a Wi-Fi device, a WiMax device, cellular communication facilities, etc.), and/or similar communication interfaces. Electronic system **1800** may include one or more antennas **1834** for wireless communication as part of wireless communication subsystem **1830** or as a separate component coupled to any portion of the system. Depending on desired functionality, wireless communication subsystem **1830** may include separate transceivers to communicate with base transceiver stations and other wireless devices and access points, which may include communicating with different data networks and/or network types, such as wireless wide-area networks (WWANs), wireless local area networks (WLANs), or wireless personal area networks (WPANs). A WWAN may be, for example, a WiMax (IEEE 802.16) network. A WLAN may be, for example, an IEEE 802.11x network. A WPAN may be, for example, a Bluetooth network, an IEEE 802.15x, or some other types of network. The techniques described herein may also be used for any combination of WWAN, WLAN, and/or WPAN. Wireless communications subsystem **1830** may permit data to be exchanged with a network, other computer systems, and/or any other devices described herein. Wireless communication subsystem **1830** may include a means for transmitting or receiving data, such as identifiers of HMD devices, position data, a geographic map, a heat map, photos, or videos, using antenna(s) **1834** and wireless link(s) **1832**.

[0130] Embodiments of electronic system **1800** may also include one or more sensors **1890**. Sensor(s) **1890** may include, for example, an image sensor, an accelerometer, a pressure sensor, a temperature sensor, a proximity sensor, a magnetometer, a gyroscope, an inertial sensor (e.g., a subsystem that combines an accelerometer and a gyroscope), an ambient light sensor, or any other similar devices or subsystems operable to provide sensory output and/or receive sensory input, such as a depth sensor or a position sensor. For example, in some implementations, sensor(s) **1890** may include one or more inertial measurement units (IMUs) and/or one or more position sensors. An IMU may generate calibration data indicating an estimated position of the HMD device relative to an initial position of the HMD device, based on measurement signals received from one or more of the position sensors. A position sensor may generate one or more measurement signals in response to motion of the HMD device. Examples of the position sensors may include, but are not limited to, one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU, or some combination thereof. The position sensors may be located external to the IMU, internal to the IMU, or some combination thereof. At least some sensors may use a structured light pattern for sensing.

[0131] Electronic system **1800** may include a display **1860**. Display **1860** may be a near-eye display, and may graphically present information, such as images, videos, and various instructions, from electronic system **1800** to a user. Such information may be derived from one or more applications **1822-1824**, virtual reality engine **1826**, one or more other hardware subsystems **1880**, a combination thereof, or any other suitable means for resolving graphical content for the user (e.g., by operating system **1825**). Display **1860** may use liquid crystal display (LCD) technology, light-emitting diode (LED) technology (including, for example, OLED, ILED, μLED, AMOLED, TOLED, etc.), light emitting polymer display (LPD) technology, or some other display technology.
[0132] Electronic system **1800** may include a user input/output interface **1870**. User input/output interface **1870** may allow a user to send action requests to electronic system **1800**. An action request may be a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application. User input/output interface **1870** may include one or more input devices. Example input devices may include a touchscreen, a touch pad, microphone(s), button(s), dial(s), switch(es), a keyboard, a mouse, a game controller, or any other suitable device for receiving action requests and communicating the received action requests to electronic system **1800**. In some embodiments, user input/output interface **1870** may provide haptic feedback to the user in accordance with instructions received from electronic system **1800**. For example, the haptic feedback may be provided when an action request is received or has been performed.
[0133] Electronic system **1800** may include a camera **1850** that may be used to take photos or videos of a user, for example, for tracking the user's eye position. Camera **1850** may also be used to take photos or videos of the environment, for example, for VR, AR, or MR applications. Camera **1850** may include, for example, a complementary metal-oxide-semiconductor (CMOS) image sensor with a few millions or tens of millions of pixels. In some implementations, camera **1850** may include two or more cameras that may be used to capture 3-D images.
[0134] In some embodiments, electronic system **1800** may include a plurality of other hardware subsystems **1880**. Each of other hardware subsystems **1880** may be a physical subsystem within electronic system **1800**. While each of other hardware subsystems **1880** may be permanently configured as a structure, some of other hardware subsystems **1880** may be temporarily configured to perform specific functions or temporarily activated. Examples of other hardware subsystems **1880** may include, for example, an audio output and/or input interface (e.g., a microphone or speaker), a near field communication (NFC) device, a rechargeable battery, a battery management system, a wired/wireless battery charging system, etc. In some embodiments, one or more functions of other hardware subsystems **1880** may be implemented in software.
[0135] In some embodiments, memory **1820** of electronic system **1800** may also store a virtual reality engine **1826**. Virtual reality engine **1826** may execute applications within electronic system **1800** and receive position information, acceleration information, velocity information, predicted future positions, or some combination thereof of the HMD device from the various sensors. In some embodiments, the information received by virtual reality engine **1826** may be used for producing a signal (e.g., display instructions) to display **1860**. For example, if the received information indicates that the user has looked to the left, virtual reality engine **1826** may generate content for the HMD device that mirrors the user's movement in a virtual environment. Additionally, virtual reality engine **1826** may perform an action within an application in response to an action request received from user input/output interface **1870** and provide feedback to the user. The provided feedback may be visual, audible, or haptic feedback. In some implementations, processor(s) **1810** may include one or more GPUs that may execute virtual reality engine **1826**.
[0136] In various implementations, the above-described hardware and subsystems may be implemented on a single device or on multiple devices that can communicate with one another using wired or wireless connections. For example, in some implementations, some components or subsystems, such as GPUs, virtual reality engine **1826**, and applications (e.g., tracking application),

may be implemented on a console separate from the head-mounted display device. In some implementations, one console may be connected to or support more than one HMD.

[0137] In alternative configurations, different and/or additional components may be included in electronic system **1800**. Similarly, functionality of one or more of the components can be distributed among the components in a manner different from the manner described above. For example, in some embodiments, electronic system **1800** may be modified to include other system environments, such as an AR system environment and/or an MR environment.

[0138] The methods, systems, and devices discussed above are examples. Various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, in alternative configurations, the methods described may be performed in an order different from that described, and/or various stages may be added, omitted, and/or combined. Also, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. Also, technology evolves and, thus, many of the elements are examples that do not limit the scope of the disclosure to those specific examples.

[0139] Specific details are given in the description to provide a thorough understanding of the embodiments. However, embodiments may be practiced without these specific details. For example, well-known circuits, processes, systems, structures, and techniques have been shown without unnecessary detail in order to avoid obscuring the embodiments. This description provides example embodiments only, and is not intended to limit the scope, applicability, or configuration of the invention. Rather, the preceding description of the embodiments will provide those skilled in the art with an enabling description for implementing various embodiments. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the present disclosure.

[0140] Also, some embodiments were described as processes depicted as flow diagrams or block diagrams. Although each may describe the operations as a sequential process, many of the operations may be performed in parallel or concurrently. In addition, the order of the operations may be rearranged. A process may have additional steps not included in the figure. Furthermore, embodiments of the methods may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the associated tasks may be stored in a computer-readable medium such as a storage medium. Processors may perform the associated tasks.

[0141] It will be apparent to those skilled in the art that substantial variations may be made in accordance with specific requirements. For example, customized or special-purpose hardware might also be used, and/or particular elements might be implemented in hardware, software (including portable software, such as applets, etc.), or both. Further, connection to other computing devices such as network input/output devices may be employed.

[0142] With reference to the appended figures, components that can include memory can include non-transitory machine-readable media. The term “machine-readable medium” and “computer-readable medium,” as used herein, refer to any storage medium that participates in providing data that causes a machine to operate in a specific fashion. In embodiments provided hereinabove, various machine-readable media might be involved in providing instructions/code to processing units and/or other device(s) for execution. Additionally or alternatively, the machine-readable media might be used to store and/or carry such instructions/code. In many implementations, a computer-readable medium is a physical and/or tangible storage medium. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Common forms of computer-readable media include, for example, magnetic and/or optical media such as compact disk (CD) or digital versatile disk (DVD), punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a programmable read-only memory

(PROM), an erasable programmable read-only memory (EPROM), a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code. A computer program product may include code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, an application (App), a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements.

[0143] Those of skill in the art will appreciate that information and signals used to communicate the messages described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0144] Terms, “and” and “or” as used herein, may include a variety of meanings that are also expected to depend at least in part upon the context in which such terms are used. Typically, “or” if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the term “one or more” as used herein may be used to describe any feature, structure, or characteristic in the singular or may be used to describe some combination of features, structures, or characteristics. However, it should be noted that this is merely an illustrative example and claimed subject matter is not limited to this example. Furthermore, the term “at least one of” if used to associate a list, such as A, B, or C, can be interpreted to mean A, B, C, or a combination of A, B, and/or C, such as AB, AC, BC, AA, ABC, AAB, ACC, AABBCCC, or the like.

[0145] Further, while certain embodiments have been described using a particular combination of hardware and software, it should be recognized that other combinations of hardware and software are also possible. Certain embodiments may be implemented only in hardware, or only in software, or using combinations thereof. In one example, software may be implemented with a computer program product containing computer program code or instructions executable by one or more processors for performing any or all of the steps, operations, or processes described in this disclosure, where the computer program may be stored on a non-transitory computer readable medium. The various processes described herein can be implemented on the same processor or different processors in any combination.

[0146] Where devices, systems, components, or modules are described as being configured to perform certain operations or functions, such configuration can be accomplished, for example, by designing electronic circuits to perform the operation, by programming programmable electronic circuits (such as microprocessors) to perform the operation such as by executing computer instructions or code, or processors or cores programmed to execute code or instructions stored on a non-transitory memory medium, or any combination thereof. Processes can communicate using a variety of techniques, including, but not limited to, conventional techniques for inter-process communications, and different pairs of processes may use different techniques, or the same pair of processes may use different techniques at different times.

[0147] The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that additions, subtractions, deletions, and other modifications and changes may be made thereunto without departing from the broader spirit and scope as set forth in the claims. Thus, although specific embodiments have been described, these are not intended to be limiting. Various modifications and equivalents are within the scope of the following claims.

[0148] Embodiments disclosed herein may include different combinations of features in view of the description. Certain embodiments are described in the following examples.

[0149] In Example 1, a pupil expander of a near-eye display comprises a waveguide transparent to display light and configured to guide the display light along a first direction, and a partial reflective mirror on a first surface of the waveguide, wherein the partial reflective mirror is parallel to the first direction and is characterized by different reflectivity at a plurality of regions along the first direction, and wherein each region of the plurality of regions of the partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the plurality of regions of the partial reflective mirror.

[0150] Example 2 includes the pupil expander of Example 1, wherein the reflectivity at the plurality of regions of the partial reflective mirror increases along the first direction.

[0151] Example 3 includes the pupil expander of Example 2, wherein the reflectivity at each respective region of the plurality of regions of the partial reflective mirror is uniform within the respective region.

[0152] Example 4 includes the pupil expander of Example 2, wherein the reflectivity of the partial reflective mirror increases continuously along the first direction.

[0153] Example 5 includes the pupil expander of any of Examples 1-4, wherein the waveguide is configured to reflect the display light at a second surface opposing the first surface by total internal reflection.

[0154] Example 6 includes the pupil expander of any of Examples 1-4, wherein the pupil expander further comprises a reflector on a second surface of the waveguide opposing the first surface, wherein the reflector is configured to reflect the display light reflected by a region of the plurality of regions of the partial reflective mirror towards another region of the plurality of regions of the partial reflective mirror.

[0155] Example 7 includes the pupil expander of any of Examples 1-6, wherein the waveguide has a bar shape and extends in the first direction.

[0156] Example 8 includes the pupil expander of any of Examples 1-6, wherein the waveguide is configured to receive an array of pupils replicated along a second direction and replicate the array of pupils along the first direction.

[0157] Example 9 includes the pupil expander of any of Examples 1-8, wherein the pupil expander further comprises one or more partial reflective mirrors embedded in the waveguide and parallel to a surface of the waveguide and the first direction.

[0158] Example 10 includes a near-eye display comprising: [0159] a first pupil expander extending in a first direction, the first pupil expander comprising: [0160] a first waveguide transparent to display light and configured to guide the display light along the first direction; and [0161] a first partial reflective mirror on a first surface of the first waveguide, wherein the first partial reflective mirror is parallel to the first direction and is characterized by different reflectivity at a first plurality of regions along the first direction, [0162] wherein each region of the first plurality of regions of the first partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the first plurality of regions of the first partial reflective mirror; and [0163] a second pupil expander configured to split the display light transmitted from each region of the first plurality of regions of the first partial reflective mirror at a second plurality of regions along a second direction that is different from the first direction.

[0164] Example 11 includes the near-eye display of Example 10, wherein the reflectivity at the first plurality of regions of the first partial reflective mirror increases along the first direction.

[0165] Example 12 includes the near-eye display of Example 11, wherein the reflectivity at each respective region of the first plurality of regions of the first partial reflective mirror is uniform within the respective region.

[0166] Example 13 includes the near-eye display of Example 11, wherein the reflectivity at the first plurality of regions of the first partial reflective mirror increases continuously along the first direction.

[0167] Example 14 includes the near-eye display of any of Examples 10-13, wherein the first waveguide of the first pupil expander is configured to reflect the display light at a second surface opposing the first surface by total internal reflection.

[0168] Example 15 includes the near-eye display of any of Examples 10-13, wherein the first pupil expander includes a first reflector on a second surface of the first waveguide opposing the first surface, the first reflector configured to reflect the display light reflected by a region of the first plurality of regions of the first partial reflective mirror towards another region of the first plurality of regions of the first partial reflective mirror.
[0169] Example 16 includes the near-eye display of any of Examples 10-15, wherein the second pupil expander comprises: a second waveguide configured to guide the display light along the second direction; and a second partial reflective mirror on a first surface of the second waveguide, wherein the second partial reflective mirror is parallel to the second direction and is characterized by different reflectivity at the second plurality of regions along the second direction, and wherein each region of the second plurality of regions of the second partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the second plurality of regions of the second partial reflective mirror.
[0170] Example 17 includes the near-eye display of Example 16, wherein the second waveguide of the second pupil expander is configured to reflect the display light at a second surface opposing the first surface of the second waveguide by total internal reflection.
[0171] Example 18 includes the near-eye display of Example 16, wherein the second pupil expander further comprises a second reflector on a second surface of the second waveguide opposing the first surface of the second waveguide, the second reflector configured to reflect the display light reflected by a region of the second plurality of regions of the second partial reflective mirror towards another region of the second plurality of regions of the second partial reflective mirror.
[0172] Example 19 includes the near-eye display of Example 16, wherein the second pupil expander includes one or more grating couplers configured to couple the display light into and/or out of the second waveguide.
[0173] Example 20 includes the near-eye display of any of Example 10-19, wherein the first pupil expander includes one or more partial reflective mirrors embedded in the first waveguide and parallel to a surface of the first waveguide and the first direction.
[0174] Example 21 includes a pupil expander of a near-eye display, the pupil expander comprising: a waveguide transparent to display light and configured to guide the display light along a first direction; and two or more partial reflective mirrors embedded in the waveguide and parallel to a surface of the waveguide and the first direction.
[0175] Example 22 includes the pupil expander of Example 21, wherein the pupil expander includes an output coupler configured to couple the display light out of the waveguide at a plurality of locations along the first direction, the output coupler comprising a surface-relief grating, a holographic grating, a polarization volume hologram, an array of partially reflective mirrors embedded in the waveguide, or an array of micro-mirrors formed at a surface of the waveguide.
[0176] Example 23 includes the pupil expander of Example 21 or 22, wherein the two or more partial reflective mirrors are evenly distributed in the waveguide along a second direction that is perpendicular to the first direction.
[0177] Example 24 includes the pupil expander of any of Examples 21-23, wherein the waveguide includes a plurality of stacked substrates.
[0178] Example 25 includes the pupil expander of Example 24, wherein each of the two or more partial reflective mirrors is formed on a substrate of the plurality of stacked substrates.
[0179] Example 26 includes the pupil expander of any of Examples 21-25, wherein each of the two or more partial reflective mirrors is characterized by a reflectivity about 50%.
[0180] Example 27 includes a near-eye display, the near-eye display comprising: [0181] a first pupil expander extending in a first direction, the first pupil expander comprising: [0182] a first waveguide transparent to display light and configured to guide the display light along the first direction; and [0183] two or more partial reflective mirrors embedded in the first waveguide and

parallel to a surface of the first waveguide and the first direction; and [0184] a second pupil expander configured to split the display light from each location of the first plurality of locations of the first pupil expander at a second plurality of locations along a second direction that is different from the first direction.
[0185] Example 28 includes the near-eye display of Example 27, wherein the first pupil expander includes a first output coupler configured to couple the display light out of the first waveguide at a first plurality of locations of the first pupil expander along the first direction, the first output coupler comprising a surface-relief grating, a holographic grating, a polarization volume hologram, an array of partially reflective mirrors embedded in the first waveguide, or an array of micro-mirrors formed at a surface of the first waveguide.
[0186] Example 29 includes the near-eye display of Example 27 or 28, wherein the two or more partial reflective mirrors are evenly distributed in the first waveguide along a direction that is perpendicular to the first direction.
[0187] Example 30 includes the near-eye display of any of Examples 27-29, wherein each of the two or more partial reflective mirrors is characterized by a reflectivity about 50%.
[0188] Example 31 includes the near-eye display of any of Examples 27-30, wherein the second pupil expander comprises: a second waveguide transparent to the display light and configured to guide the display light along the second direction; two or more partial reflective mirrors embedded in the second waveguide and parallel to a surface of the second waveguide and the second direction; and a second output coupler configured to couple the display light out of the second waveguide at the second plurality of locations of the second pupil expander along the second direction.

Claims

1. A pupil expander of a near-eye display, the pupil expander comprising: a waveguide transparent to display light and configured to guide the display light along a first direction; and a partial reflective mirror on a first surface of the waveguide, wherein the partial reflective mirror is parallel to the first direction and is characterized by different reflectivity at a plurality of regions along the first direction, wherein each region of the plurality of regions of the partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the plurality of regions of the partial reflective mirror.
2. The pupil expander of claim 1, wherein the reflectivity at the plurality of regions of the partial reflective mirror increases along the first direction.
3. The pupil expander of claim 2, wherein reflectivity at each respective region of the plurality of regions of the partial reflective mirror is uniform within the respective region.
4. The pupil expander of claim 2, wherein reflectivity of the partial reflective mirror increases continuously along the first direction.
5. The pupil expander of claim 1, wherein the waveguide is configured to reflect the display light at a second surface opposing the first surface by total internal reflection.
6. The pupil expander of claim 1, further comprising a reflector on a second surface of the waveguide opposing the first surface, wherein the reflector is configured to reflect the display light reflected by a region of the plurality of regions of the partial reflective mirror towards another region of the plurality of regions of the partial reflective mirror.
7. The pupil expander of claim 1, wherein the waveguide has a bar shape and extends in the first direction.
8. The pupil expander of claim 1, wherein the waveguide is configured to receive an array of pupils replicated along a second direction and replicate the array of pupils along the first direction.
9. The pupil expander of claim 1, further comprising one or more partial reflective mirrors embedded in the waveguide and parallel to a surface of the waveguide and the first direction.

10. A near-eye display comprising: a first pupil expander extending in a first direction, the first pupil expander comprising: a first waveguide transparent to display light and configured to guide the display light along the first direction; and a first partial reflective mirror on a first surface of the first waveguide, wherein the first partial reflective mirror is parallel to the first direction and is characterized by different reflectivity at a first plurality of regions along the first direction, wherein each region of the first plurality of regions of the first partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the first plurality of regions of the first partial reflective mirror; and a second pupil expander configured to split the display light transmitted from each region of the first plurality of regions of the first partial reflective mirror at a second plurality of regions along a second direction that is different from the first direction.
11. The near-eye display of claim 10, wherein the reflectivity at the first plurality of regions of the first partial reflective mirror increases along the first direction.
12. The near-eye display of claim 11, wherein reflectivity at each respective region of the first plurality of regions of the first partial reflective mirror is uniform within the respective region.
13. The near-eye display of claim 11, wherein reflectivity of the first partial reflective mirror increases continuously along the first direction.
14. The near-eye display of claim 10, wherein the first waveguide of the first pupil expander is configured to reflect the display light at a second surface opposing the first surface by total internal reflection.
15. The near-eye display of claim 10, wherein the first pupil expander includes a first reflector on a second surface of the first waveguide opposing the first surface, the first reflector configured to reflect the display light reflected by a region of the first plurality of regions of the first partial reflective mirror towards another region of the first plurality of regions of the first partial reflective mirror.
16. The near-eye display of claim 10, wherein the second pupil expander comprises: a second waveguide configured to guide the display light along the second direction; and a second partial reflective mirror on a first surface of the second waveguide, wherein the second partial reflective mirror is parallel to the second direction and is characterized by different reflectivity at the second plurality of regions along the second direction, wherein each region of the second plurality of regions of the second partial reflective mirror is configured to partially reflect incident light and partially transmit the incident light through the region of the second plurality of regions of the second partial reflective mirror.
17. The near-eye display of claim 16, wherein the second waveguide of the second pupil expander is configured to reflect the display light at a second surface opposing the first surface of the second waveguide by total internal reflection.
18. The near-eye display of claim 16, wherein the second pupil expander further comprises a second reflector on a second surface of the second waveguide opposing the first surface of the second waveguide, the second reflector configured to reflect the display light reflected by a region of the second plurality of regions of the second partial reflective mirror towards another region of the second plurality of regions of the second partial reflective mirror.
19. The near-eye display of claim 16, wherein the second pupil expander includes one or more grating couplers configured to couple the display light into and/or out of the second waveguide.
20. The near-eye display of claim 10, wherein the first pupil expander includes one or more partial reflective mirrors embedded in the first waveguide and parallel to a surface of the first waveguide and the first direction.