US012055659B2

(12) **United States Patent**
Gassend et al.

(10) **Patent No.: US 12,055,659 B2**
(45) **Date of Patent: Aug. 6, 2024**

(54) **OPTICAL REDIRECTOR DEVICE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 888 days.

(21) Appl. No.: **17/134,277**

(22) Filed: **Dec. 26, 2020**

(65) **Prior Publication Data**

US 2021/0199770 A1 Jul. 1, 2021

Related U.S. Application Data

(60) Provisional application No. 62/954,088, filed on Dec. 27, 2019.

(51) **Int. Cl.**
G01S 7/48 (2006.01)
G01S 7/481 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01S 7/4813*** (2013.01); ***G01S 7/4817*** (2013.01); ***G01S 7/4914*** (2013.01); ***G01S 7/493*** (2013.01); ***G01S 17/931*** (2020.01)

(58) **Field of Classification Search**
USPC 356/4.01
See application file for complete search history.

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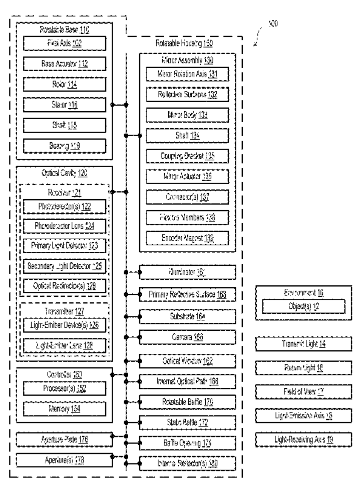
(57) **ABSTRACT**

The present disclosure relates to devices, lidar systems, and vehicles that include optical redirectors. An example lidar system includes a transmitter and a receiver. The transmitter includes at least one light-emitter device configured to transmit emission light into an environment of the lidar system. The receiver is configured to detect return light from the environment and includes a plurality of apertures, a plurality of photodetectors, and a plurality of optical redirector elements. Each optical redirector element is configured to optically couple a respective portion of return light from a respective aperture to at least one photodetector of the plurality of photodetectors.

20 Claims, 17 Drawing Sheets



(51) **Int. Cl.**

G01S 7/4914	(2020.01)
G01S 7/493	(2006.01)
G01S 17/931	(2020.01)

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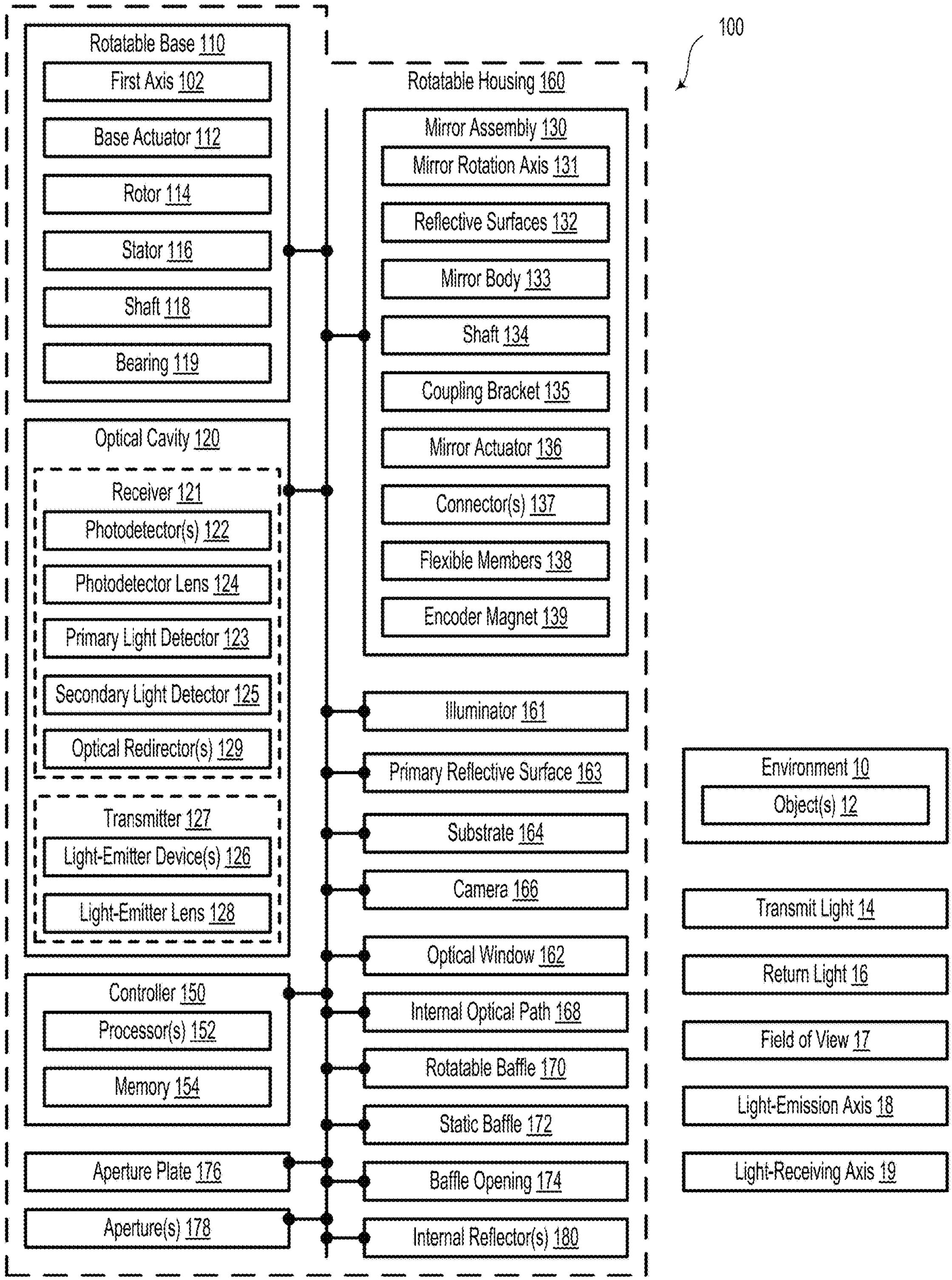
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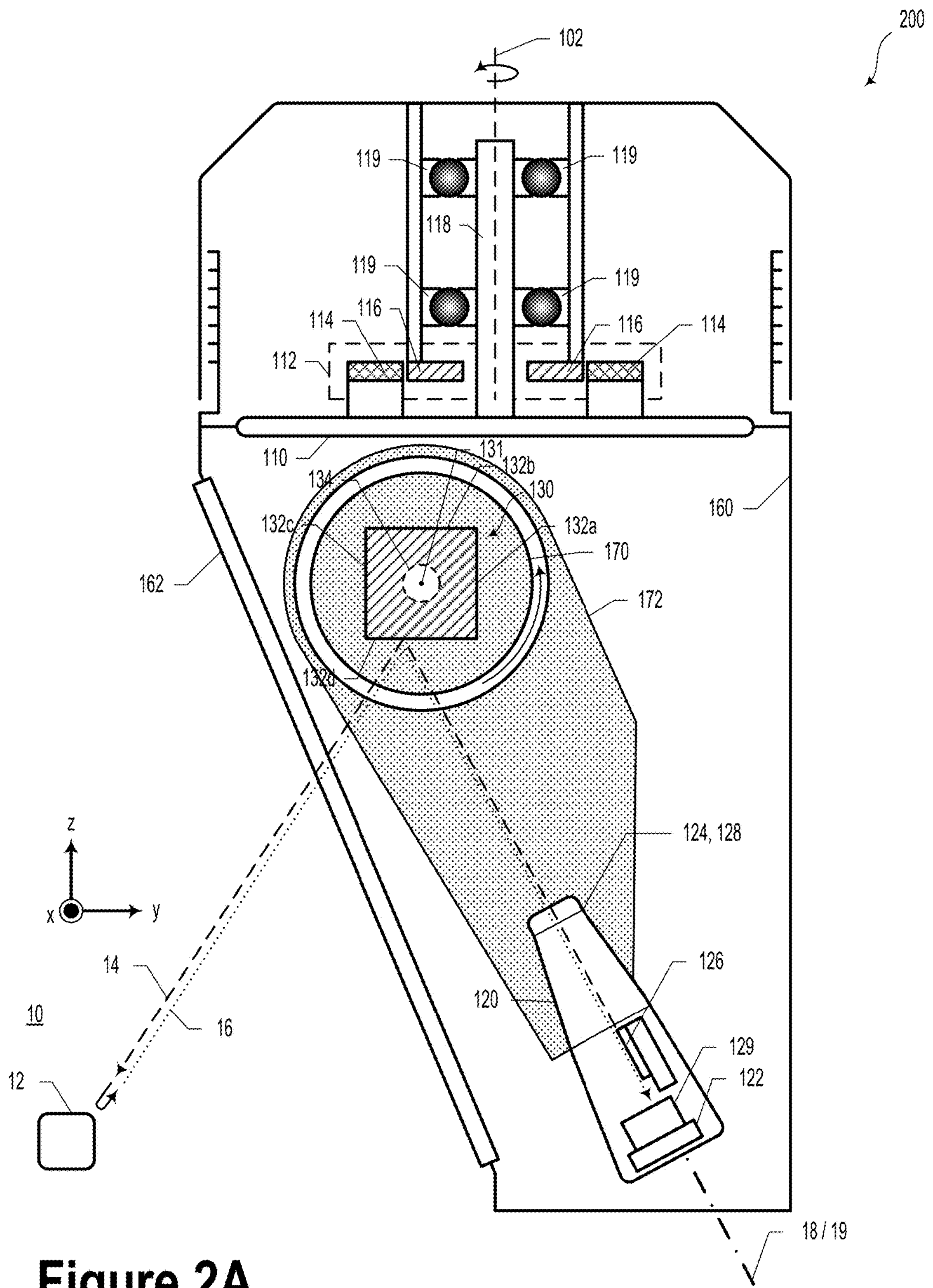
Rotatable Base 110
First Axis 102
Base Actuator 112
Rotor 114
Stator 116
Shaft 118
Bearing 119
Optical Cavity 120
Receiver 121
Photodetector(s) 122
Photodetector Lens 124
Primary Light Detector 123
Secondary Light Detector 125
Optical Redirector(s) 129
Transmitter 127
Light-Emitter Device(s) 126
Light-Emitter Lens 128
Controller 150
Processor(s) 152
Memory 154
Aperture Plate 176
Aperture(s) 178
Rotatable Housing 160
Mirror Assembly 130
Mirror Rotation Axis 131
Reflective Surfaces 132
Mirror Body 133
Shaft 134
Coupling Bracket 135
Mirror Actuator 136
Connector(s) 137
Flexible Members 138
Encoder Magnet 139
Illuminator 161
Primary Reflective Surface 163
Substrate 164
Camera 166
Optical Window 162
Internal Optical Path 168
Rotatable Baffle 170
Static Baffle 172
Baffle Opening 174
Internal Reflector(s) 180
Environment 10
Object(s) 12
Transmit Light 14
Return Light 16
Field of View 17
Light-Emission Axis 18
Light-Receiving Axis 19

Figure 1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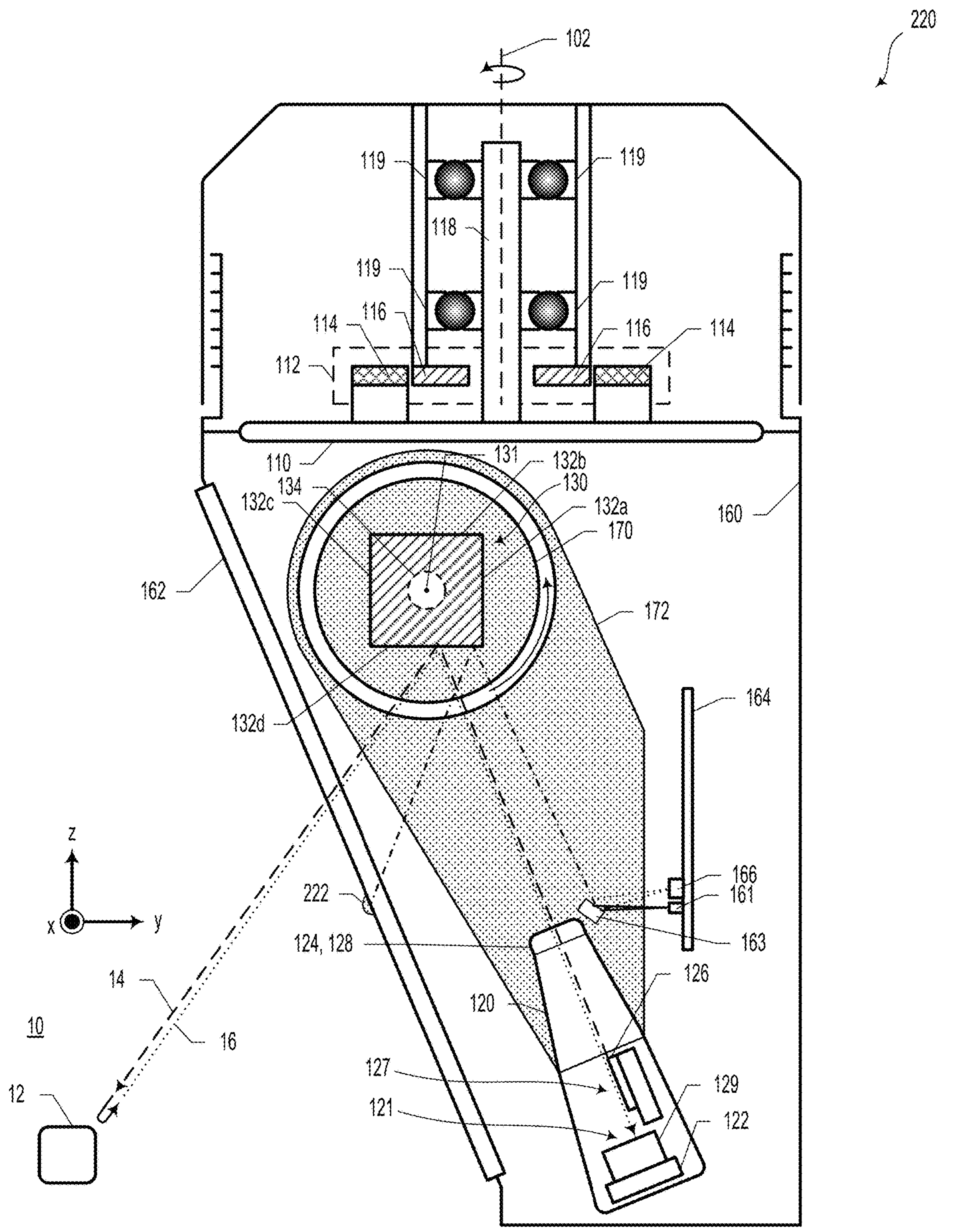
130
160
132c
132a
170
162
172
132d
z
x
y
124, 128
14
126
10
16
120
129
12
122
18 / 19

Figure 2A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172
132d
164
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222
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x
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16
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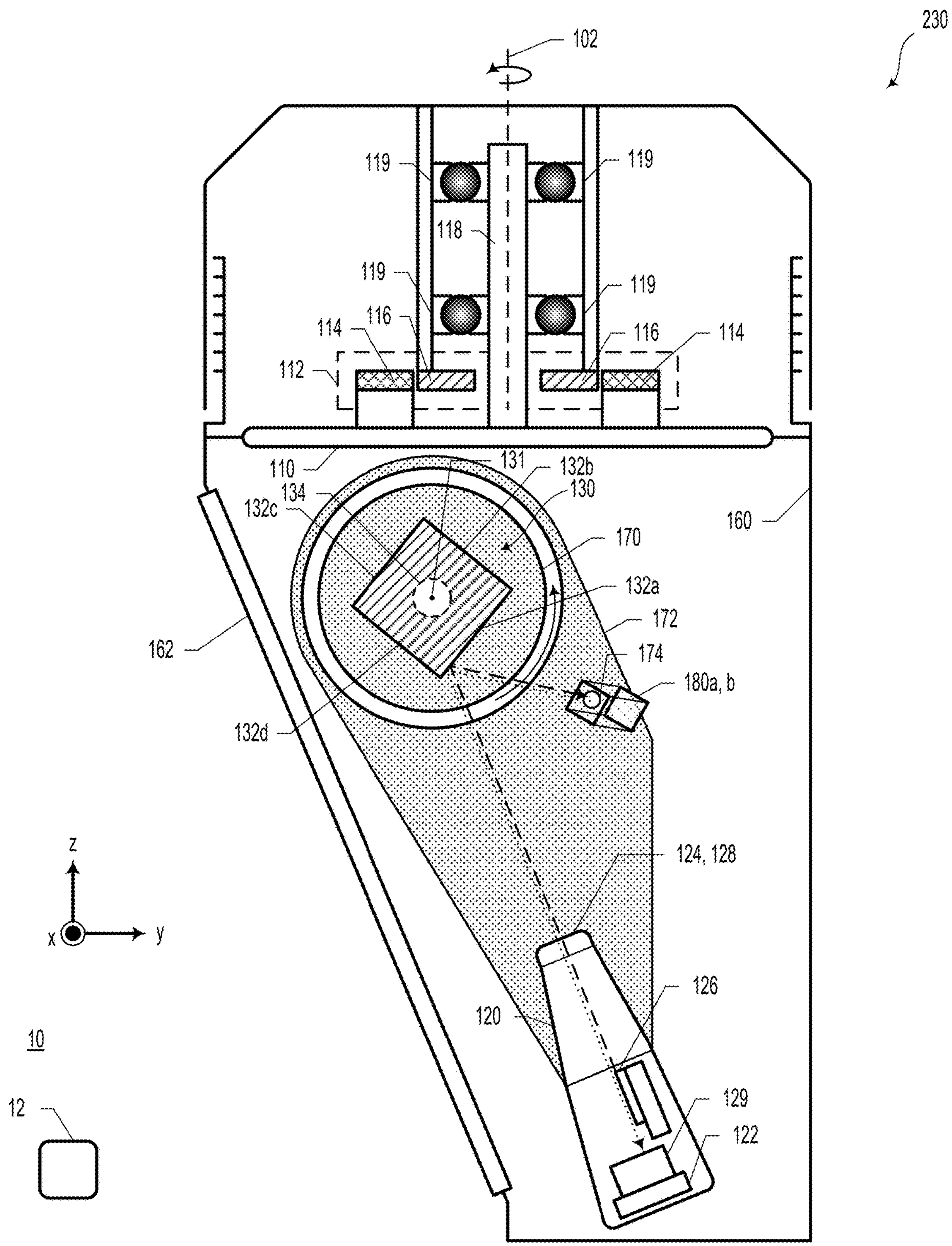
12
127
121
129
122

Figure 2B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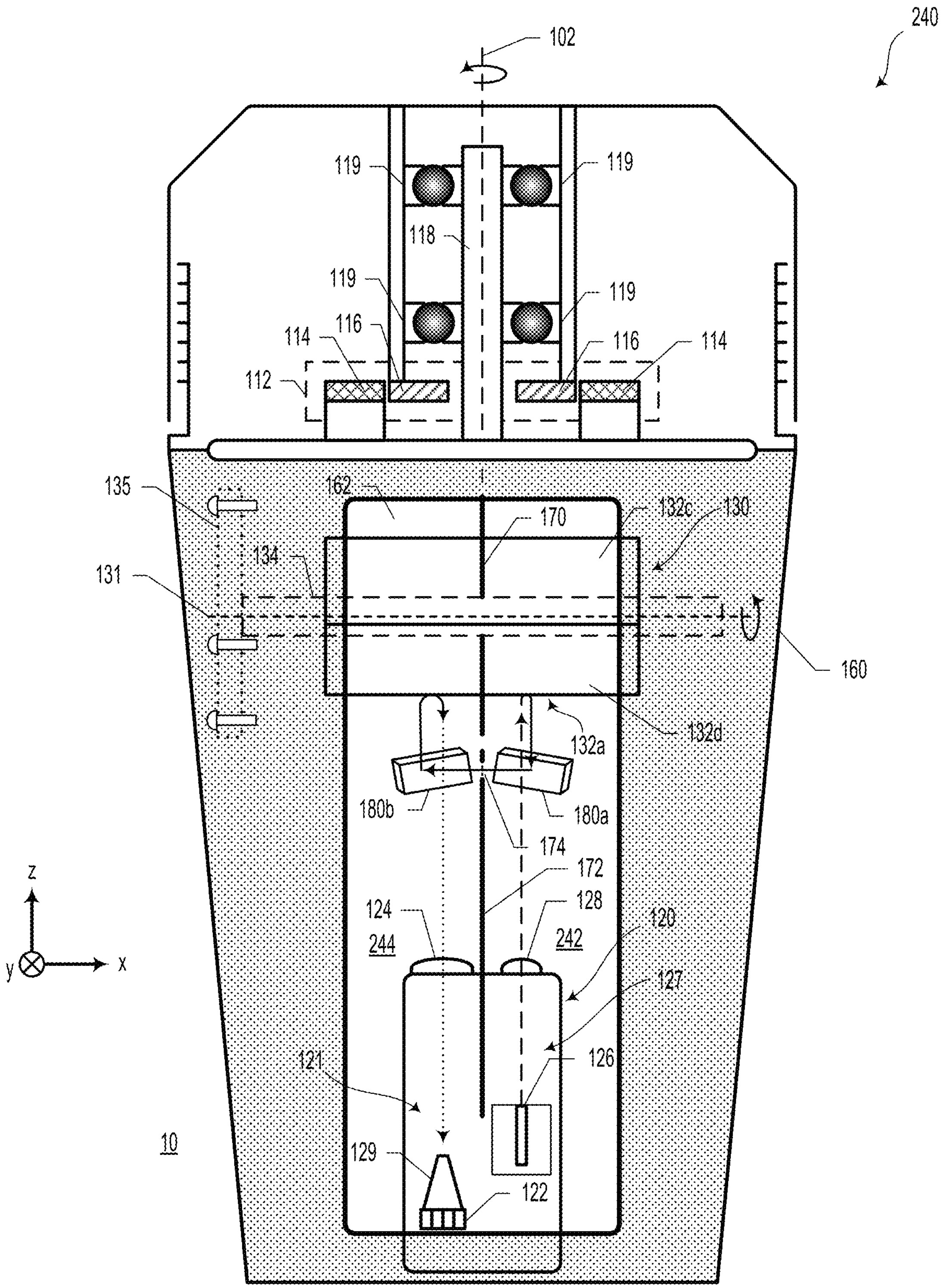
10
129
12
122

Figure 2C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160
132d
132a
180b
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174
172
124
244
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242
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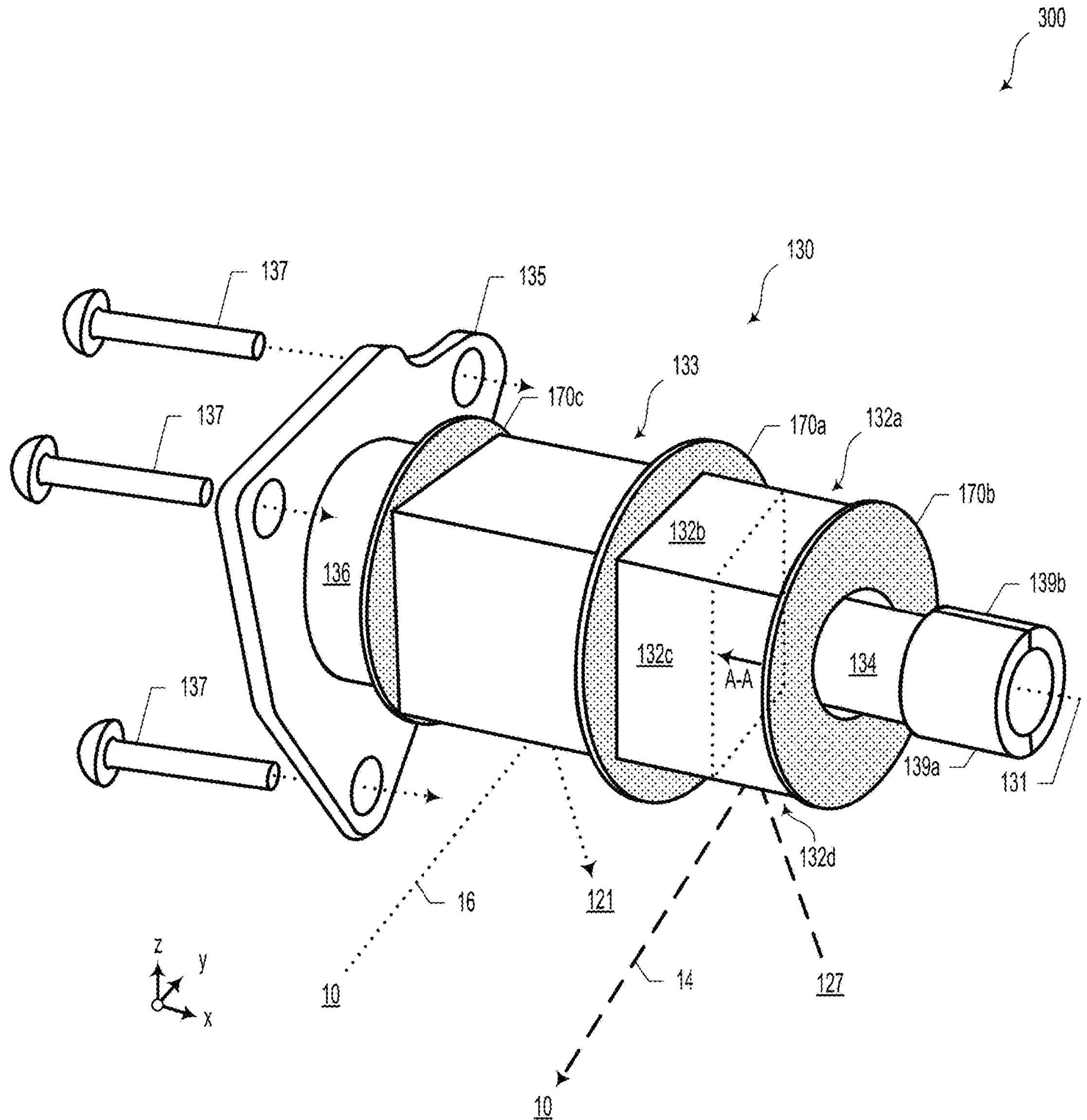
126
121
10
129
122
z
y
x

Figure 2D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137
137
170c
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132a
170b
132b
136
132c
A-A
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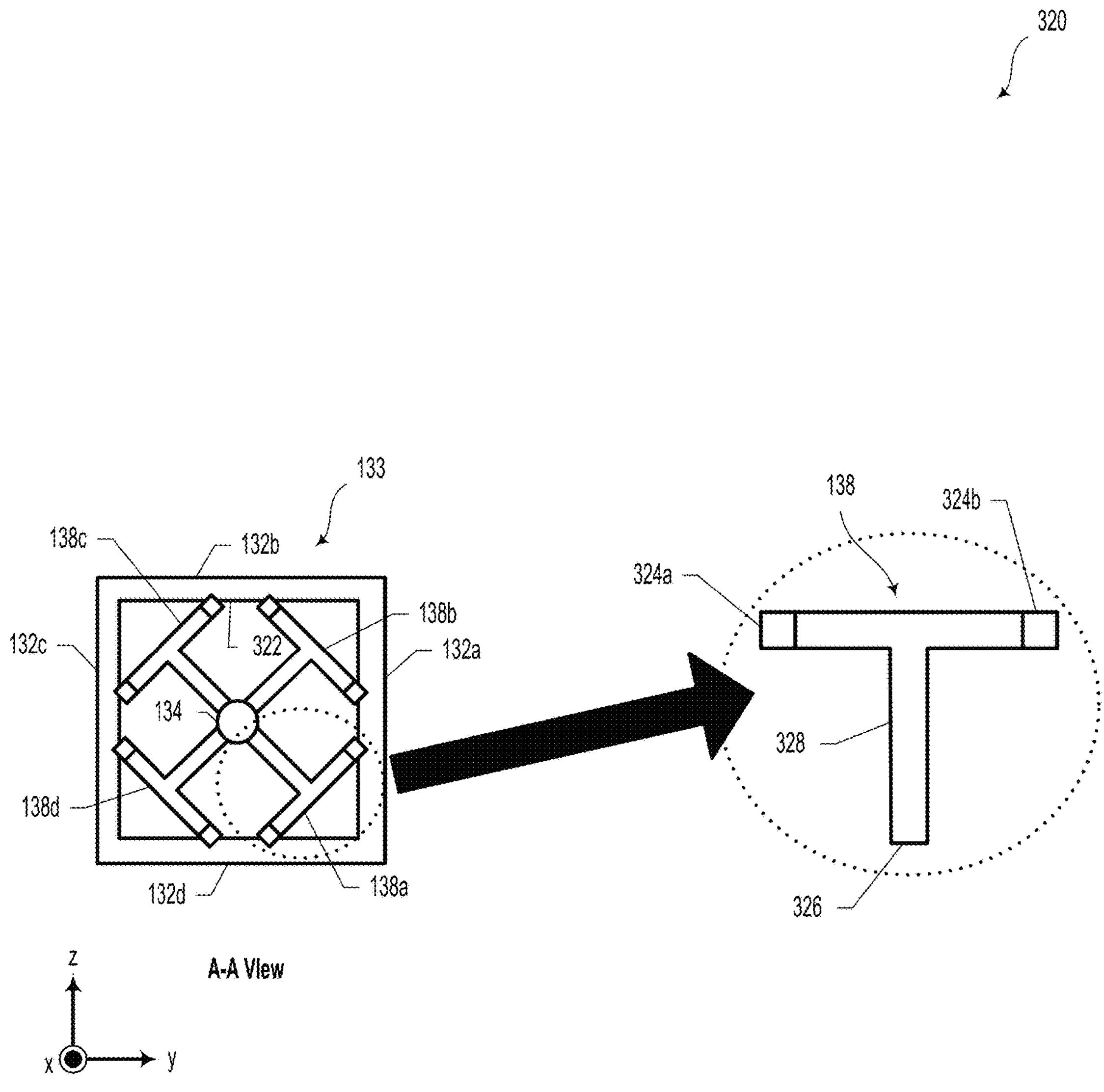
139a
131
132d
16
121
14
127
10
10
z
y
x

Figure 3A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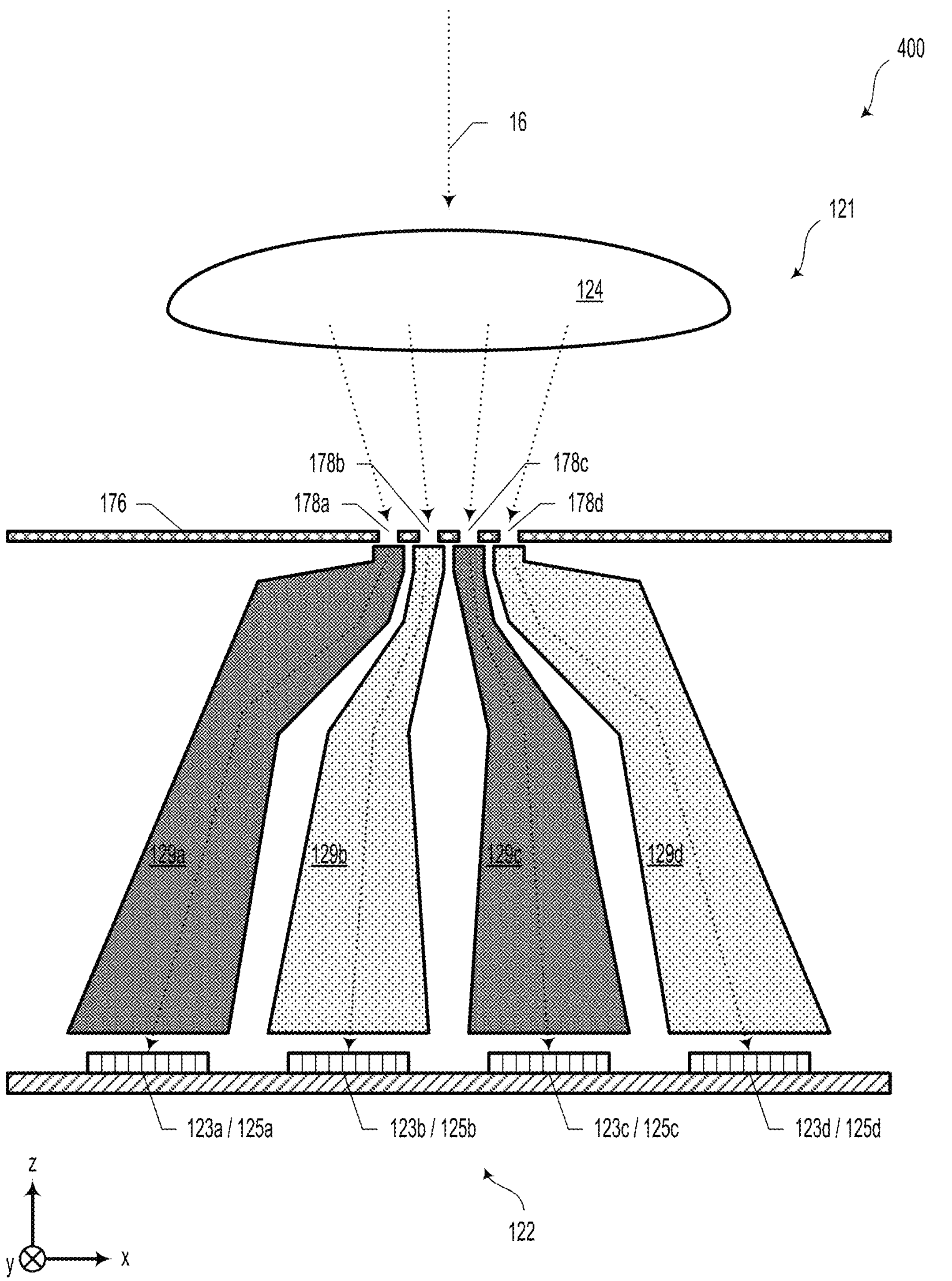
324b
324a
328
326
z
y
x
A-A View

Figure 3B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124
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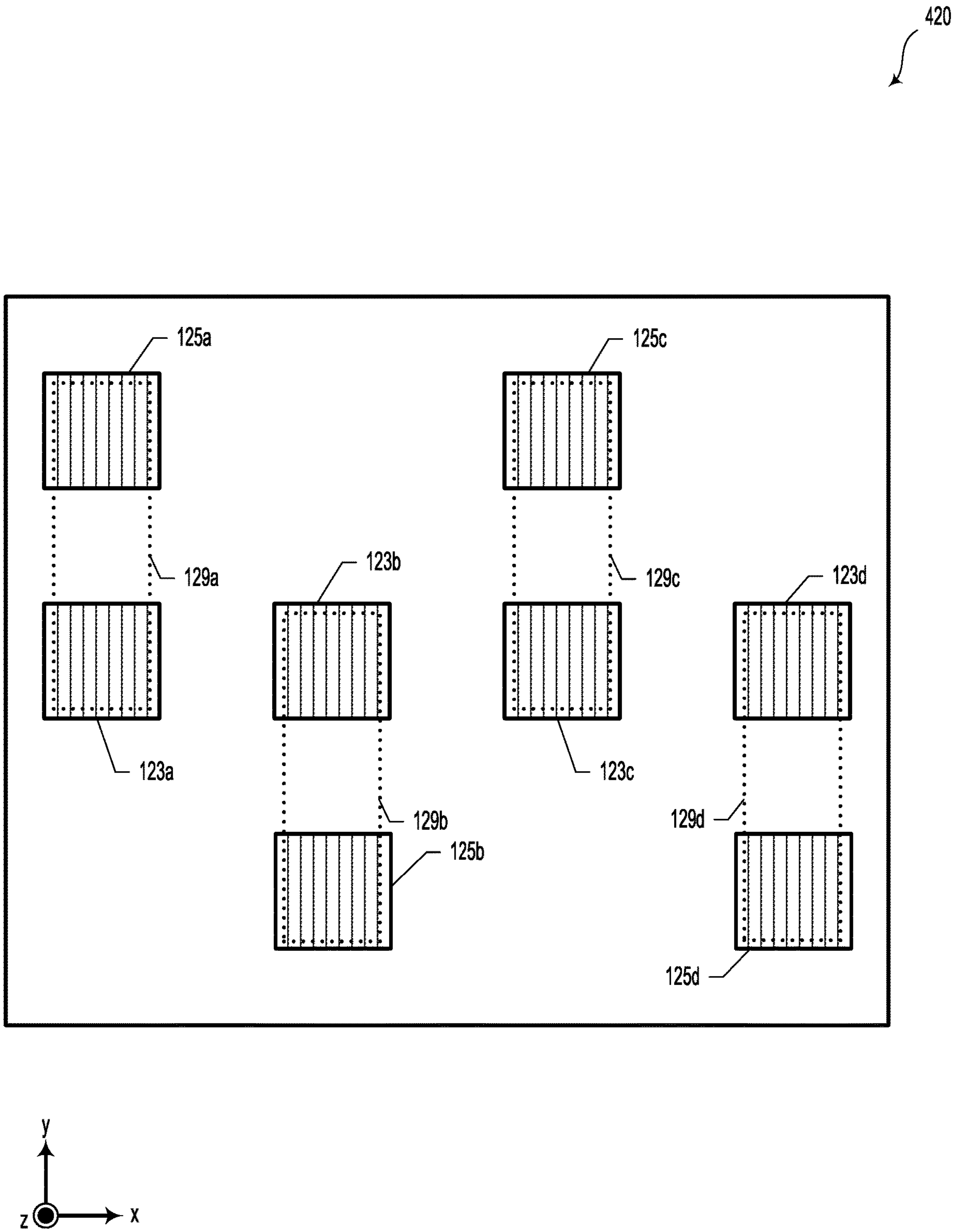
178c
176
178a
178d
129a
129b
129c
129d
123a / 125a
123b / 125b
123c / 125c
123d / 125d
122
z
y
x

Figure 4A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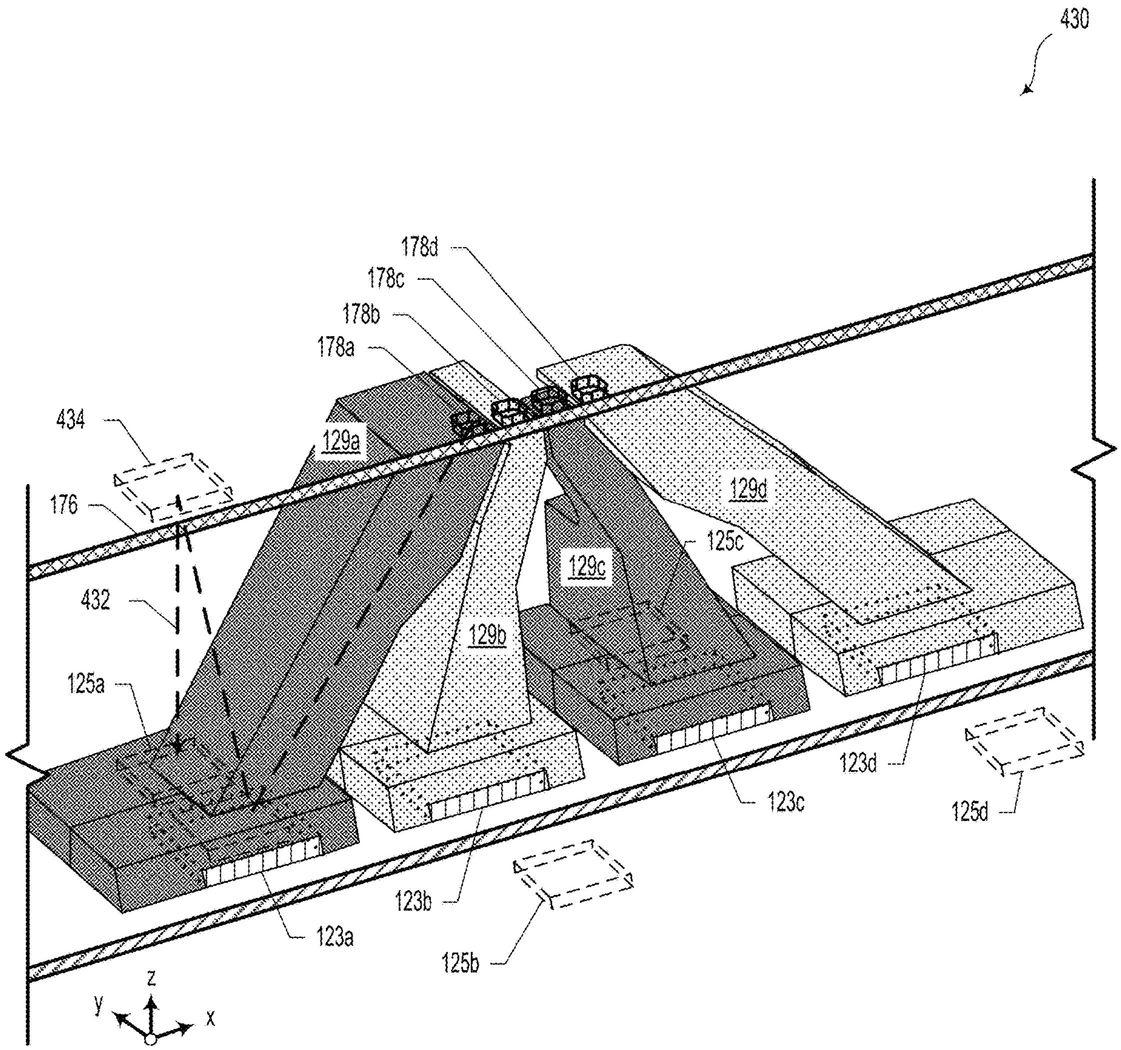
125a
125c
129a
123b
129c
123d
123a
123c
129b
129d
125b
125d
y
z
x

Figure 4B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178d
178c
178b
178a
434
129a
176
129d
125c
129c
432
129b
125a
123d
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123b
123a
125b
z
y
x

Figure 4C

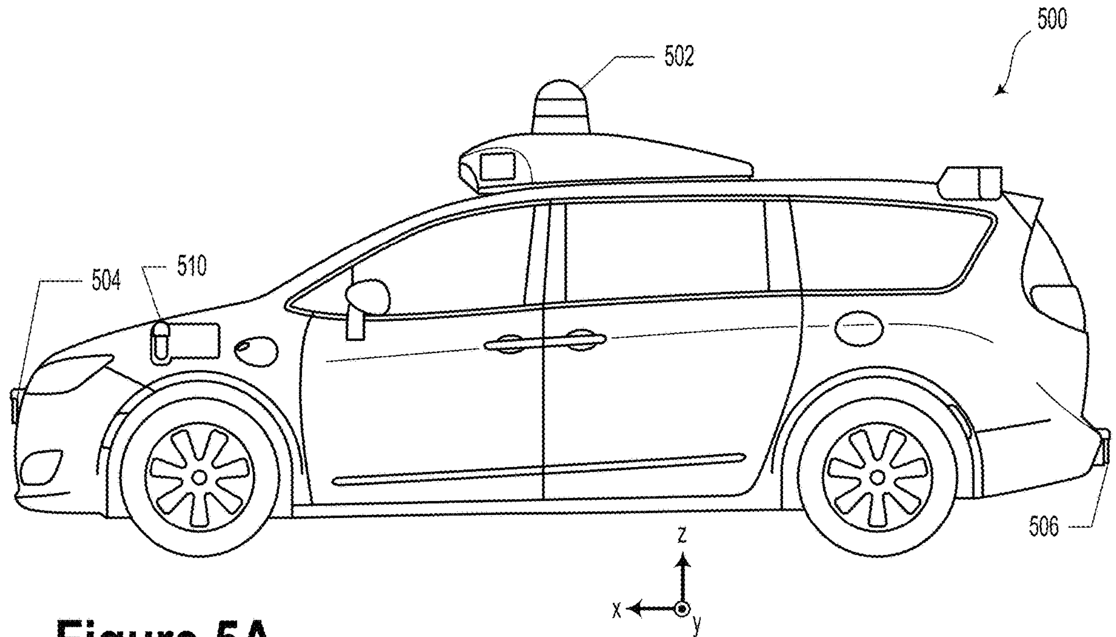

Figure 5A

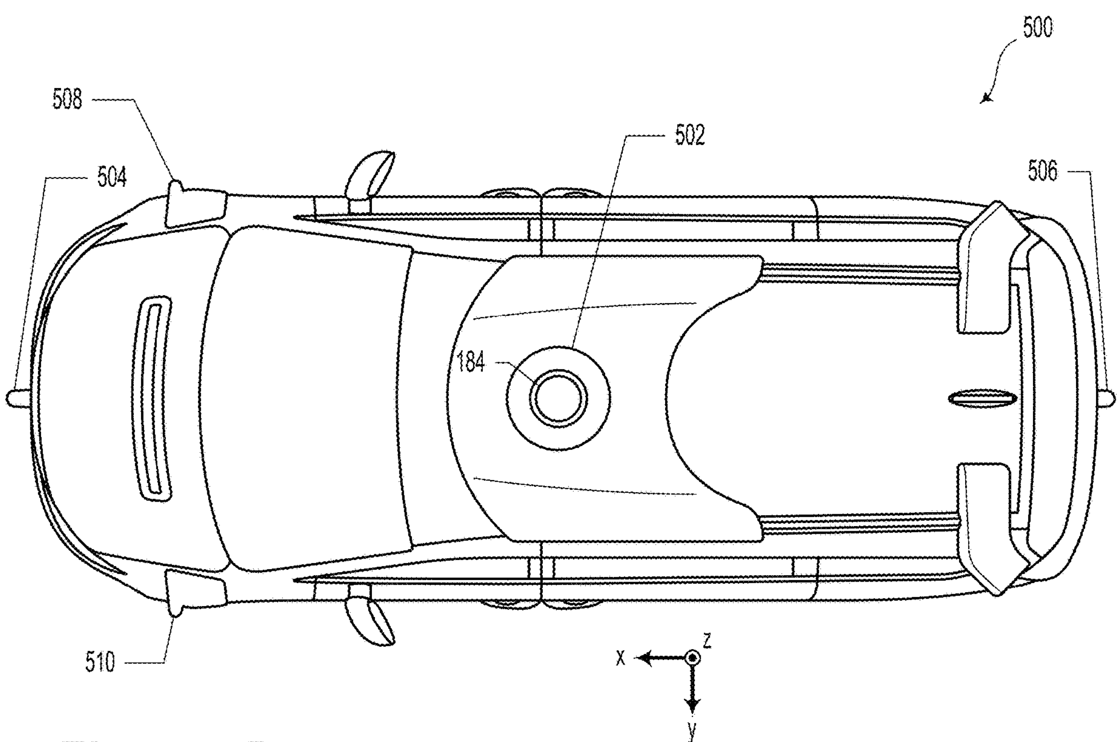

Figure 5B

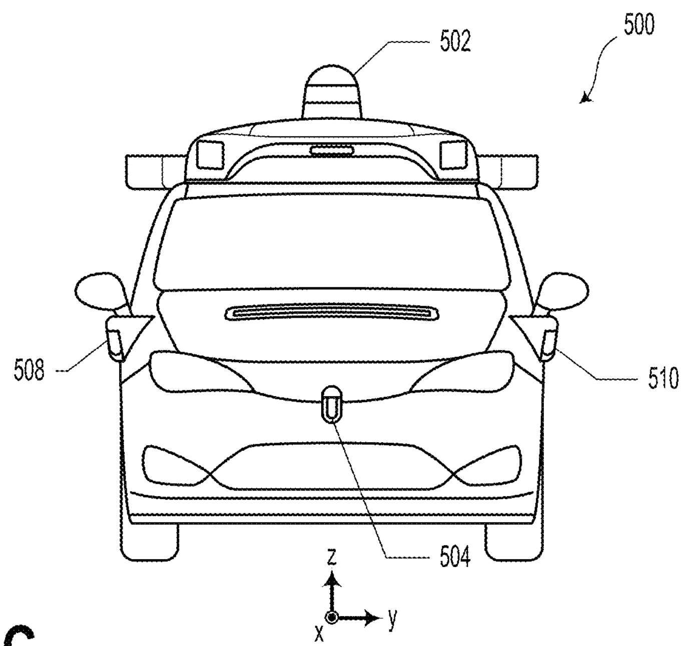

Figure 5C

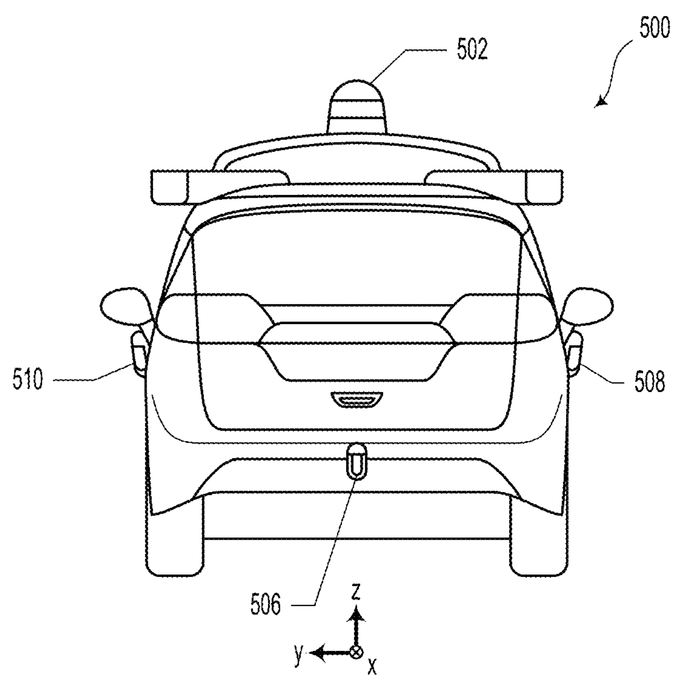

Figure 5D

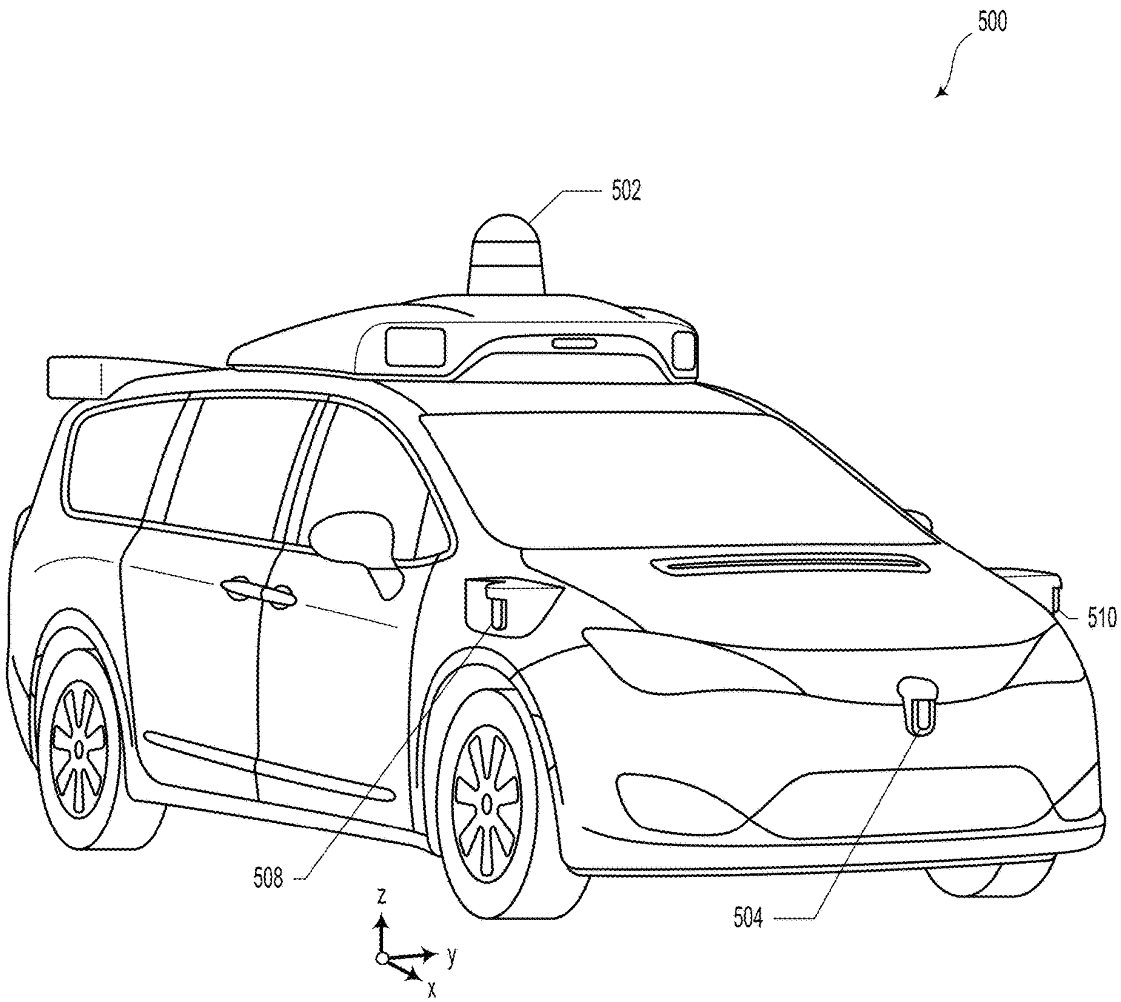

Figure 5E

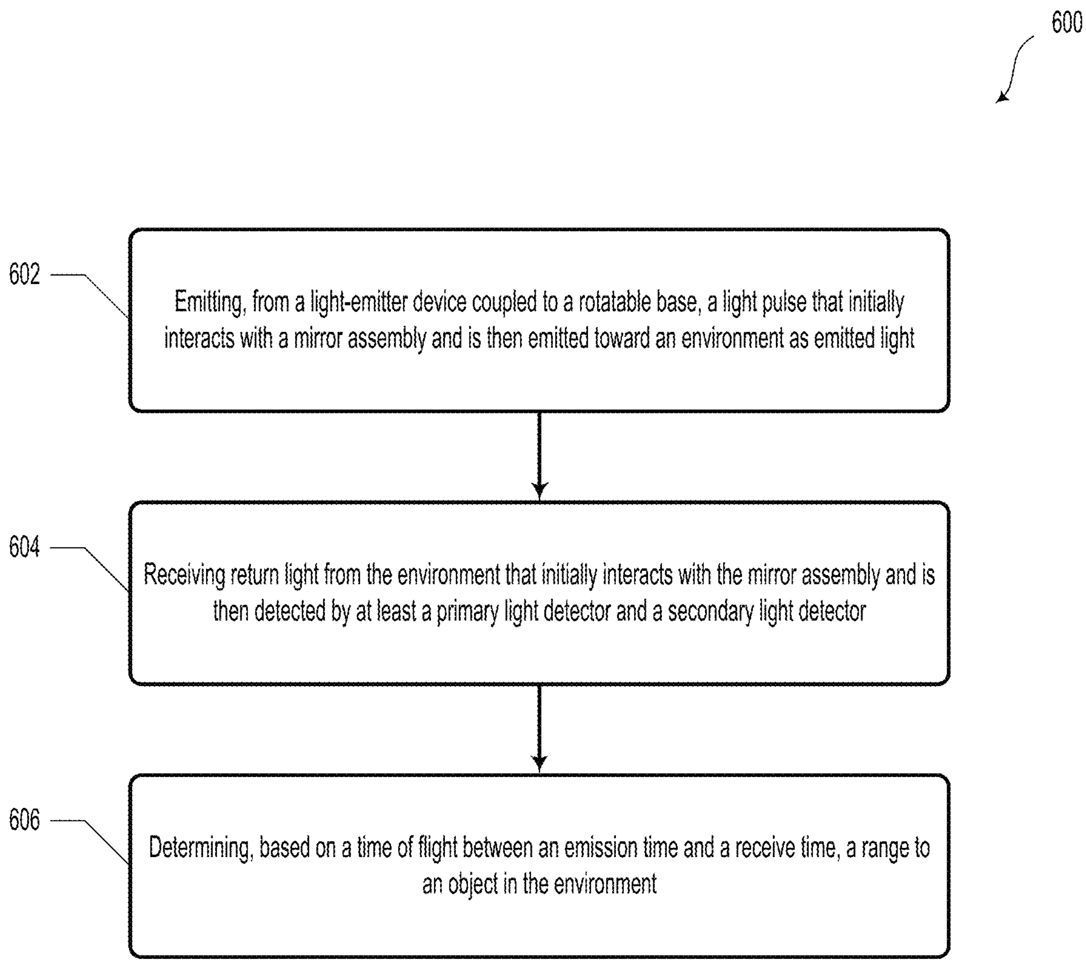
600
602
Emitting, from a light-emitter device coupled to a rotatable base, a light pulse that initially interacts with a mirror assembly and is then emitted toward an environment as emitted light
604
Receiving return light from the environment that initially interacts with the mirror assembly and is then detected by at least a primary light detector and a secondary light detector
606
Determining, based on a time of flight between an emission time and a receive time, a range to an object in the environment

Figure 6

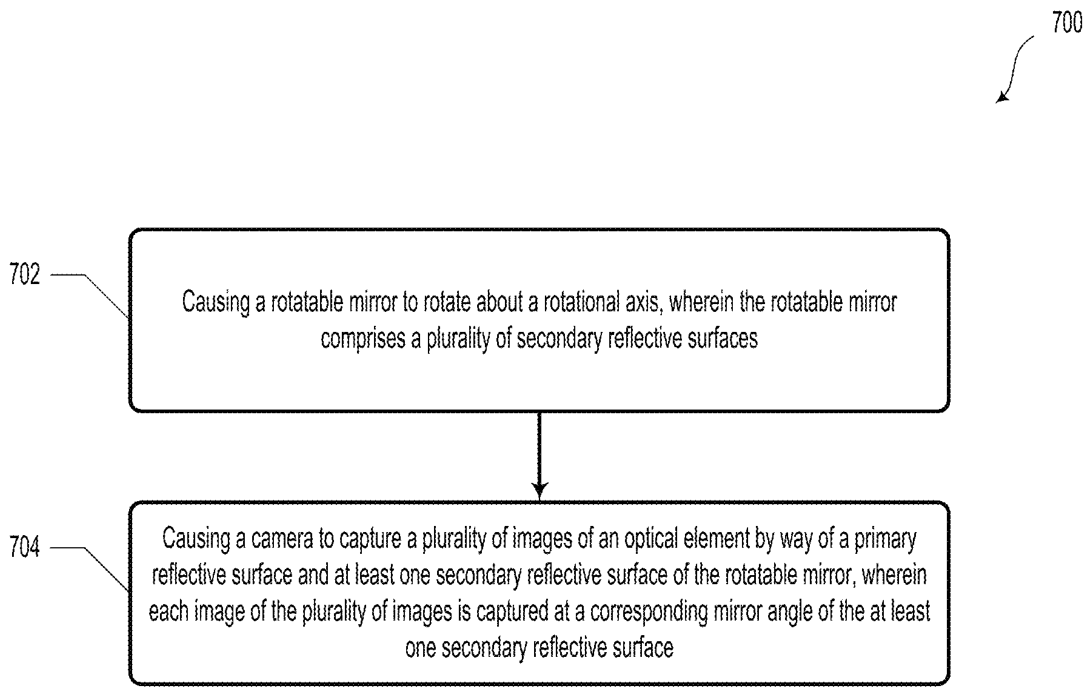
700
702
Causing a rotatable mirror to rotate about a rotational axis, wherein the rotatable mirror comprises a plurality of secondary reflective surfaces
704
Causing a camera to capture a plurality of images of an optical element by way of a primary reflective surface and at least one secondary reflective surface of the rotatable mirror, wherein each image of the plurality of images is captured at a corresponding mirror angle of the at least one secondary reflective surface

Figure 7

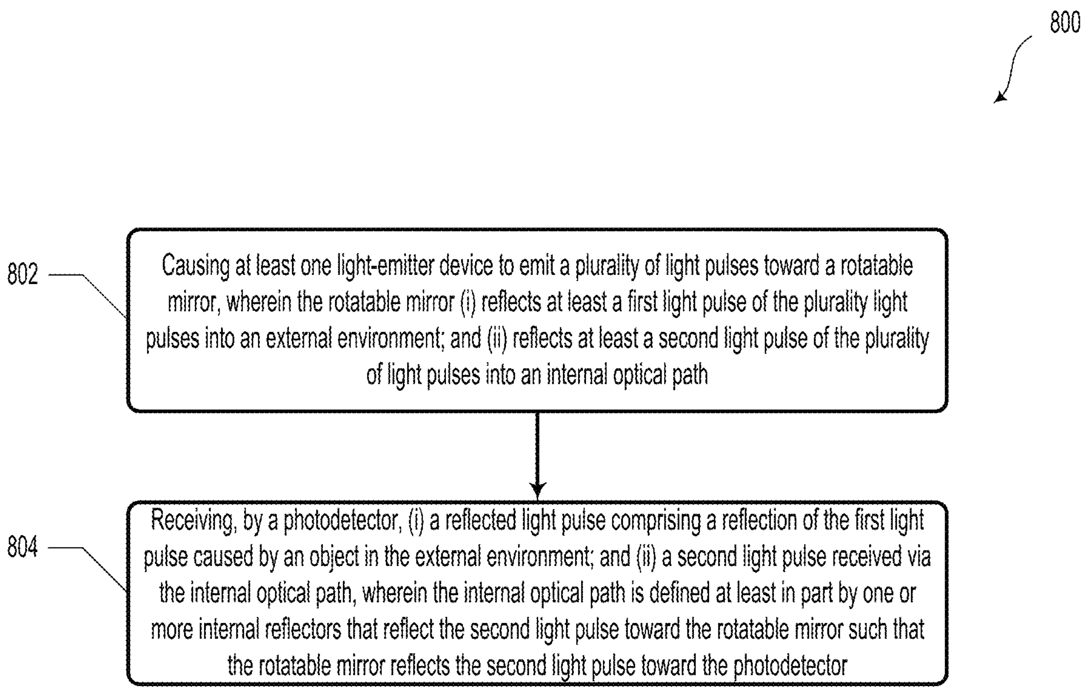
800
802
Causing at least one light-emitter device to emit a plurality of light pulses toward a rotatable mirror, wherein the rotatable mirror (i) reflects at least a first light pulse of the plurality light pulses into an external environment; and (ii) reflects at least a second light pulse of the plurality of light pulses into an internal optical path
804
Receiving, by a photodetector, (i) a reflected light pulse comprising a reflection of the first light pulse caused by an object in the external environment; and (ii) a second light pulse received via the internal optical path, wherein the internal optical path is defined at least in part by one or more internal reflectors that reflect the second light pulse toward the rotatable mirror such that the rotatable mirror reflects the second light pulse toward the photodetector

Figure 8

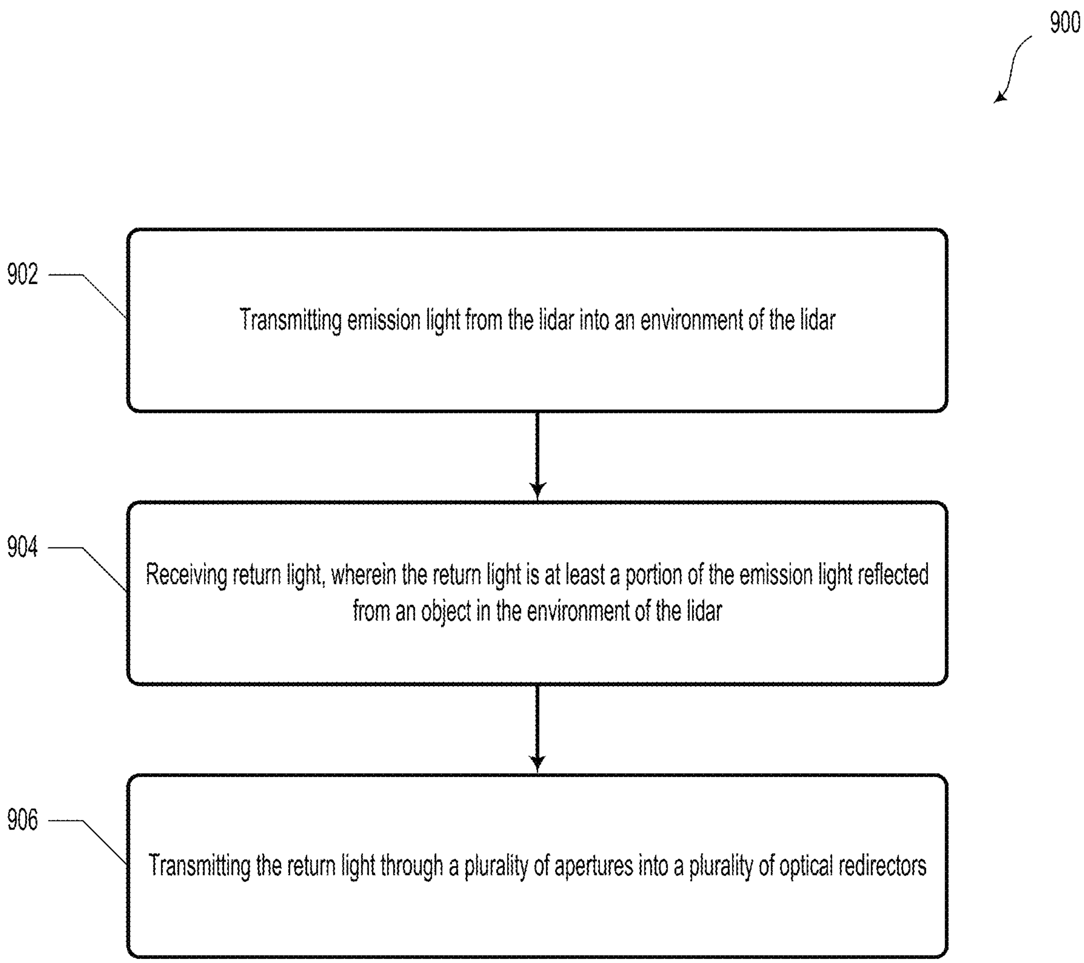
900
902
Transmitting emission light from the lidar into an environment of the lidar
904
Receiving return light, wherein the return light is at least a portion of the emission light reflected from an object in the environment of the lidar
906
Transmitting the return light through a plurality of apertures into a plurality of optical redirectors

Figure 9

OPTICAL REDIRECTOR DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Patent Application No. 62/954,088, filed Dec. 27, 2019, the content of which is herewith incorporated by reference.

BACKGROUND

A conventional Light Detection and Ranging (lidar) system may utilize a light-emitting transmitter (e.g., a laser diode) to emit light pulses into an environment. Emitted light pulses that interact with (e.g., reflect from) objects in the environment can be received by a receiver (e.g., a photodetector) of the lidar system. Range information about the objects in the environment can be determined based on a time difference between an initial time when a light pulse is emitted and a subsequent time when the reflected light pulse is received.

SUMMARY

The present disclosure generally relates to light detection and ranging (lidar) systems, which may be configured to obtain information about an environment. Such lidar devices may be implemented in vehicles, such as autonomous and semi-autonomous automobiles, trucks, motorcycles, and other types of vehicles that can navigate and move within their respective environments.

In a first aspect, a light detection and ranging (lidar) system is provided. The lidar system includes a transmitter and a receiver. The transmitter includes at least one light-emitter device configured to transmit emission light into an environment of the lidar system. The receiver is configured to detect return light from the environment. The receiver includes a plurality of apertures, a plurality of photodetectors, and a plurality of optical redirector elements. Each optical redirector element is configured to receive return light from a respective aperture, separate the return light into unequal portions, and illuminate at least two photodetectors of the plurality of photodetectors.

Optionally, the plurality of optical redirector elements substantially extends between the plurality of apertures and the plurality of photodetectors.

In a second aspect, an optical redirector device is provided. The optical redirector device includes a plurality of apertures, a plurality of photodetectors, and a plurality of optical redirectors. Each optical redirector is configured to receive return light from a respective aperture, separate the return light into unequal portions, and illuminate at least two photodetectors of the plurality of photodetectors.

Optionally, the plurality of optical redirectors substantially extends between the plurality of apertures and the plurality of photodetectors.

In a third aspect, a vehicle is provided. The vehicle includes a light detection and ranging (lidar) system. The lidar system includes a transmitter. The transmitter includes at least one light-emitter device configured to transmit emission light into an environment of the vehicle. The lidar system also includes a receiver configured to detect return light from the environment. The receiver includes a plurality of apertures, a plurality of photodetectors, and a plurality of optical redirectors. Each optical redirector is configured to receive return light from a respective aperture, separate the return light into unequal portions, and illuminate to at least two photodetectors of the plurality of photodetectors.

Optionally, the plurality of optical redirectors substantially extends between the plurality of apertures and the plurality of photodetectors.

In a fourth aspect, a method for enhancing a dynamic range of a light detection and ranging (lidar) system is provided. The method includes transmitting emission light from the lidar into an environment of the lidar. The method also includes receiving return light. The return light is at least a portion of the emission light reflected from an object in the environment of the lidar. The method also includes transmitting the return light through a plurality of apertures into a plurality of optical redirectors.

Other aspects, embodiments, and implementations will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates a system, according to an example embodiment.

FIG. **2**A illustrates a system, according to an example embodiment.

FIG. **2**B illustrates a system, according to an example embodiment.

FIG. **2**C illustrates a system, according to an example embodiment.

FIG. **2**D illustrates an alternate view of the system of FIG. **2**C, according to an example embodiment.

FIG. **3**A illustrates a mirror assembly, according to an example embodiment.

FIG. **3**B illustrates a portion of the mirror assembly of FIG. **3**A, according to an example embodiment.

FIG. **4**A illustrates a receiver, according to an example embodiment.

FIG. **4**B illustrates an alternate view of the receiver of FIG. **4**A, according to an example embodiment.

FIG. **4**C illustrates an alternate view of the receiver of FIG. **4**A, according to an example embodiment.

FIG. **5**A illustrates a vehicle, according to an example embodiment.

FIG. **5**B illustrates a vehicle, according to an example embodiment.

FIG. **5**C illustrates a vehicle, according to an example embodiment.

FIG. **5**D illustrates a vehicle, according to an example embodiment.

FIG. **5**E illustrates a vehicle, according to an example embodiment.

FIG. **6** illustrates a method, according to an example embodiment.

FIG. **7** illustrates a method, according to an example embodiment.

FIG. **8** illustrates a method, according to an example embodiment.

FIG. **9** illustrates a method, according to an example embodiment.

DETAILED DESCRIPTION

Example methods, devices, and systems are described herein. It should be understood that the words “example” and “exemplary” are used herein to mean “serving as an example, instance, or illustration.” Any embodiment or feature described herein as being an “example” or “exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or features. Other embodiments can be utilized, and other changes can be made, without departing from the scope of the subject matter presented herein.

Thus, the example embodiments described herein are not meant to be limiting. Aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are contemplated herein.

Further, unless context suggests otherwise, the features illustrated in each of the figures may be used in combination with one another. Thus, the figures should be generally viewed as component aspects of one or more overall embodiments, with the understanding that not all illustrated features are necessary for each embodiment.

I. Overview

A lidar system includes a transmitter and a receiver. The transmitter may include one or more light-emitter devices (e.g., one or more laser bars with one to eight laser diodes each) configured to transmit light into an environment of the lidar system via one or more optical elements in a transmit path (e.g., a transmit lens, a rotatable mirror, and an optical window).

The rotatable mirror could be configured to rotate about a mirror rotation axis. The rotatable mirror could be configured to interact with light pulses emitted by the one or more light-emitter devices so as to direct the light pulses toward various locations within an environment. Furthermore, the rotatable mirror may be configured to direct light pulses toward the receiver after such light pulses have interacted with the environment to form return light pulses.

In an example embodiment, the mirror rotation axis could be perpendicular to the emission axis of one or more of the light-emitter devices. In some embodiments, the emission axis of the one or more light-emitter devices could be positioned so as to not intersect the mirror rotation axis. At least a portion of the lidar system could be configured to rotate about a first axis at an azimuthal rotational rate (e.g., 3 Hz-60 Hz).

In some examples, the first axis could be perpendicular to the mirror rotation axis. In such scenarios, at least the optical window and the rotatable mirror could be rotated about the first axis so as to scan an emitted light beam through an azimuthal angle range associated with the lidar system. As the rotatable mirror rotates about the mirror rotation axis, the emitted light beam may be scanned through varying elevation angles with respect to the lidar system.

In other words, while rotating about the rotational axis, the rotatable mirror may be configured to direct the light from the laser light source(s) into an environment of the lidar system over a wide field of view in both azimuthal angle range and elevation angle range. By directing the light over this large angular field of view, the lidar system may provide ranging information about objects within a large three-dimensional volume.

In some embodiments, the lidar system could be configured to provide information about a field of view that may extend more than 180 degrees (e.g., 210 degrees or 360 degrees) in azimuth and more than 90 degrees (e.g., 95 degrees, 110 degrees, 120 degrees, 150 degrees, or more) in elevation angle range around the system. Other sizes and shapes of various fields of view are possible and contemplated. In some examples, based on utilizing multiple light-emitter devices, the lidar system could provide an azimuthal angle resolution or elevation angle resolution of less than one degree (e.g., 0.2 degrees-0.6 degrees between beams in azimuth or in elevation, or less).

In some embodiments, the rotatable mirror may include a three or four-sided mirror surface that is coupled to a shaft. Rotatable mirrors with more or fewer sides are possible and contemplated. The shaft could be made of steel and may be configured to rotate such that the four-sided mirror surface can rotate about the shaft's axis. In some embodiments, the mirror could include an injection-molded plastic (e.g., polycarbonate) body. In such scenarios, the four-sided mirror surface could include one or more deposited materials, such as gold, silicon oxide, titanium oxide, titanium, platinum, or aluminum.

Deformations in a surface of the mirror are undesirable because light pulses could be diverted to irregular and/or unknown positions within the environment. Furthermore, mismatches in the coefficient of thermal expansion (CTE) between the mirror body (e.g., plastic) and the shaft (e.g., steel) could introduce undesirable temperature-dependent deformations that could change dynamically.

In some embodiments, the body of the mirror could be substantially hollow so as to reduce deformation issues related to the CTE mismatch between the shaft and the mirror. For example, the four-sided mirror surface could be coupled to the shaft via a plurality of flexible members (e.g., four members extending toward a shaft from each apex of the four-sided mirror surface. The flexible members could be straight or curved. In some embodiments, the flexible members could be substantially stiff when in torsion, but elastic along the radial axis. In some embodiments, at least a portion of the shaft could have an octagonal cross-section or another type of symmetric cross-section (e.g., square or hexagonal cross-section, etc.). In various examples, the cross-section of the shaft could be shaped or otherwise configured to prevent slipping of the multi-sided rotatable mirror with respect to the shaft.

In some embodiments, the rotatable mirror may be configured to be easily replaceable and/or serviceable. For example, the rotatable mirror may be mechanically coupled to the shaft and drive magnet. In other embodiments, the rotatable mirror may include an optical mirror baffle, which may include a flat, disk-shaped opaque material that is configured to optically-separate the transmit path and the receive path within the optical cavity of the LIDAR system. In some examples, the rotatable mirror may be coupled to a mirror bracket that may be configured to be easily removed from other elements of the LIDAR system. In such a manner, the rotatable mirror (and related components) could be easily serviced and/or replaced. In some embodiments, the rotatable mirror may require servicing due to wear and tear of various components, such as rotational bearings, shaft wear, among other possibilities.

In some embodiments, an encoder magnet may be coupled to the shaft of the rotatable mirror. In such scenarios, the encoder magnet may be configured to provide information indicative of a rotational position of the rotatable mirror. For example, the encoder magnet could be utilized to determine a "zero-angle" of the plurality of reflective surfaces of the rotatable mirror. Among other possibilities, the encoder magnet could help improve positioning accuracy and repeatability of objects sensed within the environment. In various examples, the same magnet may serve as the encoder magnet and the mirror drive motor. That is, the same magnet may be configured to sense the mirror position as well as to rotatably actuate the shaft and mirror.

In one specific implementation, the width of the optical window may be between 20 millimeters and 25 millimeters. Other sizes are possible. In some examples, the optical window may be tilted at an offset angle (e.g., 10 degrees) relative to the first axis of rotation. In some embodiments, the lidar system may be configured to control a temperature of the optical window (e.g., to de-ice and/or reduce the likelihood of water condensation, etc.). In one embodiment, the lidar system may include one or more heating elements (e.g., perimeter resistor, transparent resistive film, etc.) positioned on, near, or adjacent to the optical window. In another embodiment, the lidar system may include an air duct configured to direct air toward the rotatable mirror, and the rotatable mirror may be arranged to redirect the air toward the optical window. As an example, the redirected air could defrost or otherwise control or adjust the temperature of the optical window.

In some embodiments, the receiver could include a plurality of optical redirector elements and a corresponding plurality of light detectors (e.g., four to sixteen detectors). The light detectors are configured to detect return light via one or more optical elements in a receive path (e.g., the optical window, the rotating mirror, a receive lens, and a pinhole aperture). The return light is light that has been transmitted from the transmitter and reflected back toward the receiver by an object in the environment. The optical redirector elements could be configured to direct return light entering the receiver by way of the pinhole aperture and the receive lens to respective light detectors. In some embodiments, the optical redirector elements could optically couple portions of the return light toward each light detector using total internal reflection. In some embodiments, the optical redirector elements could be configured to separate the respective portions of return light so as to efficiently utilize as much of the return light flux as possible.

In an example embodiment, the number of light detectors could be greater than the number of light-emitter devices. As an example, the light redirector devices could be configured to spatially separate the respective portions of the return light so as to be detected by the plurality of light detectors. In some embodiments, the optical redirector elements could separate the return light into unequal portions so as to illuminate a first light detector with a first photon flux of a first portion of return light and illuminate a second light detector with a second photon flux of a second portion of return light. In such a scenario, the first photon flux could be at least an order of magnitude different from the second photon flux. Thus, the receiver may be configured to detect a greater dynamic range within a given scene than if the respective photon fluxes provided to each photodetector were similar.

In some embodiments, the optical redirector elements could include four total internal reflection optical elements configured to spatially separate light from four pinholes spaced apart by between 400-600 microns and direct the light toward the photodetectors, which may be spaced more widely than the respective pinholes (e.g., separated by 1000 microns or more). The optical redirector elements may also provide an expanded beam to more fully fill the active area of the respective detectors. In various embodiments, the optical redirector elements could be physically grouped in pairs. In such scenarios, a first pair of optical redirector elements could be configured or otherwise shaped to interlock and/or interleave with a second pair of optical redirector elements. For example, the first and second pair of optical redirector elements could be configured to slidably couple to one another, such as via a dovetail joint. As such, the respective in-coupling ends of the optical redirector elements could be more closely spaced than might be possible with conventional injection molding processes.

In some embodiments, the pinhole aperture may be a thin plate formed from stainless steel. However, other materials are possible and contemplated. The pinhole aperture plate may be around 100 microns thick. Each pinhole could be 200-300 microns in diameter and the pinhole aperture plate may include one pinhole for each light-emitter device (e.g., four light-emitter devices, four pinholes).

In some embodiments, the plurality of light detectors could be grouped into two sets. For example, the plurality of light detectors could include four primary light detectors and four secondary light detectors. In such scenarios, a first portion of the return light could be detected by the four primary light detectors. Some of the light incident on the four primary light detectors could be reflected from a top surface of the four primary light detectors. The reflected light could be redirected and/or reflected toward the four secondary light detectors. Such scenarios could be beneficial because the optical beam does not need to be split off and other optical elements (e.g., beamsplitters, mirrors) are not necessary. In other words, the return light could be focused or directed toward the primary light detectors and a portion of the light could be reflected or deflected so as to interact with the secondary light detectors. Other ways to provide reduced coupling to the secondary light detectors are also contemplated and possible. As such, the primary light detectors could be illuminated by a majority (e.g., greater than 90%) of the return light. The secondary light detectors could be illuminated by less than 10% of the return light. In such scenarios, the combination of primary and secondary light detectors could provide a larger dynamic range (e.g., four to six orders of magnitude or more) than a standard detector array.

In some embodiments, the transmit path and the receive path could intersect with the same rotatable mirror. For example, the rotatable mirror could be shaped as a rectangular prism or triangular prism with a plurality of reflective surfaces. In such scenarios, the light emitted from the plurality of light-emitter devices could interact with a portion of the rotatable mirror so as to be redirected toward an external environment of the lidar system via the optical window. Upon interaction with objects in the external environment, at least a portion of the light could be reflected as return light. The return light could interact with the optical window and a second portion of the rotatable mirror and redirected toward the plurality of light detectors. In some embodiments, the first portion of the rotatable mirror and the second portion of the rotatable mirror could be separated by an optical mirror baffle. In such scenarios, the mirror baffle could be coupled to the rotatable mirror and could be shaped like a flat disk. The mirror baffle could be centered about the rotational axis of the rotatable mirror, such that the flat disk is oriented along a plane perpendicular to the rotational axis.

Example systems and methods could optionally utilize optical feedback. As an example, an optical feedback system could include an internal optical path through the optical baffle, and one or more internal reflectors. The transmitter and receiver could be disposed in a common optical cavity. The optical cavity could be substantially separated into a receiver portion and a transmitter portion by the optical baffle. The internal optical path could include a pinhole or other opening in the optical baffle that may optically couple the two portions of the optical cavity. As an example, the opening in the optical baffle could be a circular opening approximately 1 mm in diameter. However, openings of other sizes and/or other shapes are also contemplated and possible.

In some embodiments, the one or more internal reflectors could reflect and/or diffuse light emitted by the transmitter. In such scenarios, the one or more internal reflectors could be disposed so as to reflect and/or diffuse light emitted by the transmitter toward the internal optical path. For example, the emitted light could be reflected from a first internal reflector toward the opening in the optical baffle and into the receiver portion of the optical cavity. Once the light has been redirected into the receiver portion of the optical cavity, it may interact with a second internal reflector. The second internal reflector could be oriented or disposed so as to reflect or diffuse light toward the receiver.

In some embodiments, the receiver includes a plurality of photodetectors. The photodetectors could include, for example, photodetectors, such as silicon photomultipliers (SiPMs) or avalanche photodiodes (APDs). Other types of photodetectors are possible and contemplated. In various examples, the one or more internal reflectors could include a polycarbonate material. Other types of diffusers and/or partially reflecting surfaces and/or materials are possible and contemplated. In some embodiments, the internal reflectors could act as low-efficiency reflectors (e.g., less than 0.1% reflectivity, less than 0.05% reflectivity, or less than 10 reflected photons per billion photons emitted by the receiver). In some embodiments, the internal reflectors could be patterned (e.g., stippled, raised, dimpled, grooved, or otherwise having a non-flat/level surface). In some embodiments, an internal reflector could include a surface with a parabolic section and/or conic section. In such scenarios, the surface of the internal reflector could be curved in one dimension or two dimensions. Optionally, the size of the internal reflector could be configured, adjusted, or selected so as to tune a coupling amount.

In some examples, the optical feedback system could be utilized in lidar applications. For example, the transmitter could also act as a source of ranging light pulses (e.g., emitted from a plurality of light-emitter devices) for the lidar. Furthermore, the receiver could additionally act as a photodetector (or a photodetector array) to determine the time of flight of the light pulses so as to determine the distance to objects in the environment. In some embodiments, the light pulses received via the internal optical path may represent a more reliable "zero-time" reference than those provided by, for example, a calibration target or known features within the environment. Such calibration targets and known features are not always available within the environment. Furthermore, temperature-dependent electronic delays make a one-time calibration process time-consuming and/or inaccurate. Accordingly, a real-time optical feedback system could provide a continuous range reference from which time-dependent offsets can be determined.

Additionally or alternatively, example optical feedback systems could provide a way to more-directly estimate and/or extrapolate the transmit power. That is, in some examples, the amount of light received by the receiver via the internal reflector(s) could be proportional to an overall transmitted optical power. For example, an output signal of one or more of the photodetectors could be compared to a lookup table that provides information about associations between the output signal and the overall transmitted optical power. As such, the optical feedback system could provide a way to directly measure the optical output of a lidar system on a per-shot basis.

In some embodiments, examples systems and methods could include an occlusion detection system. Such an occlusion detection system could provide a way to determine the presence of dust, dirt, and/or cracks in the optical window or another optical element in the systems described herein. The occlusion detection system could include a camera, a flash illuminator, a primary reflective surface, and an optical element (e.g., the optical window). The camera could include a CMOS camera or another type of video capture device. The flash illuminator could include an infrared LED or another type of light-emitter device.

The flash illuminator could be configured to emit light toward the primary reflective surface. The primary reflective surface could be positioned so as to redirect the emitted light toward the rotatable mirror. In some embodiments, the primary reflective surface could be a rectangular-shaped mirror with aspect ratio of at least 8:1 (e.g., length:width). Other shapes of the primary reflective surface are possible. In such scenarios, the rotatable mirror could be configured to rotate about a rotational axis so as to sweep a field of view over a range of angles (e.g., more than 110 degrees in elevation angle). In such a manner, the flash illuminator could provide illumination light to a range of elevation angles based on a rotational position of the reflective surfaces of the rotatable mirror. In such scenarios, a long axis of the primary reflective surface could be disposed substantially parallel to the rotational axis of the rotatable mirror. While example embodiments herein include a primary reflective surface, it will be understood that, in some examples, a primary reflective surface need not be present. Furthermore, while example embodiments include the primary reflective surface as being in a particular location, it will be understood that the primary reflective surface could be located elsewhere. For example, some embodiments may include reflective surfaces along the beam path to facilitate packaging and other spatial (e.g., housing) constraints. In some embodiments, the pulse duration of the flash illuminator could be short relative to the mirror rotation speed. In such scenarios, the rotating mirror is effectively "frozen" while the illuminator briefly illuminates a desired region of the optical element by way of the mirror. For example, the illuminator could be configured to provide light pulses that have a pulse time of 10 ms, 1 ms, or less. Furthermore, the exposure time of the camera can be long relative to the rotation speed of the mirror so that multiple flashes can be used to illuminate the window, thereby increasing the amount of signal on the camera.

The optical element is optically coupled to the rotatable mirror such that at least a portion of the illumination light is incident upon the optical element. The camera could be positioned so as to capture images of the primary reflective surface. In such scenarios, the camera could capture images of various "slice" portions of the optical element as the rotatable mirror rotates about the rotational axis. In some embodiments, the camera could include a fixed focal length lens so as to focus on the optical element. As such, the occlusion detector system could be configured to detect debris, cracks, or other types of occluding objects adjacent to, or within the optical element.

In such scenarios, at least a portion of the occlusion detection system could be disposed within a same optical cavity as that of the receiver and transmitter. For example, the primary reflective surface could be positioned adjacent to, or outside the transmit path of the transmitter and/or the receive path of the receiver so as to avoid optically occluding (e.g., blocking) the primary operation of the lidar system. In such a manner, the occlusion detection system could be configured to detect occlusions on or adjacent to the optical element (e.g., primary optical window) of the lidar system.

II. Example Systems

FIG. **1** illustrates a system **100**, according to an example embodiment. In some embodiments, the system **100** could be a laser-based distance and ranging (lidar) system, or a portion thereof. In such scenarios, the system **100** could be configured to emit light pulses into an environment **10** so as to provide information indicative of objects **12** within a field of view **17**. As described herein, system **100** could be coupled to a vehicle so as to provide information about an external environment of the vehicle.

System **100** includes a rotatable base **110** configured to rotate about a first axis **102**. In some embodiments, a base actuator **112** could be operable to rotate the rotatable base **110** about the first axis **102** at an azimuthal rotational rate between 3 Hertz and 60 Hertz (e.g., between 180 revolutions per minute (RPM) and 3600 RPM). However, other azimuthal rotational rates are possible and contemplated. In some embodiments, the base actuator **112** could be controlled by the controller **150** to rotate at a desired rotational rate. In such scenarios, the controller **150** could control the base actuator **112** to rotate at a single target rotational rate and/or the controller **150** could dynamically adjust a desired rotational rate of the base actuator **112** within a range of possible rotational rates.

In some embodiments, the base actuator **112** could include an electric motor. For example, the electric motor could include a stator **116** and a rotor **114** that could be operable to rotate a shaft **118** of the rotatable base **110**. In various embodiments, the base actuator **112** could be a direct current (DC) motor, a brushless motor, or another type of rotational actuator. In some embodiments, the shaft **118** could be coupled to the rotatable base **110** by way of one or more bearings **119**. Bearings **119** could include a rotational bearing or another type of low-friction bearing.

In some embodiments, system **100** need not include a rotatable base **110**. In such scenarios, one or more elements of the system **100** within housing **160** may be configured to rotate about the first axis **102**. However, in other cases, some elements of the system **100** need not rotate about the first axis **102**. Accordingly, in such embodiments, system **100** could be utilized in line-scanning applications, single-point scan applications, among other possibilities.

The system **100** also includes a mirror assembly **130** with shaft **134** and a mirror body **133** that is configured to rotate about a mirror rotation axis **131**. In some embodiments, the mirror rotation axis **131** could be substantially perpendicular to the first axis **102** (e.g., within 0 to 10 degrees of perpendicular). In an example embodiment, a mirror actuator **136** could be configured to rotate the mirror body **133** about the mirror rotation axis **131** at a mirror rotational rate between 100 Hz to 1000 Hz (e.g., between 6,000 RPM and 60,000 RPM). In some contexts, the mirror body **133** could be configured to rotate about the mirror rotation axis **131** within a period of rotation (e.g., between 3.3 milliseconds and 1 millisecond).

The mirror actuator **136** could be a DC motor, a brushless DC motor, an AC motor, a stepper motor, a servo motor, or another type of rotational actuator. It will be understood that the mirror actuator **136** could be operated at various rotational speeds or at a desired rotational speed, and that the mirror actuator **136** could be controlled by the controller **150**.

In example embodiments, the mirror assembly **130** includes a plurality of reflective surfaces **132**. For example, the plurality of reflective surfaces **132** could include four reflective surfaces (e.g., reflective surface **132***a*, **132***b*, **132***c*, and **132***d*). In various embodiments, the reflective surfaces **132** could be formed from at least one of: gold, silicon oxide, titanium oxide, titanium, platinum, or aluminum. In such scenarios, the four reflective surfaces could be arranged symmetrically about the mirror rotation axis **131** such that a mirror body **133** of the mirror assembly **130** has a rectangular prism shape. It will be understood that the mirror assembly **130** could include more or less than four reflective surfaces. Accordingly, the mirror assembly **130** could be shaped as a multi-sided prism shape having more or less than four sides. For example, the mirror assembly **130** could have three reflective surfaces. In such scenarios, the mirror body **133** could have a triangular cross-section.

In some embodiments, the mirror body **133** could be configured to couple the plurality of reflective surfaces **132** to the shaft **134**. In such scenarios, the mirror body **133** could be substantially hollow. In various embodiments, at least a portion of the mirror body **133** could have an octagonal cross-section and/or a four-fold symmetry. In one example, mirror body **133** may include a polycarbonate material. In this example, an octagonal and/or four-fold symmetry configuration for mirror body **133** may facilitate reducing potential slippage of the polycarbonate material of the mirror body **133** on the shaft **134** during rotation of the mirror body. Other examples are possible as well.

In some embodiments, the mirror body **133** could include a plurality of flexible support members **138**. In such scenarios, at least one flexible support member **138** could be straight. Additionally or alternatively, at least one flexible support member **138** could be curved. In some embodiments, based on a geometry of the system of flexible support members, the mirror body **133** could be stiff in some directions (e.g., to transfer load) and elastic in some directions to accommodate thermal expansion. For example, the flexible support members **138** could be configured to be substantially stiff when in torsion and substantially elastic in response to forces perpendicular to the rotational axis. In various embodiments, the mirror body **133** could be formed from an injection molded material. Furthermore, the shaft **134** could be formed from steel or another structural material.

In some embodiments, the mirror assembly **130** could include an encoder magnet **139**, which could be coupled to the shaft **134**. In such scenarios, the encoder magnet **139** is configured to provide information indicative of a rotational position of the rotatable mirror assembly **130** with respect to the transmitter **127** and the receiver **121**.

In some embodiments, encoder magnet **139** may also be configured as a mirror motor magnet (e.g., included in mirror actuator **136**). In these embodiments, system **100** may use magnet **139** to facilitate both measuring and adjusting the rotational position of the rotatable mirror assembly **130**. In one example embodiment, magnet **139** may be one of a plurality of magnets (e.g., magnet ring, etc.) disposed in a circular arrangement and configured to interact with a magnetic field (e.g., generated at actuator **136**) to cause the rotation of the mirror assembly. Other embodiments are possible.

In various examples, the mirror assembly **130** could additionally or alternatively include a coupling bracket **135** configured to couple at least a portion of the mirror assembly **130** to the other elements of system **100**, such as housing **160**. The coupling bracket **135** could be configured to attach the mirror assembly **130** to the housing **160** by way of one or more connectors **137**. In such scenarios, the coupling bracket **135** and the connectors **137** could be configured to be easily removable from other elements of the system **100**. Such ease of removability could provide better recalibration, service, and/or repair options.

The system **100** additionally includes an optical cavity **120** coupled to the rotatable base **110**. The optical cavity includes a transmitter **127** having at least one light-emitter device **126** and a light-emitter lens **128**. In example embodiments, the at least one light-emitter device **126** could include one or more laser diode. Other types of light sources are possible and contemplated. The at least one light-emitter device **126** and the light-emitter lens **128** are arranged so as to define a light-emission axis **18**.

In various embodiments, the rotatable mirror assembly **130** could be configured to controllably rotate about the mirror rotation axis **131** so as to transmit emission light toward, and receive return light from, locations within the environment **10**.

The optical cavity **120** also includes a receiver **121** configured to detect return light **16** from the environment **10**. In various embodiments, the receiver **121** could include a bandpass filter configured to transmit light within a predetermined wavelength band (e.g., infrared light between 800-1600 nanometers). The receiver **121** includes a plurality of photodetectors **122**. As an example, the plurality of photodetectors **122** could include at least one solid-state single-photon-sensitive device. For example, in some embodiments, the plurality of photodetectors **122** could include one or more silicon photomultipliers (SiPMs). In such scenarios, the SiPMs could each include a plurality (e.g., a two-dimensional array) of single-photon avalanche diodes (SPADs). Additionally or alternatively, the plurality of photodetectors **122** could include an avalanche photodiode (APD), an infrared photodiode, photoconductor, a PIN diode, or another type of photodetector. Additionally, it will be understood that systems incorporating multiple photodetectors, such as a focal plane array or another type of image sensor, are also possible and contemplated.

The plurality of photodetectors **122** includes a respective set of two or more photodetectors for each light-emitter device of the at least one light-emitter device **126**. In various embodiments, the at least one light-emitter device **126** could be configured to emit light pulses that interact with the mirror assembly **130** such that the light pulses are redirected toward an environment **10** of the system **100** as transmit light **14**. In such scenarios, at least a portion of the light pulses could be reflected back toward the system **100** as return light **16** and received by the plurality of photodetectors **122** so as to determine at least one of: a time of flight, a range to an object **12**, and/or a point cloud.

In example embodiments, the photodetectors **122** could provide an output signal to the controller **150**. For example, the output signal could include information indicative of a time of flight of a given light pulse toward a given portion of the field of view **17** of the environment **10**. Additionally or alternatively, the output signal could include information indicative of at least a portion of a range map or point cloud of the environment **10**.

In some embodiments, each set of two or more photodetectors could include a primary light detector **123** and a secondary light detector **125**. The primary light detector **123** is configured to receive a first portion of return light **16** corresponding to light pulses emitted from a given light-emitter device. In such scenarios, the secondary light detector **125** is configured to receive a second portion of return light emitted from the given light-emitter device.

In various embodiments, the first portion of the return light **16** and the second portion of the return light **16** could have widely different intensities. For example, the first portion of the return light **16** could be at least an order of magnitude greater in photon flux than the second portion of the return light **16**.

In an example embodiment, the at least one light-emitter device **126** could include a four-element laser diode bar (e.g., four discrete light sources disposed on a laser bar). In such scenarios, the plurality of photodetectors **122** could include four primary light detectors (e.g., primary light detector **123*a***, **123*b***, **123*c***, and **123*d***). Each primary light detector could correspond to a respective light-emitter on the laser diode bar. Additionally, the plurality of photodetectors **122** could include four secondary light detectors (e.g., second light detector **125*a***, **125*b***, **125*c***, and **125*d***). Each secondary light detector could correspond to a respective light-emitter on the laser diode bar.

In alternate embodiments, the at least one light-emitter device **126** may include two or more laser diode bars, and a laser bar may include more or fewer than four light-emitter devices.

In some embodiments, the light-emitter device **126** could be coupled to a laser pulser circuit operable to cause the light-emitter device **126** to emit one or more laser light pulses. In such scenarios, the laser pulser circuit could be coupled to a trigger source, which could include controller **150**. The light-emitter device **126** could be configured to emit infrared light (e.g., light having a wavelength between 800-1600 nanometers (nm), such as 905 nm). However, other wavelengths of light are possible and contemplated.

The receiver **121** also includes a photodetector lens **124**. The plurality of photodetectors **122** and the photodetector lens **124** are arranged so as to define a light-receiving axis **19**.

The receiver **121** additionally includes a plurality of apertures **178**, which may be openings in an aperture plate **176**. In various embodiments, the aperture plate **176** could have a thickness between 50 microns and 200 microns. Additionally or alternatively, at least one aperture of the plurality of apertures **178** may have a diameter between 150 microns and 300 microns. However, other aperture sizes, larger and smaller than this range, are possible and contemplated. Furthermore, in an example embodiment, the respective apertures of the plurality of apertures **178** could be spaced apart by between 200 microns and 800 microns. Other aperture spacings are possible and contemplated.

The receiver **121** could also include one or more optical redirectors **129**. In such a scenario, each optical redirector **129** could be configured to optically couple a respective portion of return light **16** from a respective aperture to at least one photodetector of the plurality of photodetectors **122**. For example, each optical redirector could be configured to optically couple a respective portion of return light from a respective aperture to at least one photodetector of the plurality of photodetectors by total internal reflection.

In some embodiments, the optical redirectors **129** could be formed from an injection-moldable optical material. In such scenarios, the optical redirectors **129** are coupled together in element pairs such that a first element pair and a second element pair are shaped to slidably couple with one another. In example embodiments, the optical redirectors **129** are configured to separate the return light **16** into unequal portions so as to illuminate a first photodetector with a first photon flux of a first portion of the return light

16 and illuminate a second photodetector with a second photon flux of a second portion of the return light **16**. In some embodiments, one or more surfaces of the optical redirectors **129** could be coated or shaped so as to suppress or eliminate cross-talk between receiver channels. As an example, one or more surfaces of the optical redirectors **129** could be coated with an opaque optical material configured to suppress or eliminate cross-talk between receiver channels.

In some examples, the optical redirectors **129** may also be configured to expand a beam width of the first portion of the return light **16** projected onto the first photodetector (and/or the second portion of the return light **16** projected onto the second photodetector). In this way, for example, detection area(s) at the respective photodetectors on which respective portion(s) of return light **16** are projected may be greater than the cross-sectional areas of their associated apertures.

In various example embodiments, the rotatable base **110**, the mirror assembly **130**, and the optical cavity **120** could be disposed so as to provide a field of view **17**. In some embodiments, the field of view **17** could include an azimuthal angle range of 360 degrees about the first axis **102** and an elevation angle range of between 60 degrees and 120 degrees (e.g., at least 100 degrees) about the mirror rotation axis **131**. In one embodiment, the elevation angle range could be configured to allow system **100** to direct one or more emitted beams along the direction (and/or substantially parallel to) the first axis **102**. It will be understood the other azimuthal angle ranges and elevation angle ranges are possible and contemplated.

In some embodiments, the field of view **17** could have two or more continuous angle ranges (e.g., a "split" field of view or a discontinuous field of view). In one embodiment, the two or more continuous angle ranges may extend away from a same side of the first axis **102**. Alternatively, in another embodiment, the two or more continuous angle ranges may extend away from opposite sides of the first axis **102**. For example, a first side of the first axis **102** may be associated with elevation angles between 0 degrees and 180 degrees, and a second side of the first axis may be associated with elevation angles between 180 degrees and 360 degrees.

In some embodiments, the system **100** includes a rotatable housing **160** having an optical window **162**. The optical window **162** could include a flat window. Additionally or alternatively, the optical window **162** could include a curved window and/or a window with refractive optical power. As an example, the curved window could provide an extended field of view (compared to a flat optical window) in exchange for some loss or degradation in the quality of the optical beam. In such scenarios, the light pulses could be emitted toward, transmitted through, and received from, the environment **10** through the optical window **162**. Furthermore, although one optical window is described in various embodiments herein, it will be understood that examples with more than one optical window are possible and contemplated.

The optical window **162** could be substantially transparent to light having wavelengths such as those of the emitted light pulses (e.g., infrared wavelengths). For example, the optical window **162** could include optically transparent materials configured to transmit the emitted light pulses with a transmission efficiency greater than 80% in the infrared wavelength range. In one embodiment, the transmission efficiency of the optical window **162** may be greater than or equal to 98%. In another embodiment, the transmission efficiency of the optical window **162** may vary depending on the angles-of-incidence of the transmit and/or receive light incident on the optical window **162**. For instance, the transmission efficiency may be lower when light is incident on the optical window from relatively higher angles-of-incidence than when the light is incident from relatively lower angles-of-incidence.

In some examples, the optical window **162** could be formed from a polymeric material (e.g., polycarbonate, acrylic, etc.), glass, quartz, or sapphire. It will be understood that other optical materials that are substantially transparent to infrared light are possible and contemplated.

In some embodiments, other portions of the rotatable housing **160** could be coated with, or be formed from, an optically absorptive material such as black tape, absorptive paint, carbon black, black anodization, micro-arc oxidation treated surface or material, and/or another type of optically absorptive, anti-reflective surface or material.

The various elements of system **100** could be disposed in different arrangements. For example, in an example embodiment, at least one of the light-receiving axis **19** or the light-emission axis **18** does not intersect the mirror rotation axis **131**.

The system **100** includes a controller **150**. In some embodiments, the controller **150** includes at least one of a field-programmable gate array (FPGA) or an application-specific integrated circuit (ASIC). Additionally or alternatively, the controller **150** may include one or more processors **152** and a memory **154**. The one or more processors **152** may include a general-purpose processor or a special-purpose processor (e.g., digital signal processors, graphics processor units, etc.). The one or more processors **152** may be configured to execute computer-readable program instructions that are stored in the memory **154**. As such, the one or more processors **152** may execute the program instructions to provide at least some of the functionality and operations described herein.

The memory **154** may include, or take the form of, one or more computer-readable storage media that may be read or accessed by the one or more processors **152**. The one or more computer-readable storage media can include volatile and/or non-volatile storage components, such as optical, magnetic, organic, or other memory or disc storage, which may be integrated in whole or in part with at least one of the one or more processors **152**. In some embodiments, the memory **154** may be implemented using a single physical device (e.g., one optical, magnetic, organic or other memory or disc storage unit), while in other embodiments, the memory **154** can be implemented using two or more physical devices.

As noted, the memory **154** may include computer-readable program instructions that relate to operations of system **100**. As such, the memory **154** may include program instructions to perform or facilitate some or all of the operations or functionalities described herein.

For example, the operations could include causing the light-emitter device **126** to emit the light pulses. In such scenarios, the controller **150** could cause a pulser circuit associated with light-emitter device **126** to provide one or more current/voltage pulses to the light-emitter device **126**, which may cause the light-emitter device **126** to provide the light pulses.

The operations could also include receiving at least a first portion of reflected light pulses (e.g., return light **16**) from the field of view **17** as a detected light signal. For example, at least some of the light pulses emitted from the light-emitter device **126** via the optical window **162** (e.g., transmit light **14**) could interact with objects **12** in the environment **10** in the field of view **17** so as to provide reflected light pulses or return light **16**. At least the portion of the reflected light pulses could be received by at least one photodetector of the plurality of photodetectors **122**. In turn, the given photodetector could provide a detected light signal, which could include a photocurrent signal or a photovoltage signal.

Furthermore, the operations could include determining, based on the detected light signal, a point cloud indicative of objects **12** within the field of view **17**. In an example embodiment, determining the point cloud could be performed by controller **150**. For example, the controller **150** could determine and accumulate a plurality of spatial points based on a respective time of flight for each light pulse emitted and received. Determining the point cloud could be further based on an elevation angle of the mirror assembly **130** and an azimuthal angle of the rotatable base **110**.

It will be understood that some or all of the operations described herein could be carried out by computing devices located remotely from the controller **150** and/or other elements of system **100**.

In various embodiments, the system **100** could include at least one baffle. For example, the system **100** could include at least one rotatable baffle **170** and/or at least one static baffle **172**. In such scenarios, the at least one rotatable baffle **170** and/or at least one static baffle **172** could be configured to reduce stray light within the optical cavity **120** (e.g., light traveling internally from the light-emitter device **126** to the plurality of photodetectors **122** without first interacting with the environment around the system **100**). In an example embodiment, the static baffle **172** could include an optically-opaque material disposed between the light-receiving axis **19** and the light-emission axis **18**. In some embodiments, the rotatable baffle **170** could be coupled to the mirror body **133** and could also include an optically-opaque material configured to reduce or eliminate stray light between the transmitter portions and the receiver portions of the system **100**. In other words, a first portion of the mirror body **133** and a second portion of the mirror body **133** could be separated by the rotatable baffle **170**. In such scenarios, the rotatable baffle **170** could be shaped like a flat disk, however other shapes are contemplated and possible. The rotatable baffle **170** could be centered about, and perpendicular to, the mirror rotation axis **131**.

In some embodiments, the system **100** could include an optical feedback system. As a part of the optical feedback system, the transmitter **127** could be configured to transmit, during the period of rotation of the mirror body **133**, a plurality of light pulses toward the reflective surfaces **132** of the mirror assembly **130**. In such a scenario, the mirror assembly **130** could be configured to (i) reflect at least a first light pulse of the plurality light pulses into an environment **10** of the system **100** and (ii) reflect at least a second light pulse of the plurality of light pulses into an internal optical path **168**. In some embodiments, the internal optical path **168** may include a baffle opening **174** in the rotatable baffle **170**, the static baffle **172**, and/or in a gap between the rotatable baffle **170** and the static baffle **172**.

In such scenarios, the plurality of photodetectors **122** of the receiver **121** could be configured to (i) detect a reflected light pulse including a reflection of the first light pulse caused by an object **12** in the environment **10** and (ii) detect the second light pulse received via the internal optical path **168**. In various embodiments, the internal optical path **168** could be defined at least in part by one or more internal reflectors **180** that reflect the second light pulse toward the reflective surfaces **132** of the mirror assembly **130** such that the reflective surfaces **132** reflect the second light pulse toward the receiver **121**.

Furthermore, in such scenarios, the controller **150** could be configured to determine a distance to the object **12** in the environment **10** based on a time when the first light pulse is transmitted by the transmitter **127**, a time when the reflected light pulse is detected by the photodetector **122**, and a time when the second light pulse is detected by the photodetector **122**. In such scenarios, a first light pulse (and its corresponding reflected light pulse) could provide information indicative of a distance to an object and a second light pulse (and its corresponding reflected light pulse) could provide information indicative of a feedback distance or zero-length reference.

An occlusion detection system of system **100** could include a primary reflective surface **163**. In some embodiments, the primary reflective surface **163** could include a rectangular mirror with an aspect ratio of at least 8:1. However, it will be understood that other shapes of the primary reflective surface **163** are contemplated and possible within the context of the present disclosure. In example embodiments, the primary reflective surface **163** could include a long axis that is disposed substantially parallel to the mirror rotation axis **131**.

In such a scenario, the reflective surfaces **132** of the mirror body **133** could represent a plurality of secondary reflective surfaces. System **100** could also include a camera **166**. The camera **166** is configured to capture at least one image of an optical element (e.g., the optical window **162**) by way of the primary reflective surface **163** and at least one secondary reflective surface of the mirror body **133**.

In such scenarios, the controller **150** may be configured to carry out further operations relating to occlusion detection. Such operations could include causing the camera **166** to capture a plurality of images of the optical element by way of the primary reflective surface **163** and at least one secondary reflective surface of the mirror body **133**. Each image of the plurality of images is captured at a corresponding mirror angle of the at least one secondary reflective surface.

The system **100** additionally includes an illuminator **161**. In some embodiments, the illuminator **161** could include an infrared light-emitting diode (LED). In such scenarios, the operations of the controller **150** could additionally include while causing the camera **166** to capture the plurality of images, causing the illuminator **161** to emit light to illuminate the optical element by way of the primary reflective surface **163** and at least one secondary reflective surface of the mirror body **133**.

The operations may additionally include determining an aggregate image of the optical element based on the plurality of images and the corresponding mirror angles of the at least one secondary reflective surface.

Additionally or alternatively, the operations could include determining, based on the aggregate image, that at least one occlusion object is present on the optical element.

In some embodiments, the camera includes a fixed focal length lens configured to focus on the optical element by way of the primary reflective surface and the at least one secondary reflective surface. As an example, the camera could include a video capture device.

FIG. **2A** illustrates a system **200**, according to an example embodiment. System **200** could be similar or identical to system **100**, which is illustrated and described in relation to FIG. **1**. For example, system **200** could include a rotatable base **110**. The rotatable base **110** could be configured to rotate about first axis **102**. Furthermore, system **200** could include an optical cavity **120**, which could include light-emitter device **126**, light-emitter lens **128**, photodetector

122, and photodetector lens **124**. Furthermore, in some embodiments, system **200** could include a mirror assembly **130**. The mirror assembly **130** could include a plurality of reflective surfaces **132***a*, **132***b*, and **132***c* and a shaft **134**. The mirror assembly **130** could be configured to rotate about a mirror rotation axis **131**.

In some embodiments, the light-emitter device **126** and the light-emitter lens **128** could form a light-emission axis **18**. As illustrated in FIG. **2**A, light pulses emitted by the light-emitter device **126** could interact with reflective surface **132***d* so as to be reflected toward the optical window **162** and transmitted toward the object **12** in the environment **10**.

In some embodiments, the photodetector **122** and the photodetector lens **124** could form a light-receiving axis **19**. Light pulses emitted by the light-emitter device **126** could be reflected or otherwise interact with the environment and could be received as return light **16** by way of the reflective surfaces **132** (e.g., reflective surface **132***d*) and observed at the plurality of photodetectors **122** by way of one or more optical redirectors **129**.

FIG. **2**B illustrates a system **220**, according to an example embodiment. System **220** could be similar or identical to system **100** and system **200**, as illustrated and described in relation to FIGS. **1** and **2**A, respectively. In some embodiments, system **220** could include an occlusion detection system. The occlusion detection system could be configured to provide information indicative of a presence of an occlusion object **222** associated with (e.g., coupled to) the optical window **162**. It will be understood that while FIG. **2**B illustrates the occlusion object **222** as being on an external surface of the optical window **162**, other occlusion objects could be located elsewhere, such as along an internal surface of the optical window **162** or as an integral part of the optical window **162**, itself, such as a crack or a cloudy or opaque region of the optical window **162**.

As illustrated in FIG. **2**B, system **220** could include a transmitter **127** and a receiver **121**. System **220** includes an optical window **162** and a primary reflective surface **163**. System **220** also includes a mirror assembly **130** configured to rotate about a mirror rotation axis **131**. The mirror assembly **130** includes a plurality of reflective surfaces **132**, referred to here as secondary reflective surfaces.

The system **220** includes a camera **166** that is configured to capture at least one image of the optical window **162** by way of the primary reflective surface **163** and at least one secondary reflective surface of the mirror assembly **130**.

The system **220** also includes a controller (e.g., controller **150**) having at least one processor and a memory. The at least one processor executes program instructions stored in the memory so as to carry out operations. The operations include causing the mirror assembly **130** to rotate about the mirror rotation axis **131**.

The operations also include causing the camera **166** to capture a plurality of images of the optical window **162** by way of the primary reflective surface **163** and at least one secondary reflective surface of the mirror assembly **130**. Each image of the plurality of images is captured at a corresponding mirror angle of the at least one secondary reflective surface.

In some embodiments, the operations include determining an aggregate image of the optical window **162** based on the plurality of images and the corresponding mirror angles of the at least one secondary reflective surface.

In some embodiments, the operations of controller **150** could additionally include determining, based on the aggregate image, that at least one occlusion object **222** is present on, or integral to, the optical window **162**. In some embodiments, in response to determining the at least one occlusion object **222**, the controller **150** could adjust subsequent operations of the system **100** to account for the occlusion object **222**. For example, the controller **150** could adjust lidar scans and/or camera images so as to ignore or adjust point cloud and/or image information that corresponds to a region of the field of view **17** that could be affected by the occlusion object **222**. In other embodiments, the controller **150** could provide a notification about the occlusion object **222**. Based on the notification, the system **100** could transmit a service request to clean the optical window **162** and/or cause an associated vehicle (e.g., vehicle **500**) to travel to a service location for optical window cleaning. In other embodiments, the system **100** could provide a notification to request further information from other sensors (e.g., other lidar systems) that could provide information about regions of the field of view **17** that might be obscured or otherwise affected by the occlusion object **222**. Other ways to obtain backup or substitute information from other sensor systems are possible and contemplated. Furthermore, it will be understood that other adjustments could be made to the operations of system **100** so as to compensate for the presence of the occlusion object and/or to maintain safe and reliable operations of the system **100**.

FIG. **2**C illustrates a system **230**, according to an example embodiment. System **230** could illustrate an optical feedback system, which could include one or more internal reflectors **180** (e.g., first internal reflector **180***a* and second internal reflector **180***b*). In example embodiments, the first internal reflector **180***a* and the second internal reflector **180***b* could be diffuse reflectors.

As illustrated in FIG. **2**C, a particular rotational angle of the mirror body **133** and corresponding reflective surfaces **132** could result in an emitted light pulse (herein referred to as a "second light pulse") being reflected from a transmitter portion of the mirror body **133** toward the first internal reflector **180***a*. In such a scenario, the first internal reflector **180***a* could be configured to reflect the second light pulse through the baffle opening **174** toward the second internal reflector **180***b*. The second internal reflector **180***b* could be configured to reflect the second light pulse toward a receiver portion of the mirror body **133** and corresponding reflective surfaces **132**. In turn, the reflective surface **132** could reflect the second light pulse toward the receiver **121**.

FIG. **2**D illustrates an alternate view **240** of the system **230** of FIG. **2**C, according to an example embodiment. As illustrated in FIG. **2**D, the transmitter **127** includes a light-emitter lens **128** configured to transmit light pulses into a first space **242** between the light-emitter lens **128** and a first portion of the mirror body **133**. Furthermore, the receiver **121** includes a photodetector lens **124** configured to receive light pulses reflected by a second portion of the mirror body **133** into a second space **244** between the second portion of the mirror body **133** and the photodetector lens **124**. In such scenarios, the first internal reflector **180***a* could be disposed in the first space **242** and the second reflector could be disposed in the second space **244**.

As illustrated in FIG. **2**D, the static baffle **172** separates the first space **242** and the second space **244**. In such a scenario, the static baffle **172** includes a baffle opening **174**. As illustrated, the first internal reflector **180***a* could be configured to reflect the second light pulse toward the second internal reflector **180***b* through the baffle opening **174**.

In an example embodiment, the mirror body **133** and corresponding reflective surfaces **132** could reflect a "first light pulse" into the environment **10** during a first part of the period of rotation of the mirror body **133**. In such a scenario, the mirror body **133** and corresponding reflective surfaces **132** could reflect the second light pulse toward the first internal reflector **180***a* during a second part of the period of rotation of the mirror body **133**.

As described herein, the light pulses received via the internal optical path **168** could provide a more reliable "zero-time" reference for system **100** than those provided by, for example, a calibration target and/or known features within the environment.

Additionally or alternatively, the optical feedback systems described herein could provide a way to directly estimate and/or extrapolate the transmit power of light pulses emitted by the transmitter **127**. That is, in some examples, the amount of light received by the receiver **121** via the internal reflector(s) **180** could be proportional to an overall transmitted optical power. In such scenarios, an output signal of one or more of the photodetectors could be compared to a lookup table that provides information about associations between the output signal and the overall transmitted optical power. As such, the optical feedback system could provide a way to directly measure the optical output of the transmitter **127** of system **100** on a per-shot basis.

FIG. **3**A illustrates a mirror assembly **300**, according to an example embodiment. Mirror assembly **300** could be similar or identical to the mirror assembly **130** illustrated and described in relation to FIG. **1**. For example, mirror assembly **300** could include a plurality of reflective surfaces **132***a*, **132***b*, **132***c*, and **132***d*. The mirror assembly **300** could additionally include a shaft **134**, which could be configured to rotate about the mirror rotation axis **131**.

In some embodiments, the transmitter **127** could emit light pulses toward the mirror assembly **300** along a light-emission axis **18**. A reflective surface **132***d* of the mirror assembly **300** could reflect such light pulses such that they are transmitted toward an external environment **10**.

In such examples, light from the environment **10** (e.g., return light **16**) could be reflected by the reflective surface **132***d* of the mirror assembly **300**. In some embodiments, the received light could be directed along light-receiving axis **19** toward the receiver **121**.

FIG. **3**B illustrates a portion **320** of the mirror assembly **300** of FIG. **3**A, according to an example embodiment. The shaft **134** and the respective reflective surfaces **132***a*, **132***b*, **132***c*, and **132***d* could be coupled by way of one or more flexible members **138** (e.g., flexible members **138***a*, **138***b*, **138***c*, and **138***d*). In some embodiments, flexible members **138***a*, **138***b*, **138***c*, and **138***d* could provide a flexible (e.g., flexural) structural support between the shaft **134** and an interior surface **322** of the mirror body **133**.

In example embodiments, the flexible members **138** could be t-shaped. Additionally or alternatively, the flexible members **138** could have an elongated t-shape. That is, the t-shape could be extended lengthwise along the x-axis. Other shapes are possible and contemplated.

In some embodiments, the flexible members **138** could each include two first ends **324***a* and **324***b* and a second end **326**. In such a scenario, the two first ends **324***a* and **324***b* and the second end **326** could be coupled by way of a t-shaped member **328**. As illustrated, the two first ends **324***a* and **324***b* could couple to two different interior surfaces that correspond to (are located opposite) two different reflective surfaces **132** of the mirror body **133**.

In some embodiments, the two first ends **324***a* and **324***b* could be formed from a first material and the second end **326** could be formed from a second, different, material. As an example, various portions of the support member **138** could be formed from, without limitation, plastic (e.g., polypropylene, polyethylene, polycarbonate, silicone, etc.), rubber (e.g., latex, etc.), metal (e.g., aluminum, steel, titanium, etc.), and/or ceramic. It will be understood that other materials and material combinations are possible and contemplated within the scope of the present disclosure.

In example embodiments, the materials and/or geometry for one or more elements of the flexible members **138** could be selected so as to reduce or minimize the effect of differences in the coefficient of thermal expansion between, for example, the shaft **134** and the reflective surfaces **132**. For example, the two first ends **324***a* and **324***b* could be selected to be silicone so as to provide a compliant, flexible material that is relatively insensitive to thermal variations. Additionally or alternatively, in some embodiments, the t-shaped member **328** could be formed from a flexible material so as to reduce or minimize the forces upon, or relative displacement of, the reflective surfaces **132** from the shaft **134**. Such forces and/or displacement could be due, at least in part, to differences in the coefficient of thermal expansion. Accordingly, by utilizing the disclosed flexible members **138**, mirror assembly **130** and/or other portions of system **100** could be less affected by fluctuation in temperature, temperature-dependent material bowing or displacement, and/or long term temperature-cycling effects (e.g., thermal destressing).

FIG. **4**A illustrates a receiver **400**, according to an example embodiment. Receiver **400** could be similar or identical to receiver **121**, as illustrated and described in relation to FIG. **1**. Receiver **400** could include an optical redirector device, which could be configured to receive return light **16** by way of photodetector lens **124**. Receiver **400** could also include an aperture plate **176**. The aperture plate **176** could include a plurality of apertures (e.g., apertures **178***a*, **178***b*, **178***c*, and **178***d*). In an example embodiment, at least one aperture of the plurality of apertures has a diameter between 150 microns and 300 microns. The plurality of apertures includes a set of openings formed in an aperture plate. In such scenarios, the aperture plate could have a thickness between 50 microns and 200 microns.

Receiver **400** includes a plurality of photodetectors **122** (e.g., primary light detectors **123***a*, **123***b*, **123***c*, and **123***d* and second light detectors **125***a*, **125***b*, **125***c*, and **125***d*).

Receiver **400** additionally includes a plurality of optical redirectors **129** (e.g., optical redirectors **129***a*, **129***b*, **129***c*, and **129***d*). Each optical redirector **129***a*, **129***b*, **129***c*, and **129***d* is configured to optically couple a respective portion of return light **16** from a respective aperture **178***a*, **178***b*, **178***c*, or **178***d* to at least one photodetector of the plurality of photodetectors.

In some embodiments, each optical redirector **129***a*, **129***b*, **129***c*, and **129***d* is configured to optically couple a respective portion of return light **16** from a respective aperture **178***a*, **178***b*, **178***c*, or **178***d* to at least one photodetector of the plurality of photodetectors **122** by total internal reflection.

In various embodiments, the optical redirectors **129** could be formed from an injection-moldable optical material. For example, the optical redirectors **129** could be formed from a polymeric thermoplastic optical material such as acrylic (polymethyl methacrylate or PMMA), polystyrene, polycarbonate, Cyclic Olefin Polymer (COP), Cyclic Olefin Copolymer (COC), or various copolymers, such as NAS, a copolymer of 70% polystyrene and 30% acrylic. Additionally or alternatively, some embodiments may include various polyaryletherketone (PAEK)-based materials and/or polysulfonanones (PSU, PPSU, PES, etc) or polyetherimide (PEI). It will be understood that other optical materials are possible and contemplated.

The optical redirectors **129** could be coupled together in element pairs such that a first element pair and a second element pair are shaped to slidably couple with one another. For example, as illustrated in FIG. **4**A, optical redirector **129***a* and optical redirector **129***c* could be physically coupled and could represent the first element pair. Similarly, optical redirector **129***b* and optical redirector **129***d* could be physically coupled and could represent the second element pair. As such, the first element pair and the second element pair could be configured to be assembled by sliding them together along the y-axis.

It will be understood that while two-element pairs could be shaped so as to slidably couple together with one another (e.g., providing four optical channels), other ways to mechanically assemble the optical redirectors are possible and contemplated. For example, the optical redirectors could be partitioned into two groups that may be slidably coupled to one another, which may provide for 4, 6, 8, 10, or more optical channels. Furthermore, it will be understood that the optical redirectors **129** could be arranged so as to provide between 2-64 optical channels, or more. Yet further, other ways to form the optical redirectors **129** are possible and contemplated. For example, processes such as laser-cutting, semiconductor processing, and/or 3D printing are possible and contemplated to form the optical redirectors **129**.

FIG. **4**B illustrates an alternate view **420** of the receiver **400** of FIG. **4**A, according to an example embodiment. As illustrated in FIG. **4**B, the alternate view **420** could include a partial overhead view of the primary light detectors **123***a*, **123***b*, **123***c*, and **123***d* and the secondary light detectors **125***a*, **125***b*, **125***c*, and **125***d*. Furthermore, optical redirectors **129***a*, **129***b*, **129***c*, and **129***d* could each be optically coupled to a respective primary light detector and a corresponding secondary light detector.

While FIG. **4**B illustrates a four-by-two array of light detectors (e.g., four primary light detectors in a first row and four secondary light detectors in a second row), it will be understood that other light detector geometries and layouts are possible and contemplated. For example, an alternative light detector layout could include a central row of four primary light detectors, an upper row of two secondary light detectors, and a lower row of two further secondary light detectors. Other arrangements are possible and contemplated.

FIG. **4**C illustrates an alternate view **430** of the receiver **400** of FIG. **4**A, according to an example embodiment. As illustrated in FIG. **4**C, the alternate view **430** includes an oblique angle view of the receiver **400** and the optical redirectors **129***a*, **129***b*, **129***c*, and **129***d*. In some embodiments, incident light could enter through an aperture (e.g., aperture **178***a*) and interact with primary light detectors **123***a*. In some embodiments, a portion **432** of the incident light could be reflected from a top surface of the primary light detector **123***a* and subsequently reflected from a reflective surface **434** so as to interact with the secondary light detector **125***a*. In various examples, it will be understood that various optical paths are contemplated and possible. For example, a portion of the incident light could be allowed to exit the redirector (e.g., via loss of total internal reflection), such a portion of the incident light could be provided to the secondary detector by way of an external feature, such as a reflective element disposed along an underside of the aperture plate **176**.

While FIGS. **4**A-**4**C illustrate an example embodiment, it will be understood that other optical redirector designs could be utilized so as to couple incident light between an input aperture and the photodetectors. For example, an example embodiment may include an optical redirector that substantially confines the light in a single optical plane (ignoring the divergence in the incoming beam). Additionally or alternatively, the optical redirector could be configured to direct light out-of-plane.

In some embodiments, the optical redirector could include a lensed surface. As an example, the lensed surface could be utilized on the input and/or output surface of the optical redirector. Such lensed surfaces could be beneficially configured to control the divergence of the optical beam and facilitate uniform optical coverage of the photodetector. Additionally or alternatively, at least one surface of the optical redirector could include a rippled surface, which may provide an engineered diffuser and an alternative way to control optical beam divergence.

Yet further, it will be understood that one or more redirector channels could be incorporated or combined into a single optical redirector body. In such a scenario, each redirector channel could include an entrance aperture, an exit aperture, and one or more intermediate control surfaces. The redirector channel may be made of a solid, transparent material, or it may be hollow. Both the entrance and exit apertures, as well as some or all of the intermediate control surfaces may be configured to manipulate the incoming light via refraction, e.g. a prism with one or more facets, a lens in one or two directions, or an engineered diffusing pattern, or via reflection, e.g. a planar reflector with one or more facets, a curved reflector with optical power in one of two directions, or an engineered diffusing reflector. In various examples, optical reflectivity may be provided by the use of total internal reflection, or via the application of reflective coatings. In one embodiment, the redirector channel could be comprised of a solid transparent material, with entrance and exit apertures oriented to be nearly normal with the incoming light, and a pair of reflective facets disposed between the apertures. In a second embodiment, the redirector channel could be substantially similar to the first example, but the exit aperture is at a significant angle with respect to the exiting light, and one of the intermediate reflectors is formed of multiple facets which serve to compress the beam pattern in one direction, thereby offsetting the elongation of the beam pattern caused by the oblique intersection between the exit aperture and the beam. In a third embodiment, the redirector channel is comprised of a solid material, and consists only of an entrance aperture and an exit aperture, and the entrance aperture is inclined with respect to the incoming light so as to refract the incident light towards the exit aperture.

III. Example Vehicles

FIGS. **5**A, **5**B, **5**C, **5**D, and **5**E illustrate a vehicle **500**, according to an example embodiment. The vehicle **500** could be a semi- or fully-autonomous vehicle. While FIGS. **5**A-**5**E illustrate vehicle **500** as being an automobile (e.g., a passenger van), it will be understood that vehicle **500** could include another type of autonomous vehicle, robot, or drone that can navigate within its environment using sensors and other information about its environment.

The vehicle **500** may include one or more sensor systems **502**, **504**, **506**, **508**, and **510**. In some embodiments, sensor systems **502**, **504**, **506**, **508**, and **510** could include LIDAR sensors having a plurality of light-emitter devices arranged over a range of angles with respect to a given plane (e.g., the x-y plane).

One or more of the sensor systems **502**, **504**, **506**, **508**, and **510** may be configured to rotate about an axis (e.g., the z-axis) perpendicular to the given plane so as to illuminate an environment around the vehicle **500** with light pulses. Based on detecting various aspects of reflected light pulses (e.g., the elapsed time of flight, polarization, intensity, etc.), information about the environment may be determined.

In an example embodiment, sensor systems **502**, **504**, **506**, **508**, and **510** may be configured to provide respective point cloud information that may relate to physical objects within the environment of the vehicle **500**. While vehicle **500** and sensor systems **502**, **504**, **506**, **508**, and **510** are illustrated as including certain features, it will be understood that other types of sensor systems are contemplated within the scope of the present disclosure.

An example embodiment may include a system having a plurality of light-emitter devices. The system may include a transmit block of a lidar device. For example, the system may correspond to (or may be included in) a lidar device of a vehicle (e.g., a car, a truck, a motorcycle, a golf cart, an aerial vehicle, a boat, etc.). Each light-emitter device of the plurality of light-emitter devices is configured to emit light pulses along a respective beam elevation angle. The respective beam elevation angles could be based on a reference angle or reference plane. In some embodiments, the reference plane may be based on an axis of motion of the vehicle **500**.

While lidar systems with single light-emitter devices are described and illustrated herein, lidar systems with multiple light-emitter devices (e.g., a light-emitter device with multiple laser bars on a single laser die) are also contemplated. For example, light pulses emitted by one or more laser diodes may be controllably directed about an environment of the system. The angle of emission of the light pulses may be adjusted by a scanning device such as, for instance, a mechanical scanning mirror and/or a rotational motor. For example, the scanning devices could rotate in a reciprocating motion about a given axis and/or rotate about a vertical axis. In another embodiment, the light-emitter device may emit light pulses towards a spinning prism mirror, which may cause the light pulses to be emitted into the environment based on an angle of the prism mirror angle when interacting with each light pulse. Additionally or alternatively, scanning optics and/or other types of electro-opto-mechanical devices are possible to scan the light pulses about the environment. Embodiments utilizing a plurality of fixed beams are also contemplated within the context of the present disclosure.

In some embodiments, a single light-emitter device may emit light pulses according to a variable shot schedule and/or with variable power per shot, as described herein. That is, emission power and/or timing of each laser pulse or shot may be based on a respective elevation angle of the shot. Furthermore, the variable shot schedule could be based on providing a desired vertical spacing at a given distance from the lidar system or from a surface (e.g., a front bumper) of a given vehicle supporting the lidar system. As an example, when the light pulses from the light-emitter device are directed downwards, the power-per-shot could be decreased due to a shorter anticipated maximum distance to target. Conversely, light pulses emitted by the light-emitter device at an elevation angle above a reference plane may have a relatively higher power-per-shot so as to provide sufficient signal-to-noise to adequately detect pulses that travel longer distances.

In some embodiments, the power/energy-per-shot could be controlled for each shot in a dynamic fashion. In other embodiments, the power/energy-per-shot could be controlled for successive set of several pulses (e.g., 10 light pulses). That is, the characteristics of the light pulse train could be changed on a per-pulse basis and/or a per-several-pulse basis.

While FIGS. **5**A-**5**E illustrates various lidar sensors attached to the vehicle **500**, it will be understood that the vehicle **500** could incorporate other types of sensors, such as a plurality of optical systems (e.g., cameras), radars, or ultrasonic sensors.

In an example embodiment, vehicle **500** could include a lidar system (e.g., system **100**) configured to emit light pulses into an environment of the vehicle **500** so as to provide information indicative of objects within a default field of view. For example, vehicle **500** could include an optical system (e.g., system **100**) having a rotatable base (e.g., rotatable base **110**) configured to rotate about a first axis (e.g., first axis **102**). The optical system could also include a mirror assembly (e.g., mirror assembly **130**). The mirror assembly could be configured to rotate about a mirror rotation axis (e.g., mirror rotation axis **131**). In some embodiments, the mirror rotation axis is substantially perpendicular to the first axis.

The optical system also includes an optical cavity (e.g., optical cavity **120**) coupled to the rotatable base. In such scenarios, the optical cavity includes at least one light-emitter device (e.g., light-emitter device **126**) and a light-emitter lens (e.g., light-emitter lens **128**). The at least one light-emitter device and the light-emitter lens are arranged so as to define a light-emission axis (e.g., light-emission axis **18**).

The optical system additionally includes a plurality of photodetectors (e.g., photodetectors **122**. In an example embodiment, the plurality of photodetectors includes a respective set of two or more photodetectors for each light-emitter device of the at least one light-emitter device. The optical system also includes a photodetector lens (e.g., photodetector lens **124**. In such scenarios, the plurality of photodetectors and the photodetector lens are arranged so as to define a light-receiving axis (e.g., light-receiving axis **19**).

In some embodiments, each set of two or more photodetectors could include a primary light detector (e.g., primary light detector **123**) and a secondary light detector (e.g., secondary light detector **125**). In such scenarios, the primary light detector is configured to receive a first portion of return light emitted from a given light-emitter device. Furthermore, the secondary light detector is configured to receive a second portion of return light emitted from the given light-emitter device.

In some embodiments, the first portion of the return light is at least an order of magnitude greater in photon flux than the second portion of the return light.

IV. Example Methods

FIG. **6** illustrates a method **600**, according to an example embodiment. It will be understood that the method **600** may include fewer or more steps or blocks than those expressly illustrated or otherwise disclosed herein. Furthermore, respective steps or blocks of method **600** may be performed in any order and each step or block may be performed one or more times. In some embodiments, some or all of the blocks or steps of method **600** may be carried out by controller **150** and/or other elements of system **100**, **200**, 220, or 230 as illustrated and described in relation to FIGS. 1, 2A, 2B, and 2C, respectively.

Block 602 includes emitting, from a light-emitter device coupled to a rotatable base, a light pulse that initially interacts with a mirror assembly and is then emitted toward an environment as emitted light

Block 604 includes receiving return light from the environment that initially interacts with the mirror assembly and is then detected by at least a primary light detector and a secondary light detector.

Block 606 includes determining, based on a time of flight between an emission time and a receive time, a range to an object in the environment.

In some embodiments, method 600 may additionally include causing the rotatable base to rotate about a first axis, causing the mirror assembly to rotate about a mirror rotation axis, and, while the mirror assembly is rotating, repeating the emitting, receiving, and determining steps so as to form a point cloud. The point cloud includes a plurality of ranges or range data within a three-dimensional representation of the environment.

FIG. 7 illustrates a method 700, according to an example embodiment. It will be understood that the method 700 may include fewer or more steps or blocks than those expressly illustrated or otherwise disclosed herein. Furthermore, respective steps or blocks of method 700 may be performed in any order and each step or block may be performed one or more times. In some embodiments, some or all of the blocks or steps of method 700 may be carried out by controller 150 and/or other elements of system 100, 200, 220, or 230 as illustrated and described in relation to FIGS. 1, 2A, 2B, and 2C, respectively.

Block 702 includes causing a rotatable mirror (e.g., mirror body 133) to rotate about a rotational axis (e.g., mirror rotation axis 131). In such scenarios, the rotatable mirror could include a plurality of secondary reflective surfaces (e.g., reflective surfaces 132).

Block 704 includes causing a camera (e.g., camera 166) to capture a plurality of images of an optical element (e.g., optical window 162) by way of a primary reflective surface (e.g., primary reflective surface 163) and at least one secondary reflective surface of the rotatable mirror. Each image of the plurality of images is captured at a corresponding mirror angle of the at least one secondary reflective surface.

In some embodiments, method 700 could additionally include determining an aggregate image of the optical element based on the plurality of images and the corresponding mirror angles of the at least one secondary reflective surface.

In such scenarios, method 700 could include determining, based on the aggregate image, that at least one occlusion object is present on the optical element.

Method 700 could additionally include, while causing the camera to capture the plurality of images, causing an illuminator (e.g., illuminator 161) to emit light to illuminate the optical element by way of the primary reflective surface and the rotatable mirror.

FIG. 8 illustrates a method 800, according to an example embodiment. It will be understood that the method 800 may include fewer or more steps or blocks than those expressly illustrated or otherwise disclosed herein. Furthermore, respective steps or blocks of method 800 may be performed in any order and each step or block may be performed one or more times. In some embodiments, some or all of the blocks or steps of method 800 may be carried out by controller 150 and/or other elements of system 100, 200, 220, or 230 as illustrated and described in relation to FIGS. 1, 2A, 2B, and 2C, respectively.

Block 802 includes causing at least one light-emitter device (e.g., light-emitter device 126) to emit a plurality of light pulses toward a rotatable mirror (e.g., mirror assembly 130). The rotatable mirror (i) reflects at least a first light pulse of the plurality light pulses into an external environment (e.g., environment 10); and (ii) reflects at least a second light pulse of the plurality of light pulses into an internal optical path (e.g., internal optical path 168).

Block 804 includes receiving, by a photodetector (e.g., photodetectors 122), (i) a reflected light pulse that includes a reflection of the first light pulse caused by an object (e.g., object 12) in the external environment (e.g., environment 10); and (ii) a second light pulse received via the internal optical path. The internal optical path is defined at least in part by one or more internal reflectors (e.g., internal reflector 180) that reflect the second light pulse toward the rotatable mirror such that the rotatable mirror reflects the second light pulse toward the photodetector.

Additionally or alternatively, method 800 could include determining a distance to the object in the external environment based on a time when the first light pulse is emitted by the light-emitter device, a time when the reflected light pulse is detected by the photodetector, and a time when the second light pulse is detected by the photodetector.

FIG. 9 illustrates a method 900, according to an example embodiment. It will be understood that the method 900 may include fewer or more steps or blocks than those expressly illustrated or otherwise disclosed herein. Furthermore, respective steps or blocks of method 900 may be performed in any order and each step or block may be performed one or more times. In some embodiments, some or all of the blocks or steps of method 900 may be carried out by controller 150 and/or other elements of system 100, 200, 220, or 230 as illustrated and described in relation to FIGS. 1, 2A, 2B, and 2C, respectively.

Method 900 may be for enhancing a dynamic range of a light detection and ranging (lidar) system. Block 902 could include transmitting emission light (e.g., transmit light 14) from the lidar (e.g., system 100) into an environment of the lidar (e.g., environment 10).

Block 904 may include receiving return light (e.g., return light 16). The return light is at least a portion of the emission light reflected from an object (e.g., object 12) in the environment of the lidar.

Block 906 includes transmitting the return light through a plurality of apertures (e.g., apertures 178) into a plurality of optical redirectors (e.g., optical redirectors 129).

The arrangements shown in the Figures should not be viewed as limiting. It should be understood that other embodiments may include more or less of each element shown in a given Figure. Further, some of the illustrated elements may be combined or omitted. Yet further, an illustrative embodiment may include elements that are not illustrated in the Figures.

A step or block that represents a processing of information can correspond to circuitry that can be configured to perform the specific logical functions of a herein-described method or technique. Alternatively or additionally, a step or block that represents a processing of information can correspond to a module, a segment, or a portion of program code (including related data). The program code can include one or more instructions executable by a processor for implementing specific logical functions or actions in the method or technique. The program code and/or related data can be stored on any type of computer readable medium such as a storage device including a disk, hard drive, or other storage medium.

The computer readable medium can also include non-transitory computer readable media such as computer-readable media that store data for short periods of time like register memory, processor cache, and random access memory (RAM). The computer readable media can also include non-transitory computer readable media that store program code and/or data for longer periods of time. Thus, the computer readable media may include secondary or persistent long term storage, like read only memory (ROM), optical or magnetic disks, compact-disc read only memory (CD-ROM), for example. The computer readable media can also be any other volatile or non-volatile storage systems. A computer readable medium can be considered a computer readable storage medium, for example, or a tangible storage device.

While various examples and embodiments have been disclosed, other examples and embodiments will be apparent to those skilled in the art. The various disclosed examples and embodiments are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims.

What is claimed is:

1. A light detection and ranging (lidar) system comprising:

a transmitter comprising:

at least one light-emitter device configured to transmit emission light into an environment of the lidar system; and

a receiver configured to detect return light from the environment, the receiver comprising:

a first aperture;

a second aperture;

a first primary photodetector;

a first secondary photodetector;

a second primary photodetector;

a second secondary photodetector, wherein the first primary photodetector and the second primary photodetector are aligned along a first axis relative to one another, and wherein the first secondary photodetector and the second secondary photodetector are on opposite sides of the first axis relative to one another;

a first optical redirector configured to:

receive return light from the first aperture;

separate the return light received from the first aperture into portions; and

illuminate the first primary photodetector and the first secondary photodetector with the portions of the separated return light received from the first aperture; and

a second optical redirector configured to:

receive return light from the second aperture;

separate the return light received from the second aperture into portions; and

illuminate the second primary photodetector and the second secondary photodetector with the portions of the separated return light received from the second aperture.

2. The lidar system of claim **1**,

wherein the first optical redirector is configured to optically couple the return light received from the first aperture to the first primary photodetector and the first secondary photodetector by total internal reflection, and

wherein the second optical redirector is configured to optically couple the return light received from the second aperture to the second primary photodetector and the second secondary photodetector by total internal reflection.

3. The lidar system of claim **1**, wherein the first optical redirector and the second optical redirector are formed from an injection-moldable optical material.

4. The lidar system of claim **1**, wherein the first optical redirector and the second optical redirector are coupled together in an element pair that is shaped to slidably couple with another element pair of the receiver.

5. The lidar system of claim **1**, wherein the first aperture or the second aperture has a diameter between 150 microns and 300 microns.

6. The lidar system of claim **1**, wherein the first aperture and the second aperture comprise a set of openings formed in an aperture plate, and wherein the aperture plate has a thickness between 50 microns and 200 microns.

7. The lidar system of claim **1**, wherein the first aperture and the second aperture are spaced apart by between 200 microns and 800 microns.

8. The lidar system of claim **1**, wherein the first primary photodetector and the second primary photodetector are spaced apart by at least 1000 microns.

9. The lidar system of claim **1**,

wherein the first aperture and the second aperture are aligned along a second axis relative to one another, and

wherein the second axis is parallel to the first axis.

10. The lidar system of claim **1**,

wherein the first optical redirector is further configured to:

illuminate the first primary photodetector with a first photon flux; and

illuminate the first secondary photodetector with a second photon flux,

wherein the second optical redirector is further configured to:

illuminate the second primary photodetector with a third photon flux; and

illuminate the second secondary photodetector with a fourth photon flux, wherein the first photon flux is greater than the second photon flux, and wherein the third photon flux is greater than the fourth photon flux.

11. The lidar system of claim **1**, wherein the first primary photodetector, the first secondary photodetector, the second primary photodetector, or the second secondary photodetector comprises a solid-state single-photon-sensitive device.

12. A receiver comprising:

a first aperture;

a second aperture;

a first primary photodetector;

a first secondary photodetector;

a second primary photodetector;

a second secondary photodetector, wherein the first primary photodetector and the second primary photodetector are aligned along a first axis relative to one another, and wherein the first secondary photodetector and the second secondary photodetector are on opposite sides of the first axis relative to one another;

a first optical redirector configured to:

receive return light from the first aperture;

separate the return light received from the first aperture into portions; and illuminate the first primary photodetector and the first secondary photodetector with the portions of the separated return light received from the first aperture; and

a second optical redirector configured to:

receive return light from the second aperture;

separate the return light received from the second aperture into portions; and

illuminate the second primary photodetector and the second secondary photodetector with the portions of the separated return light received from the second aperture.

13. The receiver of claim **12**,

wherein the first optical redirector is configured to optically couple the return light received from the first aperture to the first primary photodetector and the first secondary photodetector by total internal reflection, and

wherein the second optical redirector is configured to optically couple the return light received from the second aperture to the second primary photodetector and the second secondary photodetector by total internal reflection.

14. The receiver of claim **12**, wherein the first optical redirector and the second optical redirector are formed from an injection-moldable optical material.

15. The receiver of claim **12**, wherein the first optical redirector and the second optical redirector are coupled together in an element pair that is shaped to slidably couple with another element pair of the receiver.

16. The receiver of claim **12**, wherein the first aperture or the second aperture has a diameter between 150 microns and 300 microns.

17. The receiver of claim **12**, wherein the first aperture and the second aperture comprise a set of openings formed in an aperture plate, and wherein the aperture plate has a thickness between 50 microns and 200 microns.

18. The receiver of claim **12**, wherein the first primary photodetector, the first secondary photodetector, the second primary photodetector, or the second secondary photodetector comprises a solid-state single-photon-sensitive device.

19. A vehicle comprising:

a light detection and ranging (lidar) system comprising:

a transmitter comprising:

at least one light-emitter device configured to transmit emission light into an environment of the vehicle; and

a receiver configured to detect return light from the environment, the receiver comprising:

a first aperture;

a second aperture;

a first primary photodetector;

a first secondary photodetector;

a second primary photodetector;

a second secondary photodetector, wherein the first primary photodetector and the second primary photodetector are aligned along a first axis relative to one another, and wherein the first secondary photodetector and the second secondary photodetector are on opposite sides of the first axis relative to one another;

a first optical redirector configured to:

receive return light from the first aperture;

separate the return light received from the first aperture into portions; and

illuminate the first primary photodetector and the first secondary photodetector with the portions of the separated return light received from the first aperture; and

a second optical redirector configured to:

receive return light from the second aperture;

separate the return light received from the second aperture into portions; and

illuminate the second primary photodetector and the second secondary photodetector with the portions of the separated return light received from the second aperture.

20. A method for enhancing a dynamic range of a light detection and ranging (lidar) system, the method comprising:

transmitting emission light from the lidar system into an environment of the lidar system;

receiving return light at a first aperture of the lidar system and a second aperture of the lidar system, wherein the return light is at least a portion of the emission light reflected from an object in the environment of the lidar system;

receiving, by a first optical redirector of the lidar system from the first aperture, the return light received by the first aperture;

receiving, by a second optical redirector of the lidar system from the second aperture, the return light received by the second aperture;

separating, by the first optical redirector, the return light received from the first aperture into portions;

separating, by the second optical redirector, the return light received from the second aperture into portions;

illuminating, by the first optical redirector, a first primary photodetector of the lidar system and a first secondary photodetector of the lidar system with the portions of the separated return light received from the first aperture; and

illuminating, by the second optical redirector, a second primary photodetector of the lidar system and a second secondary photodetector of the lidar system with the portions of the separated return light received from the second aperture, wherein the first primary photodetector and the second primary photodetector are aligned along a first axis relative to one another, and wherein the first secondary photodetector and the second secondary photodetector are on opposite sides of the first axis relative to one another transmitting the return light through a plurality of apertures into a plurality of optical redirectors.

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