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Pennecot et al.

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(54) **METHODS AND SYSTEMS FOR LIDAR OPTICS ALIGNMENT**

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G01S 17/06 (2006.01)
G01S 17/42 (2006.01)
G01S 7/481 (2006.01)
G02B 27/62 (2006.01)

(52) **U.S. Cl.**

CPC **G01S 7/4972** (2013.01); **G01S 7/4815** (2013.01); **G01S 7/4817** (2013.01); **G01S 7/51** (2013.01); **G01S 17/06** (2013.01); **G01S 17/42** (2013.01); **G02B 27/62** (2013.01)

(58) **Field of Classification Search**

CPC G01C 1/04; G01C 3/08; G01C 15/00
See application file for complete search history.

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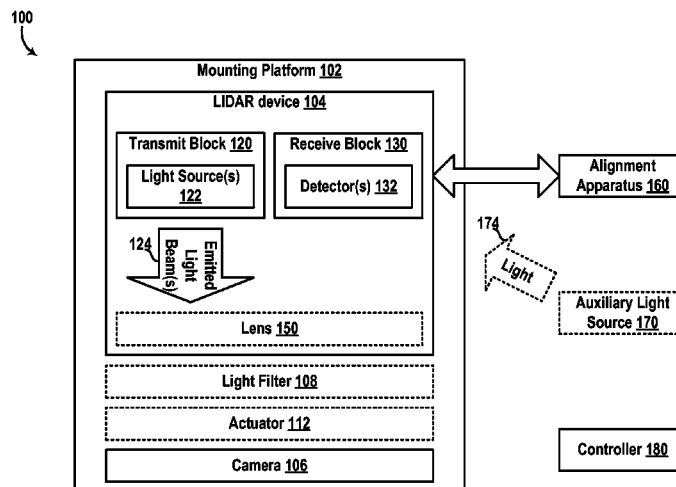
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(57) **ABSTRACT**

A method is provided that involves mounting a transmit block and a receive block in a LIDAR device to provide a relative position between the transmit block and the receive block. The method also involves locating a camera at a given position at which the camera can image light beams emitted by the transmit block and can image the receive block. The method also involves obtaining, using the camera, a first image indicative of light source positions of one or more light sources in the transmit block and a second image indicative of detector positions of one or more detectors in the receive block. The method also involves determining at least one offset based on the first image and the second image. The method also involves adjusting the relative position between the transmit block and the receive block based at least in part on the at least one offset.

20 Claims, 23 Drawing Sheets



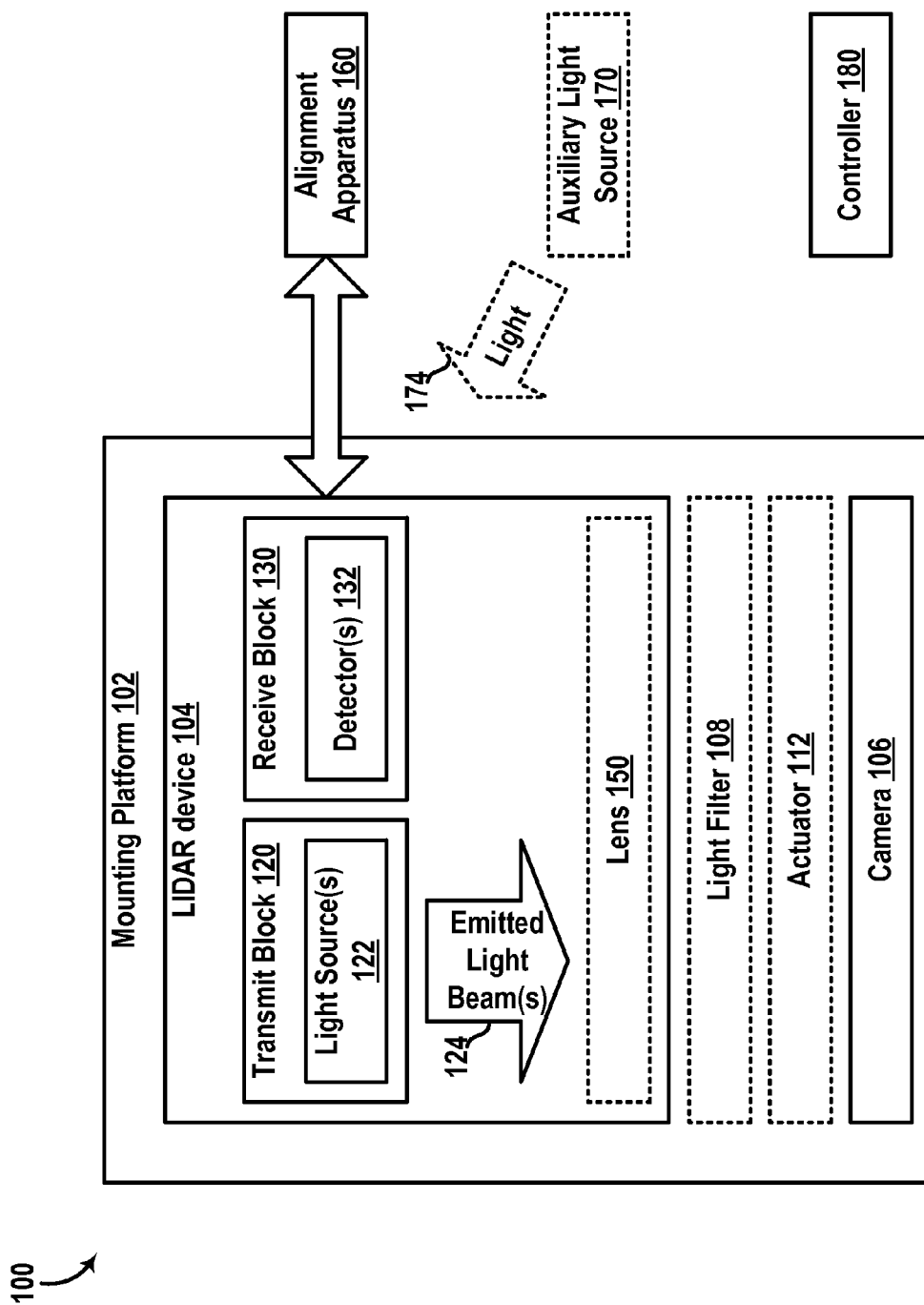


FIG. 1

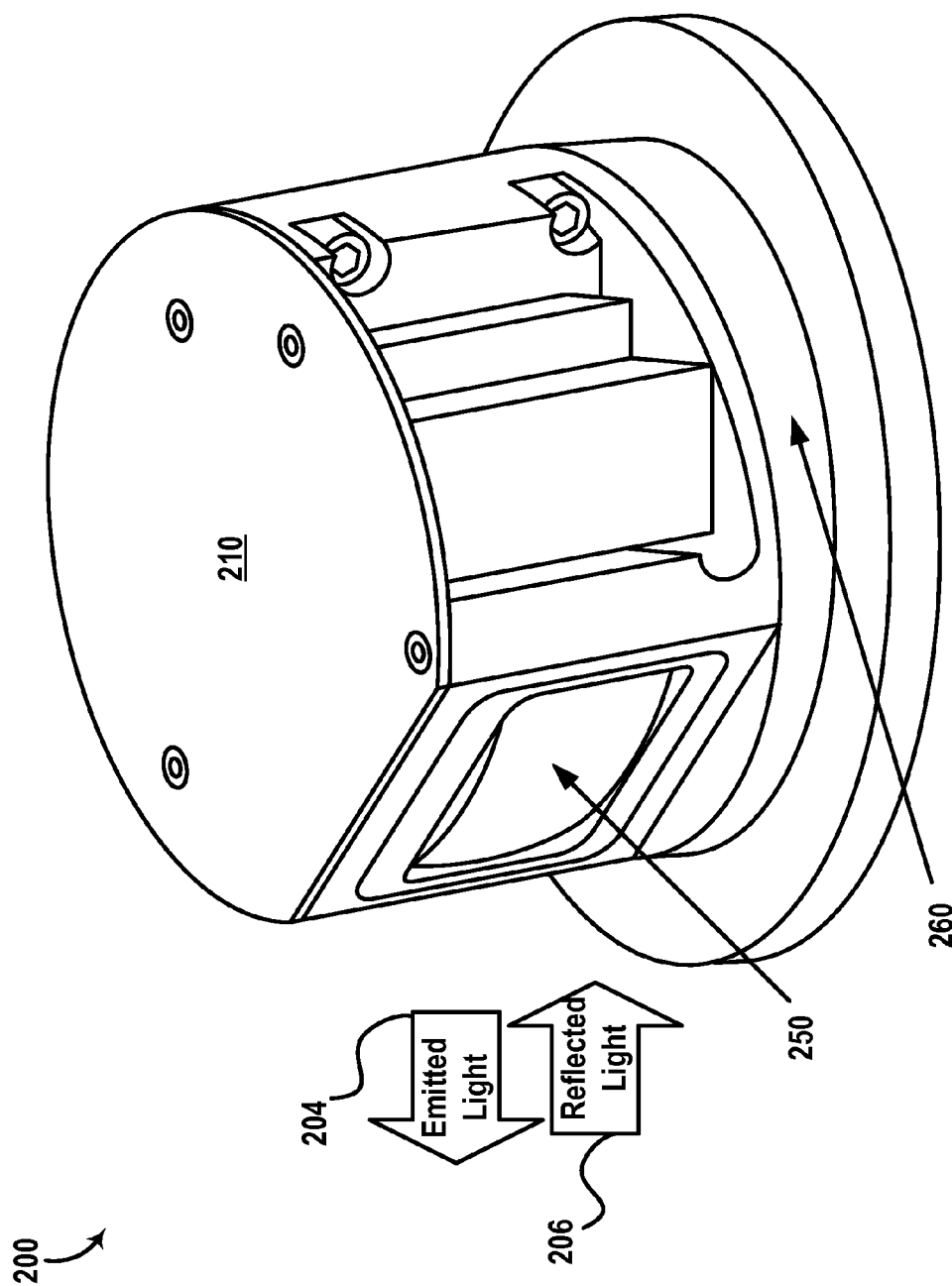


FIG. 2A

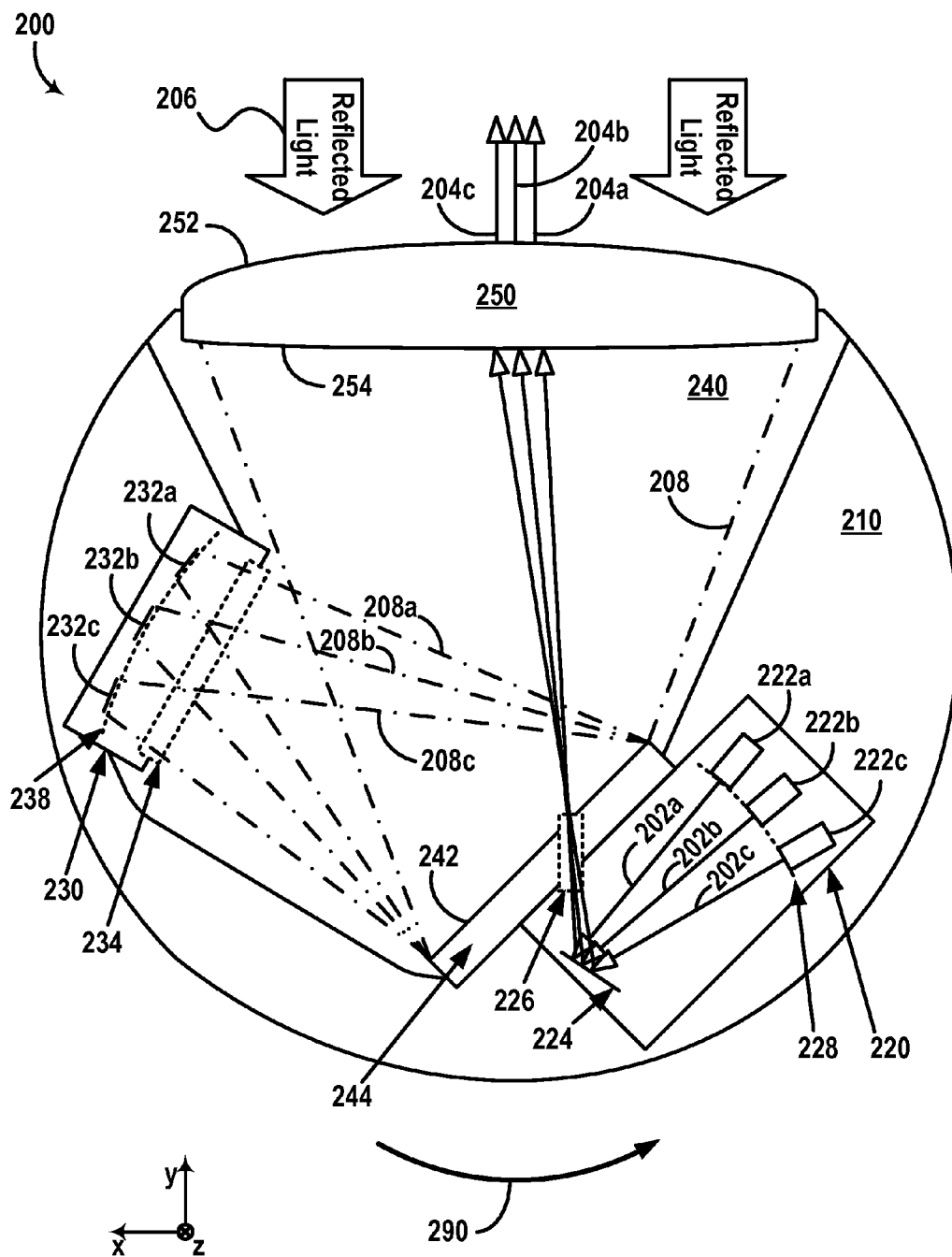


FIG. 2B

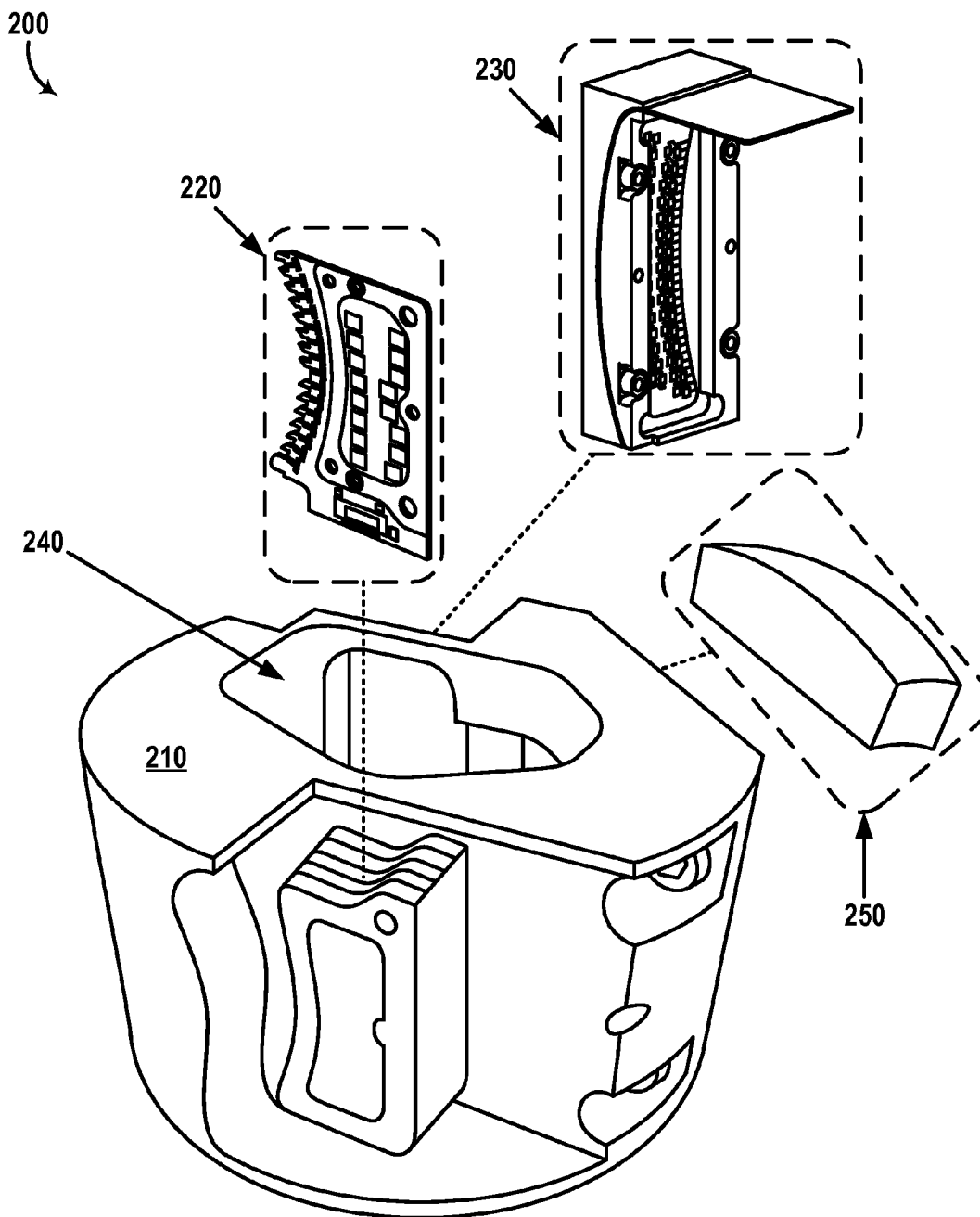


FIG. 2C

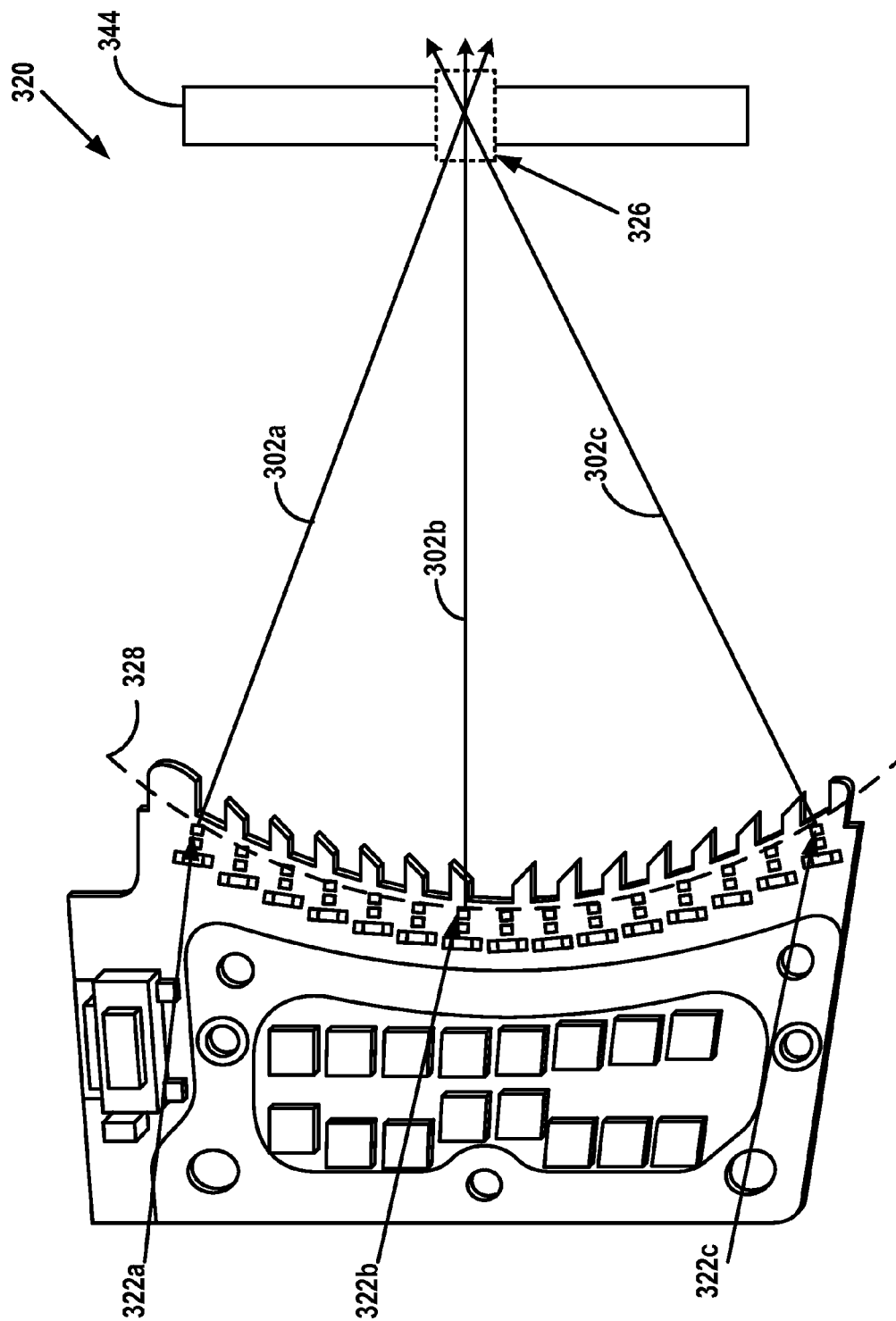


FIG. 3

FIG. 4A

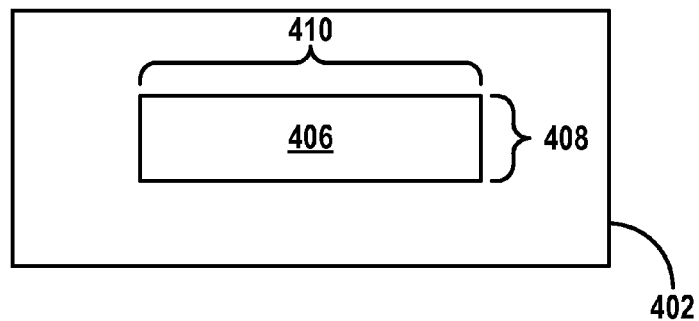


FIG. 4B

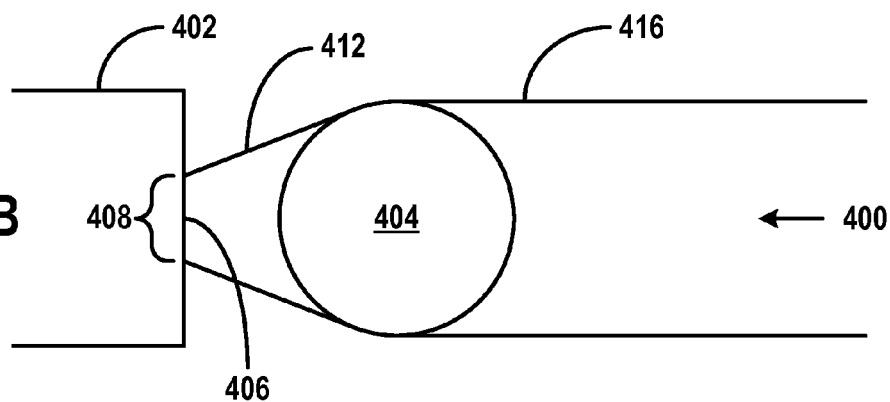
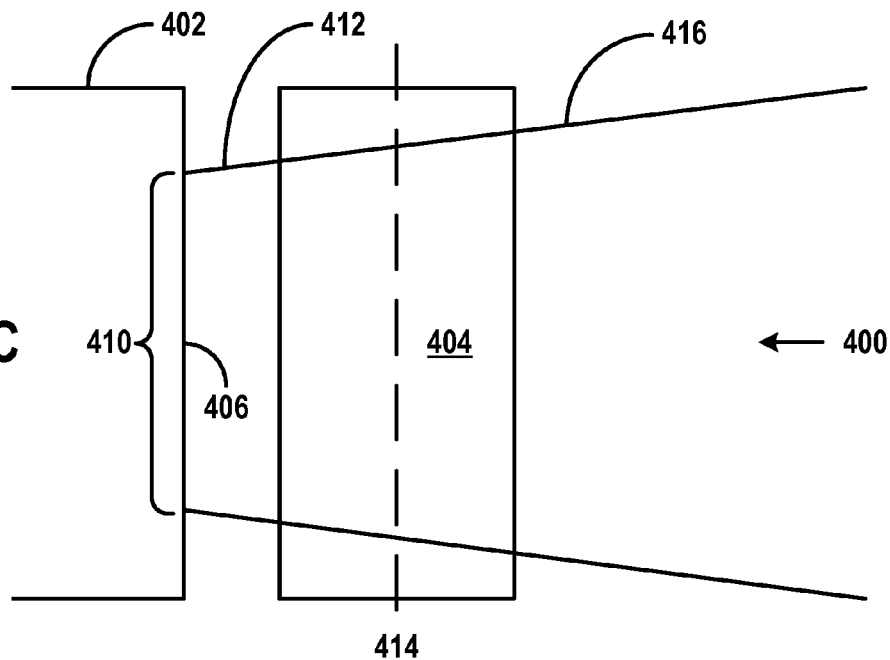


FIG. 4C



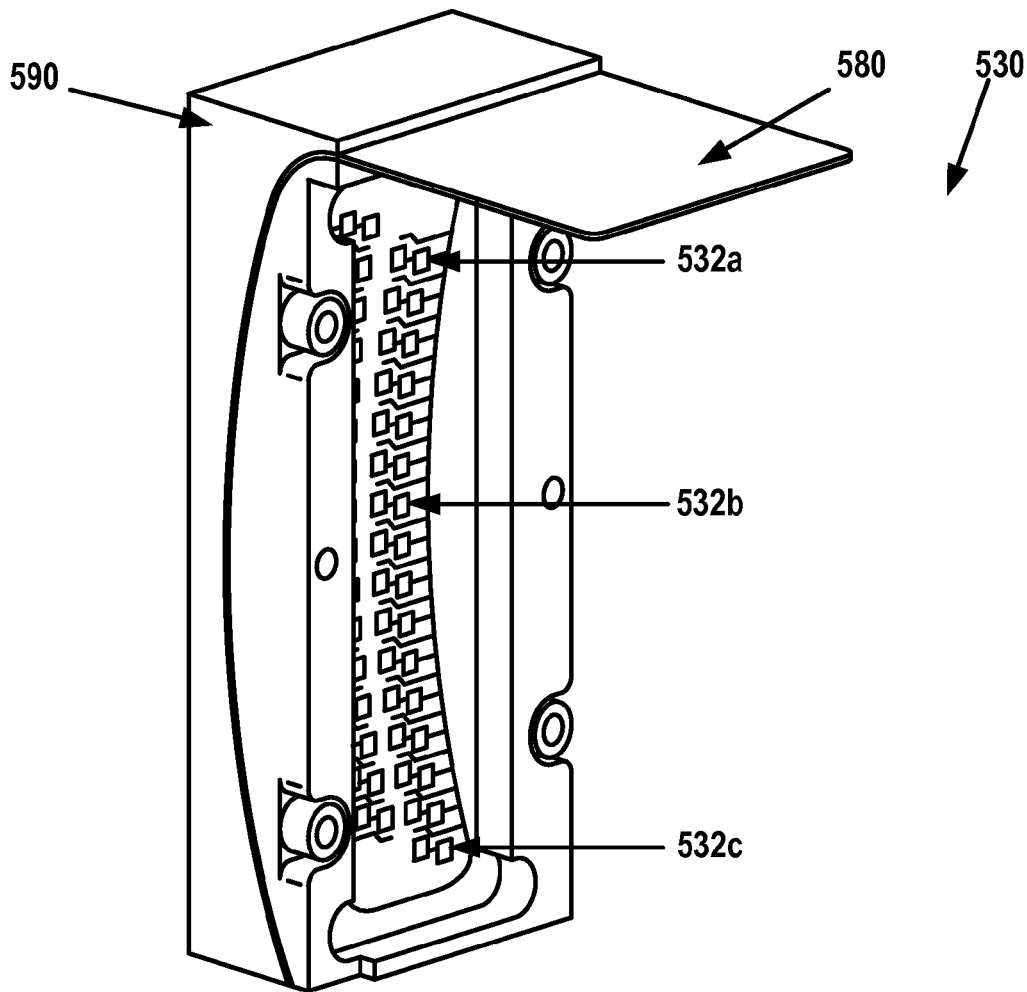


FIG. 5A

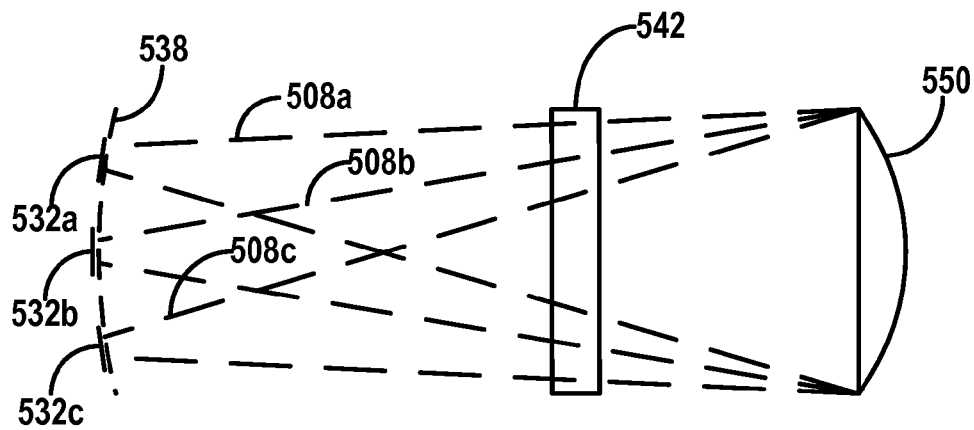


FIG. 5B

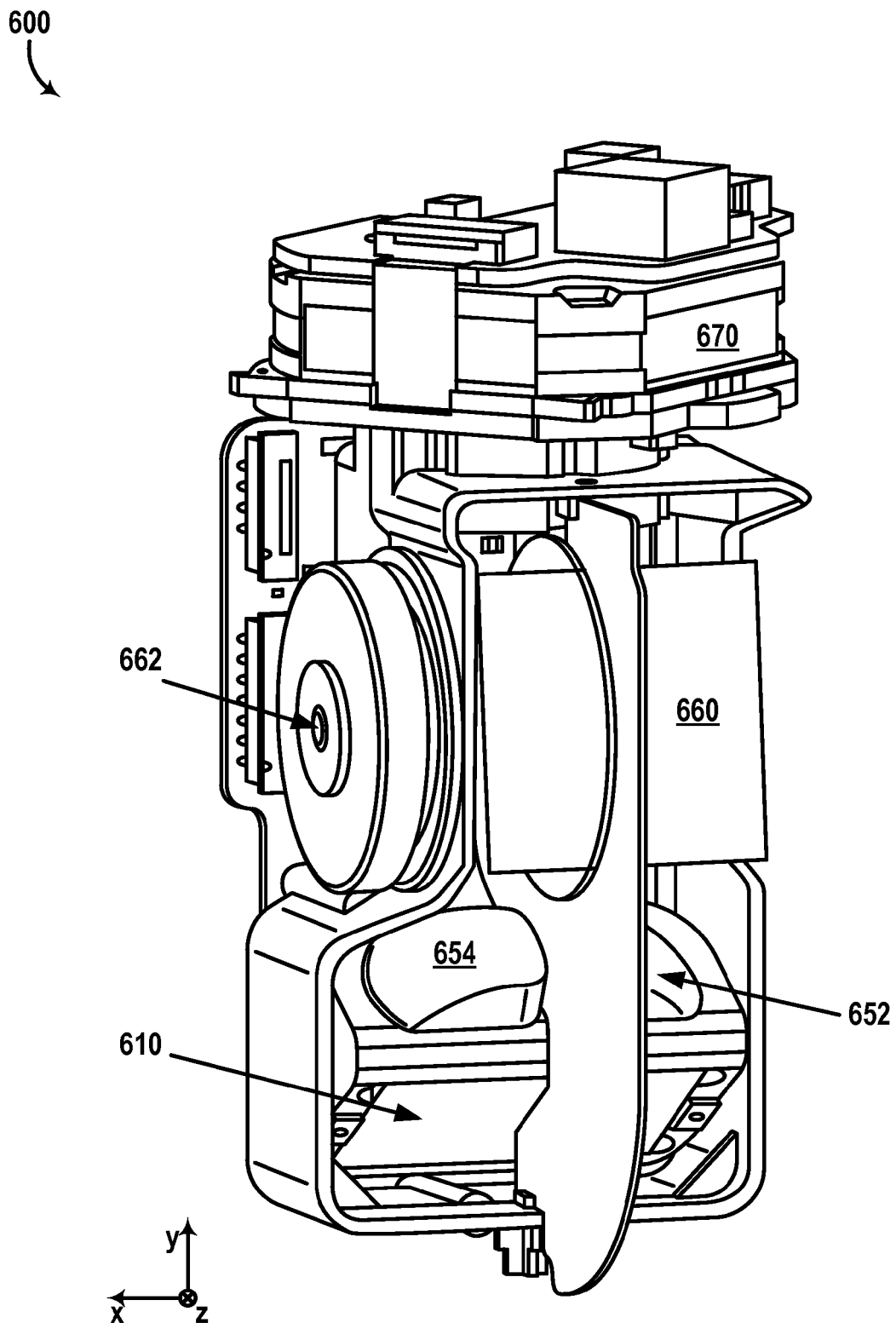


FIG. 6A

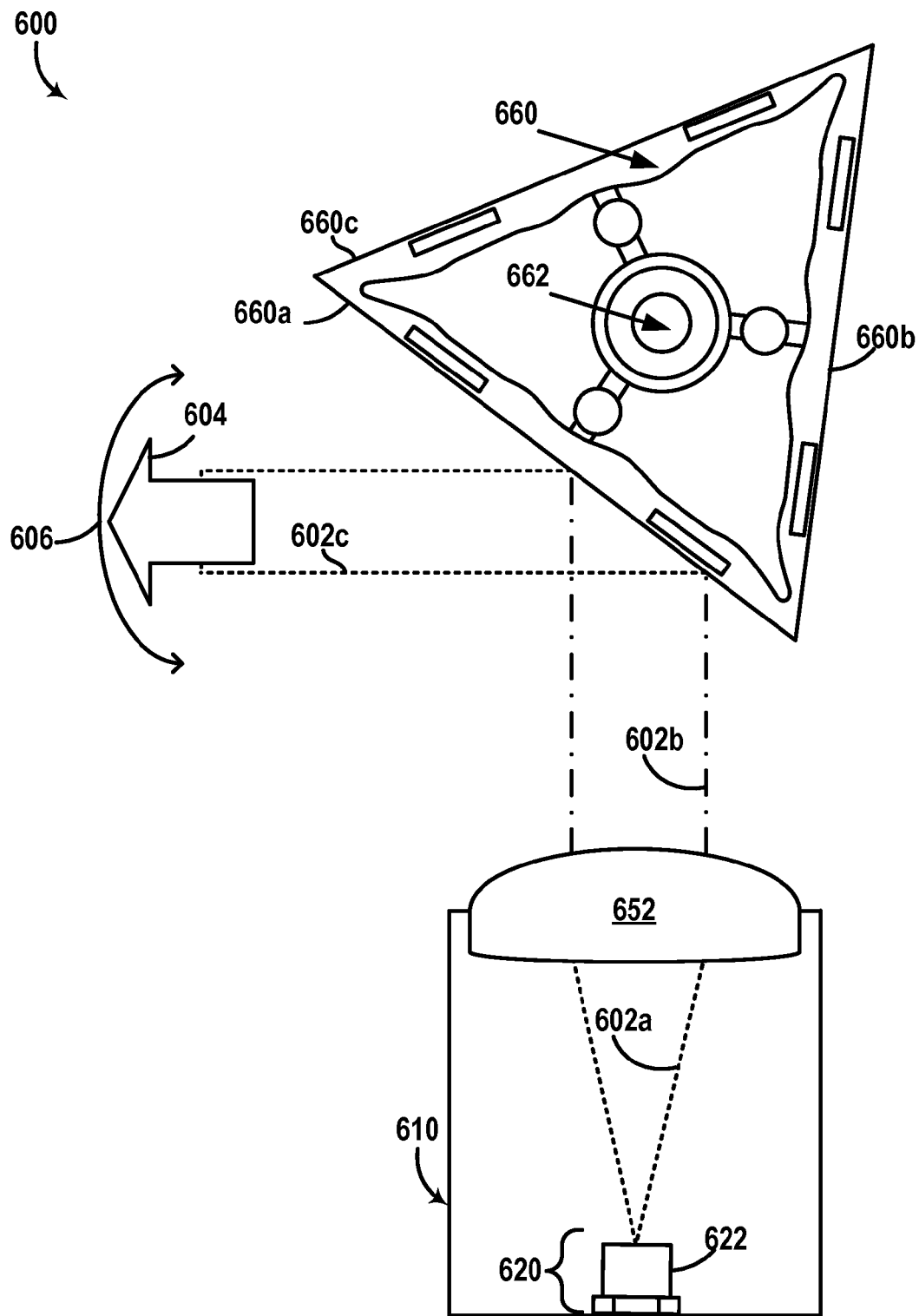


FIG. 6B

610
↘

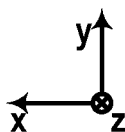
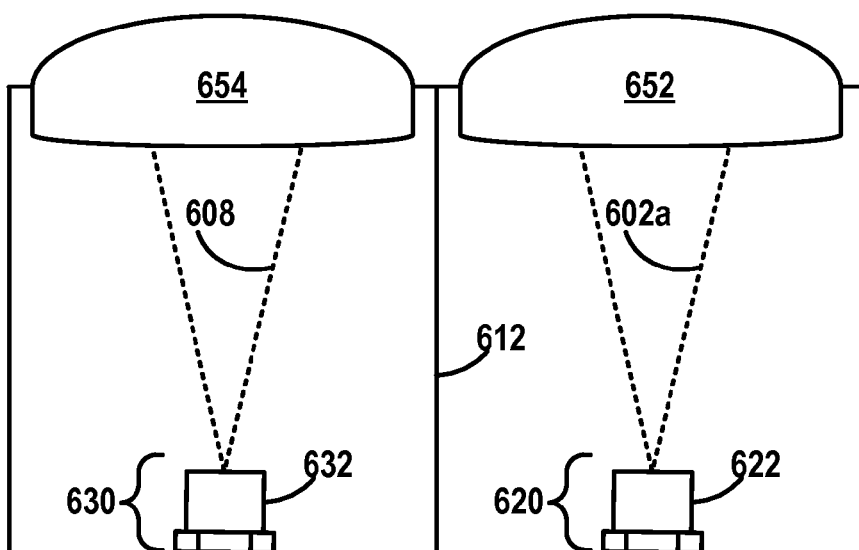


FIG. 6C

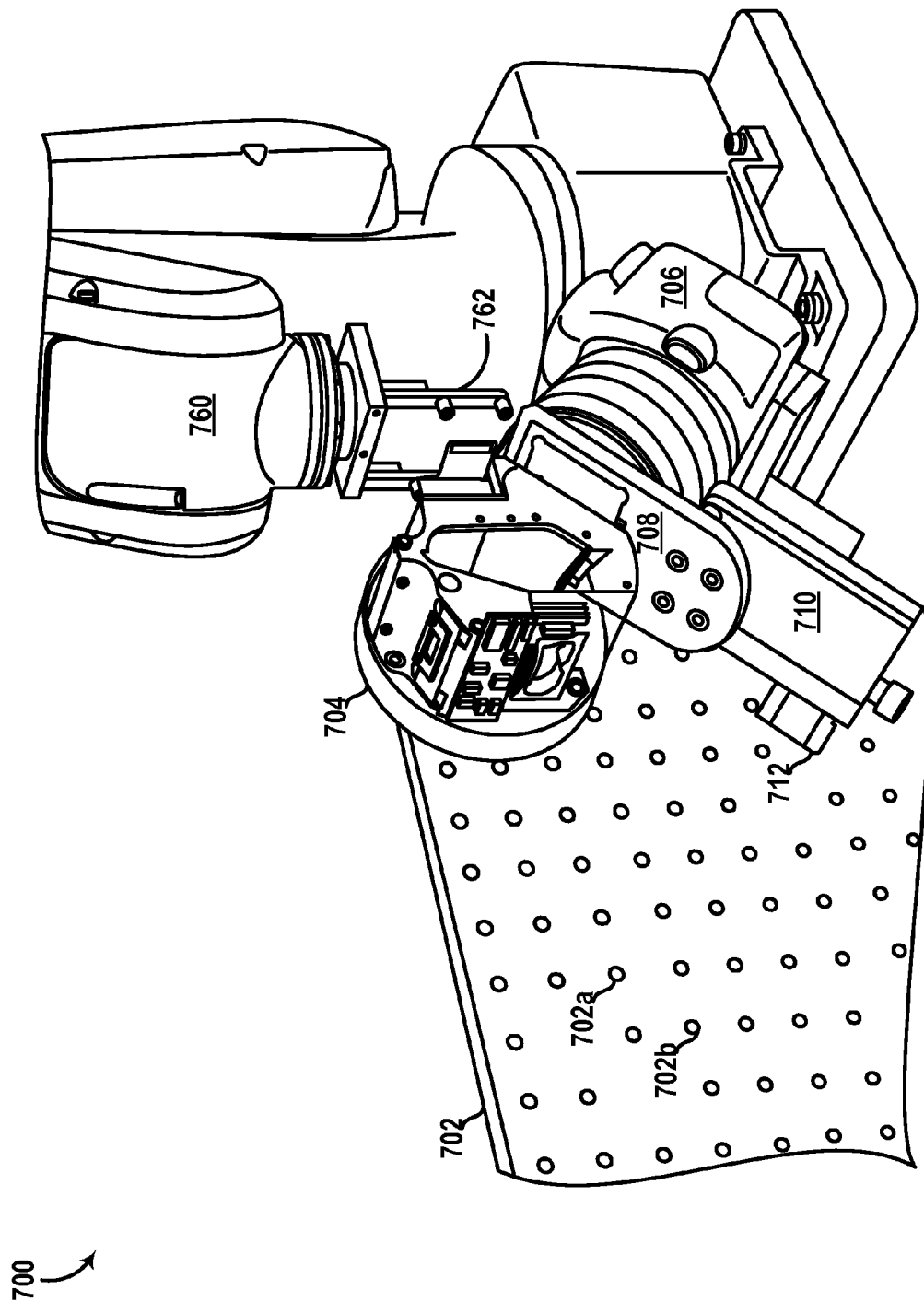


FIG. 7A

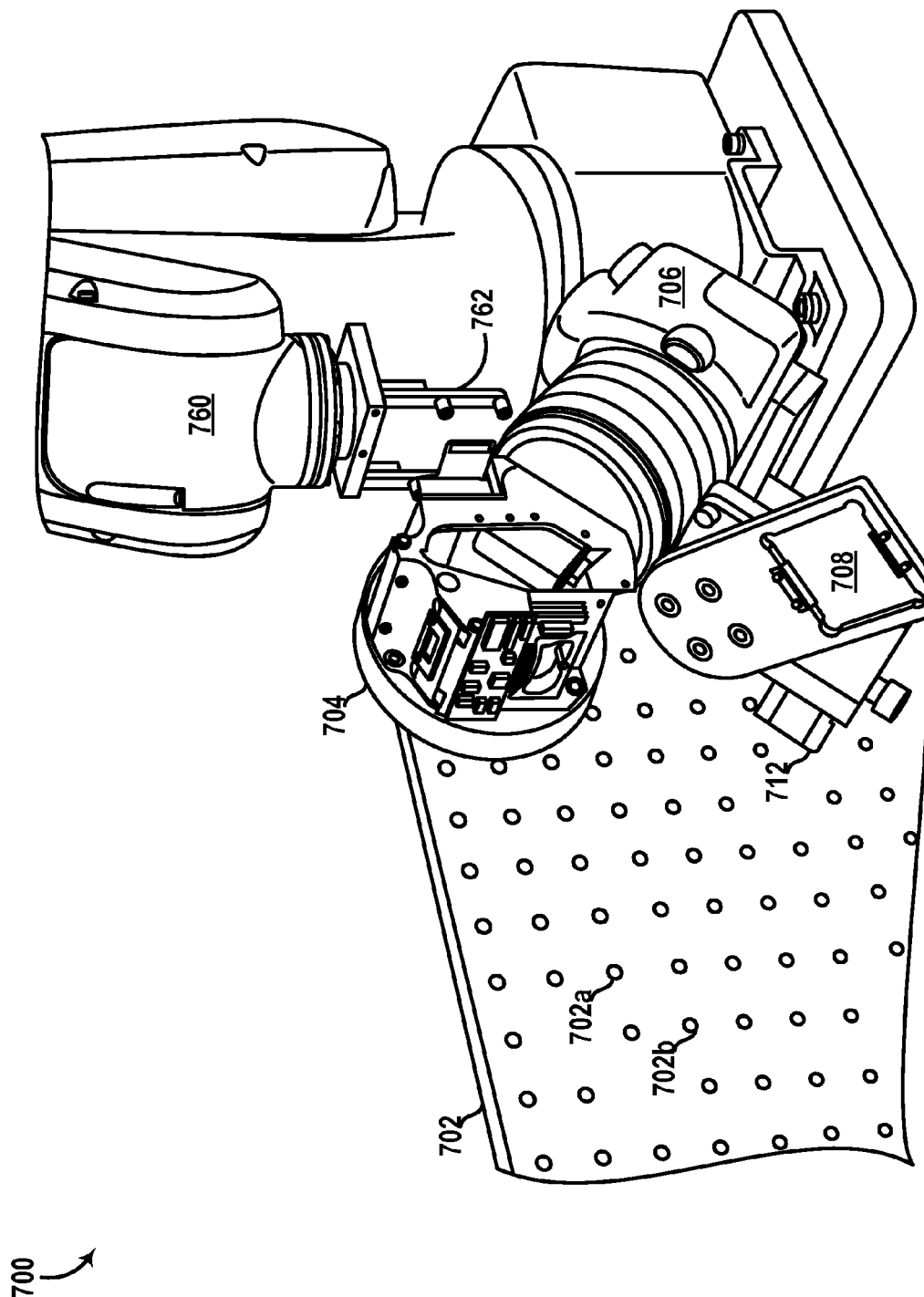


FIG. 7B

700
↘

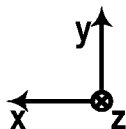
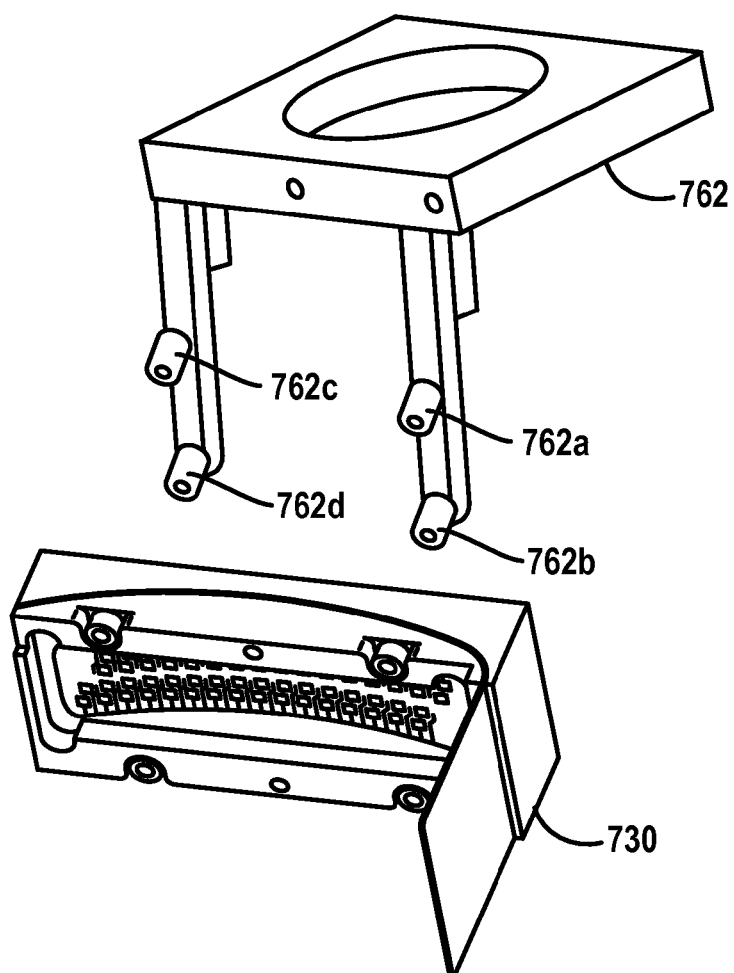


FIG. 7C

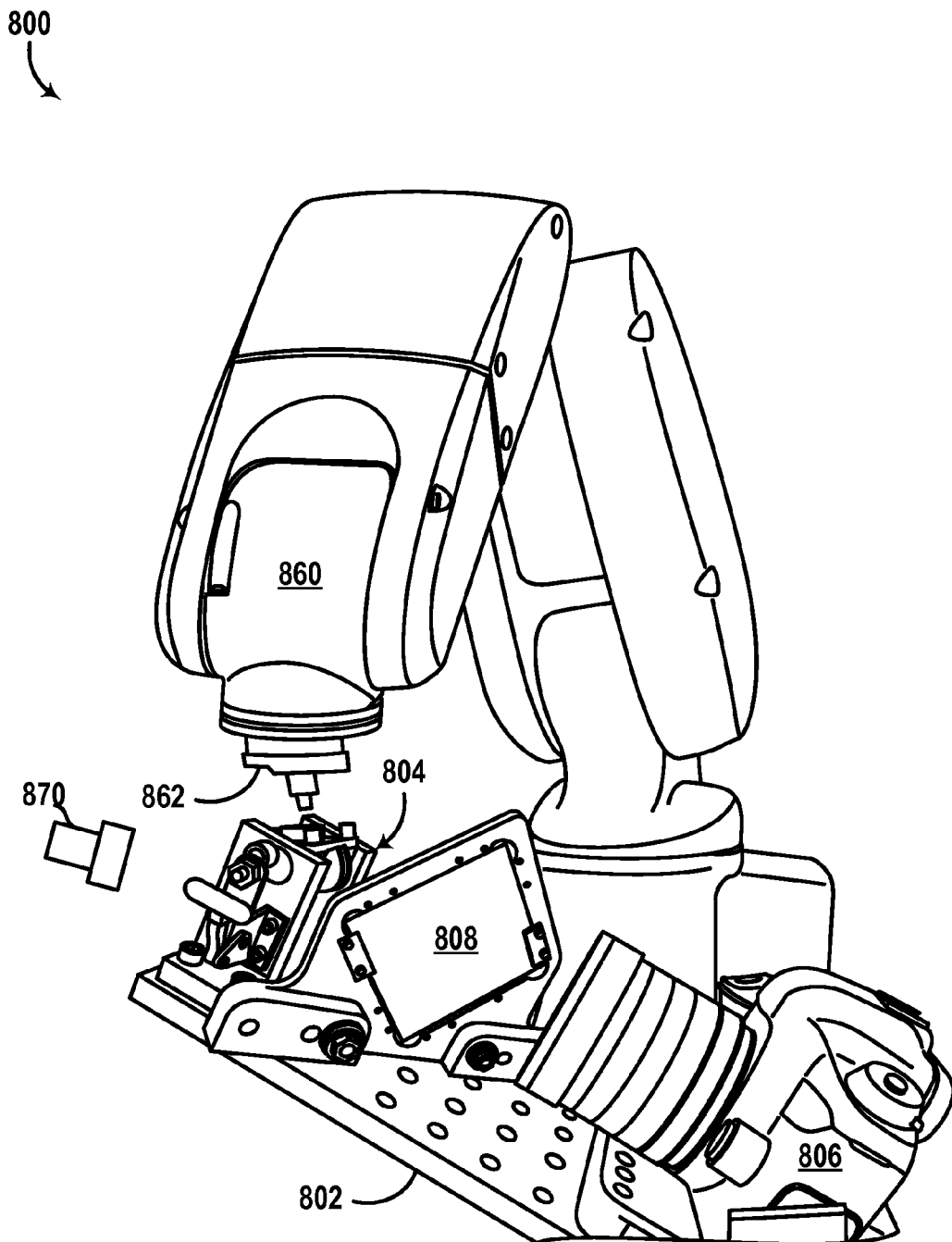
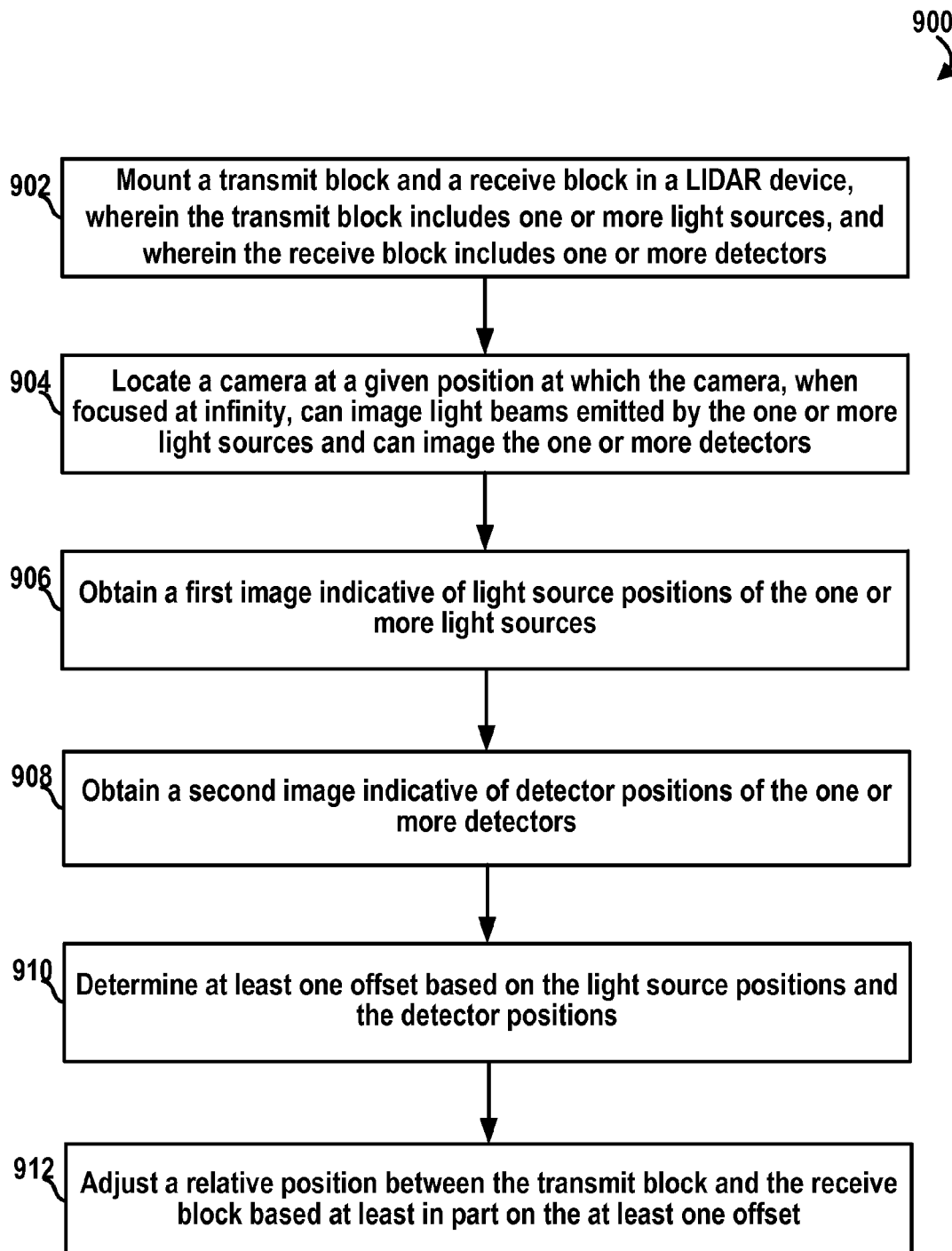


FIG. 8

**FIG. 9**

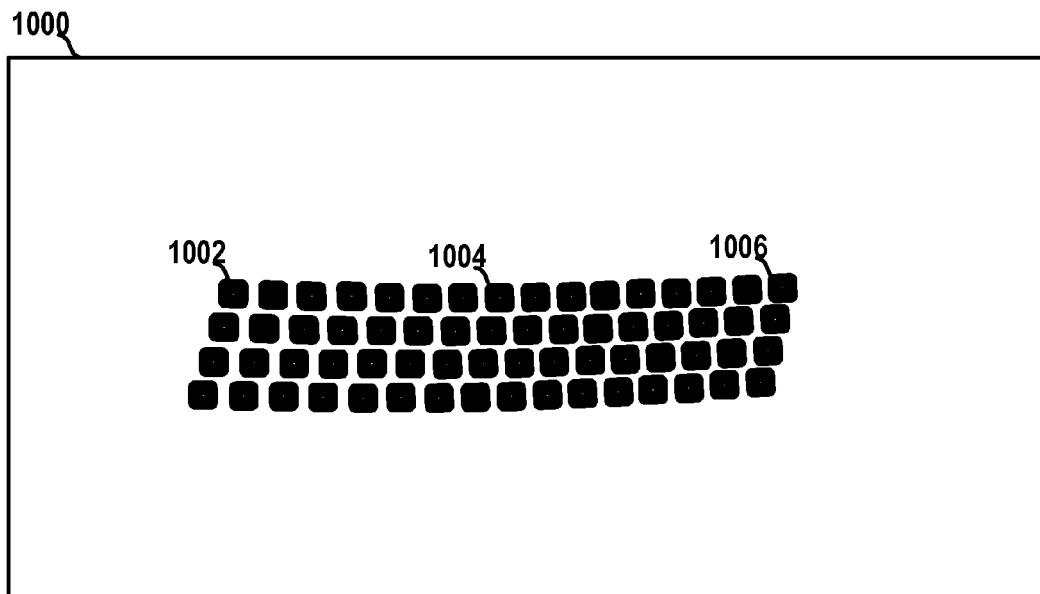


FIG. 10

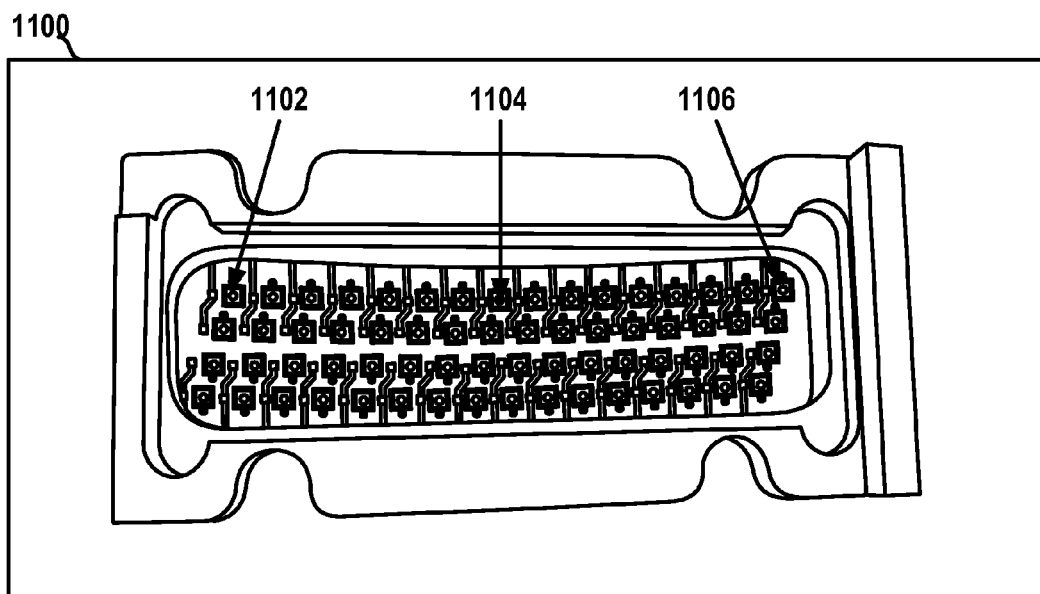


FIG. 11

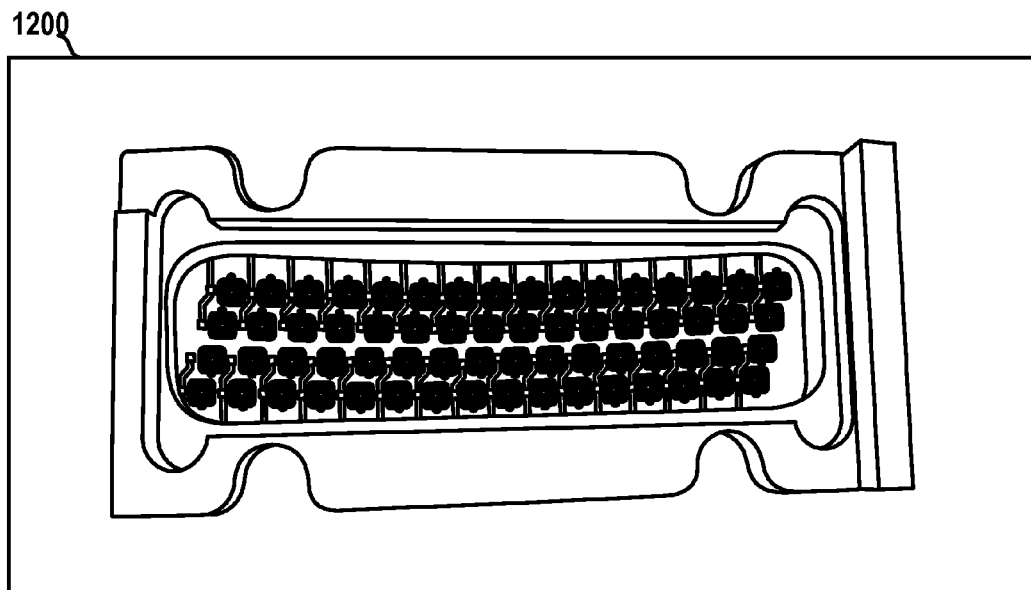


FIG. 12

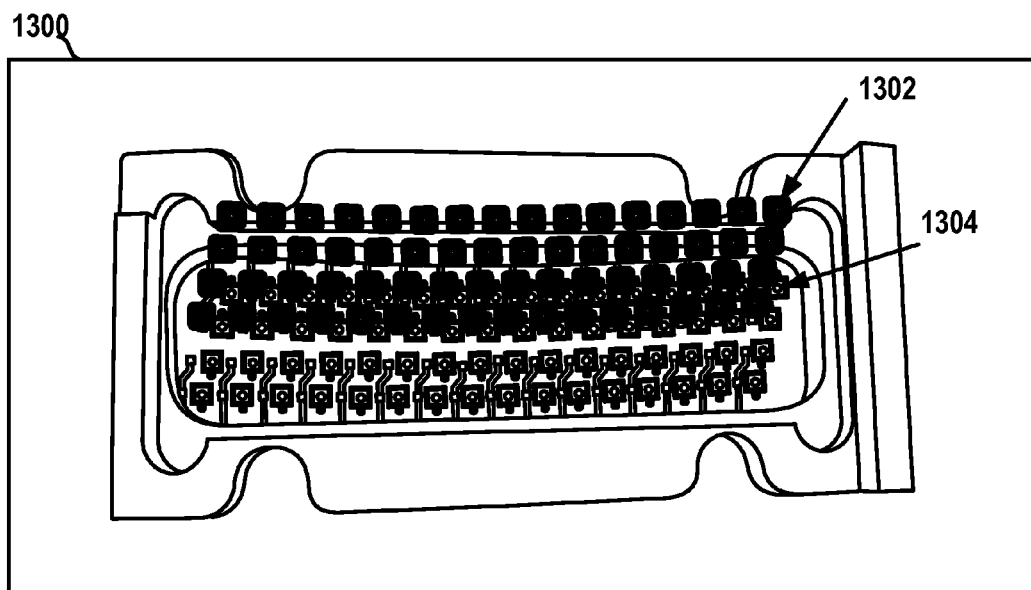


FIG. 13

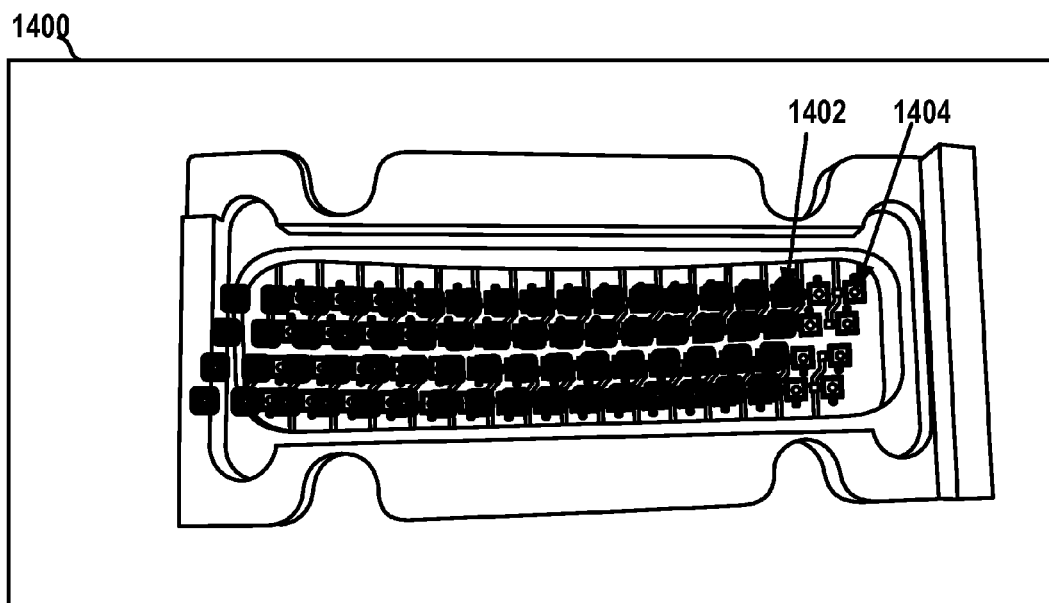


FIG. 14

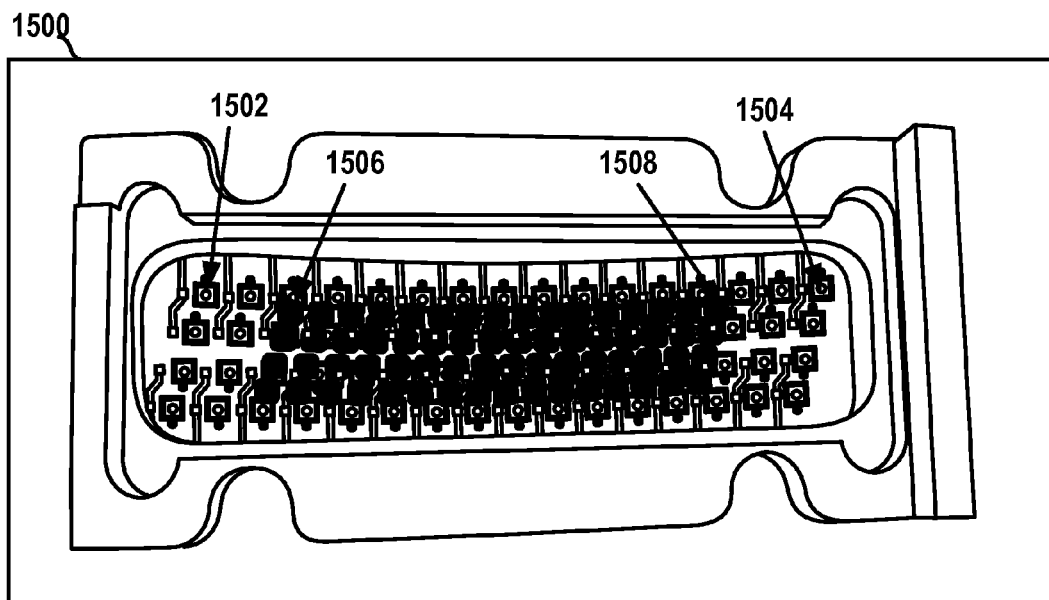


FIG. 15

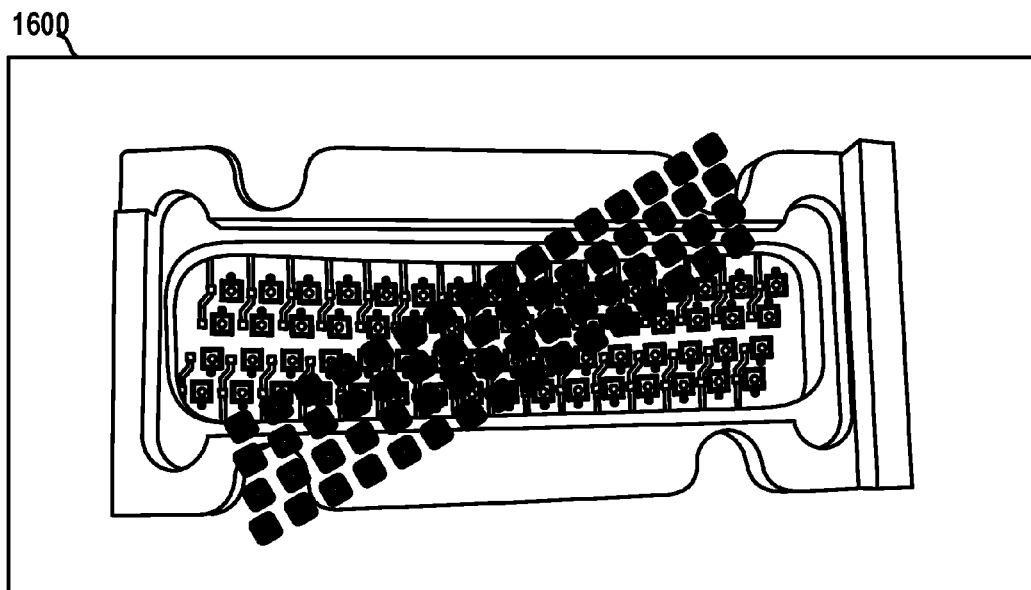


FIG. 16

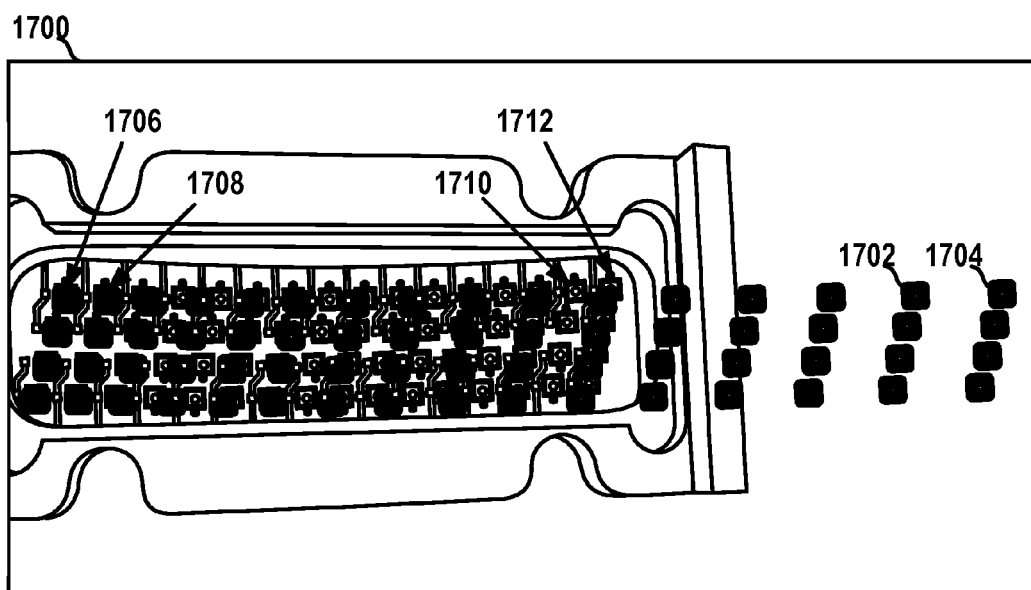


FIG. 17

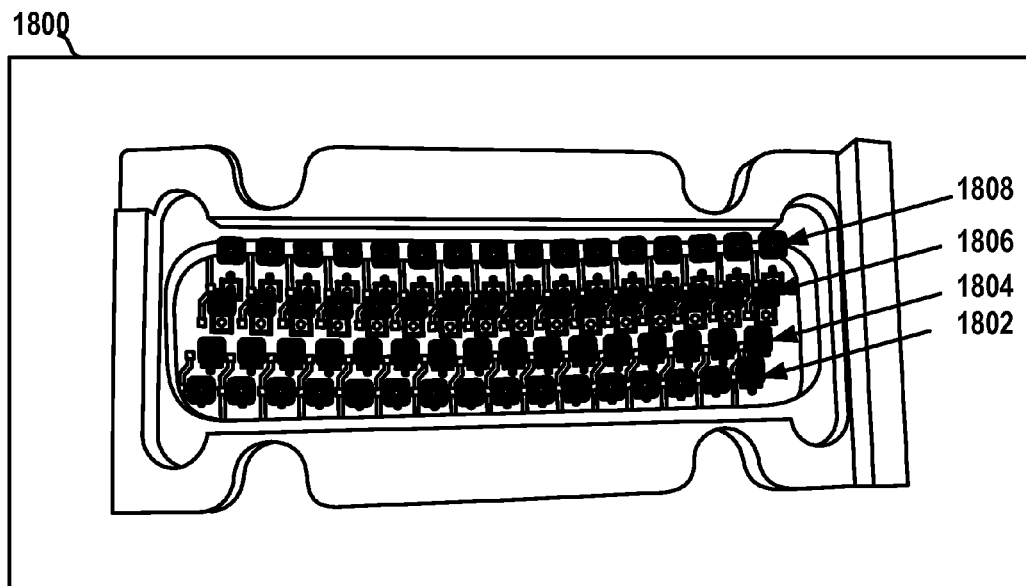


FIG. 18

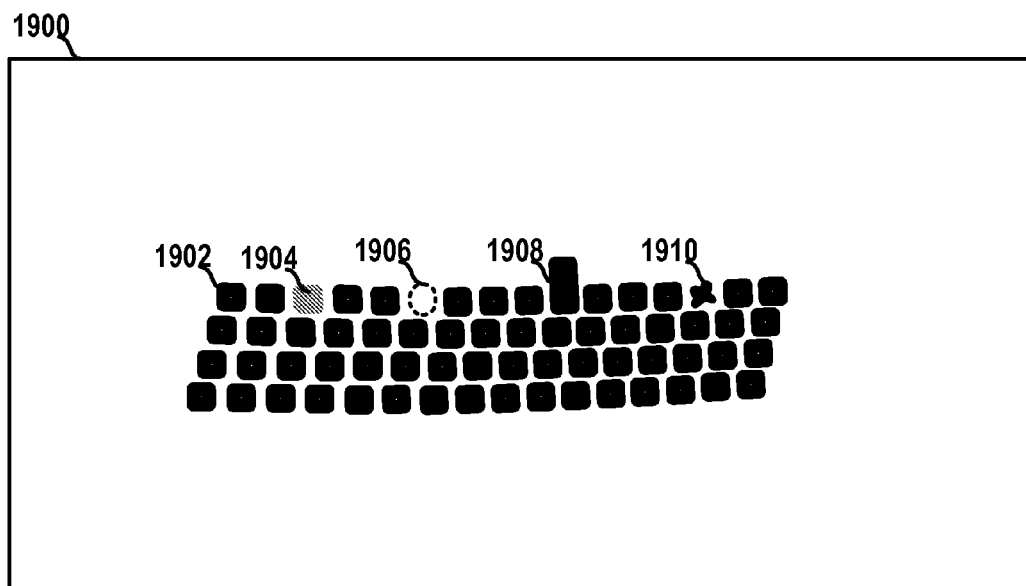
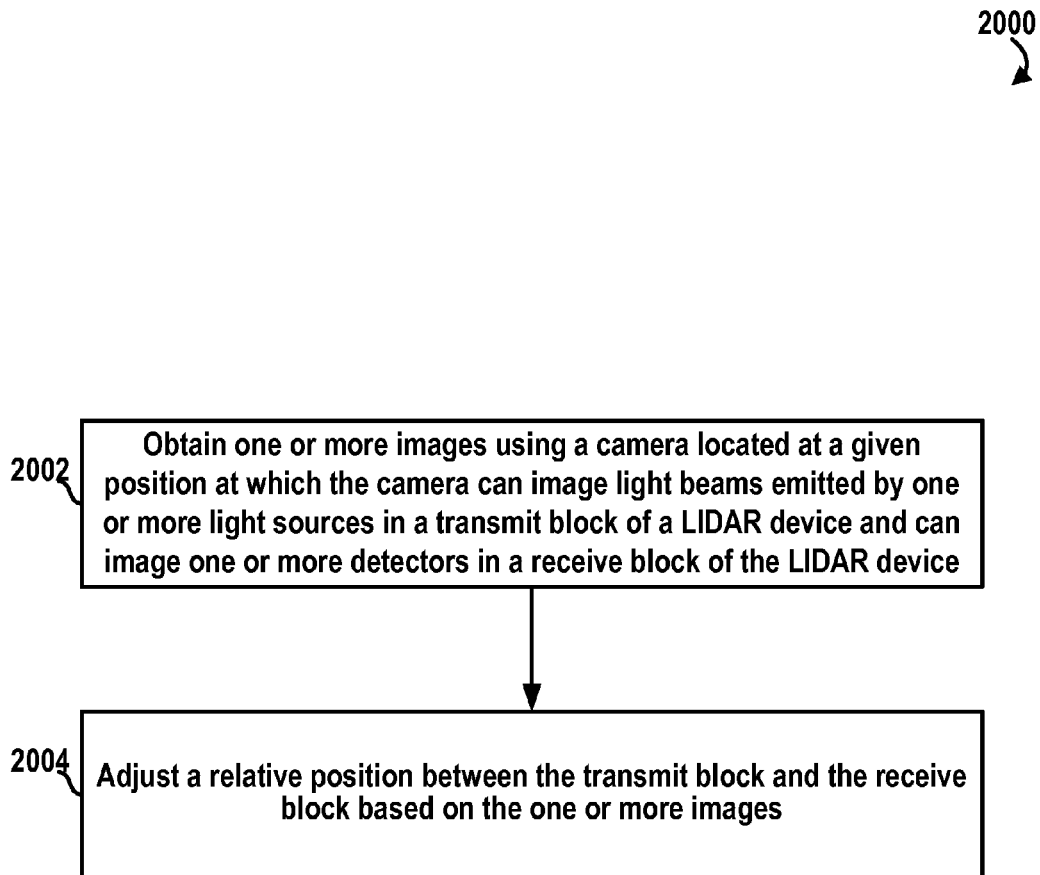


FIG. 19

**FIG. 20**

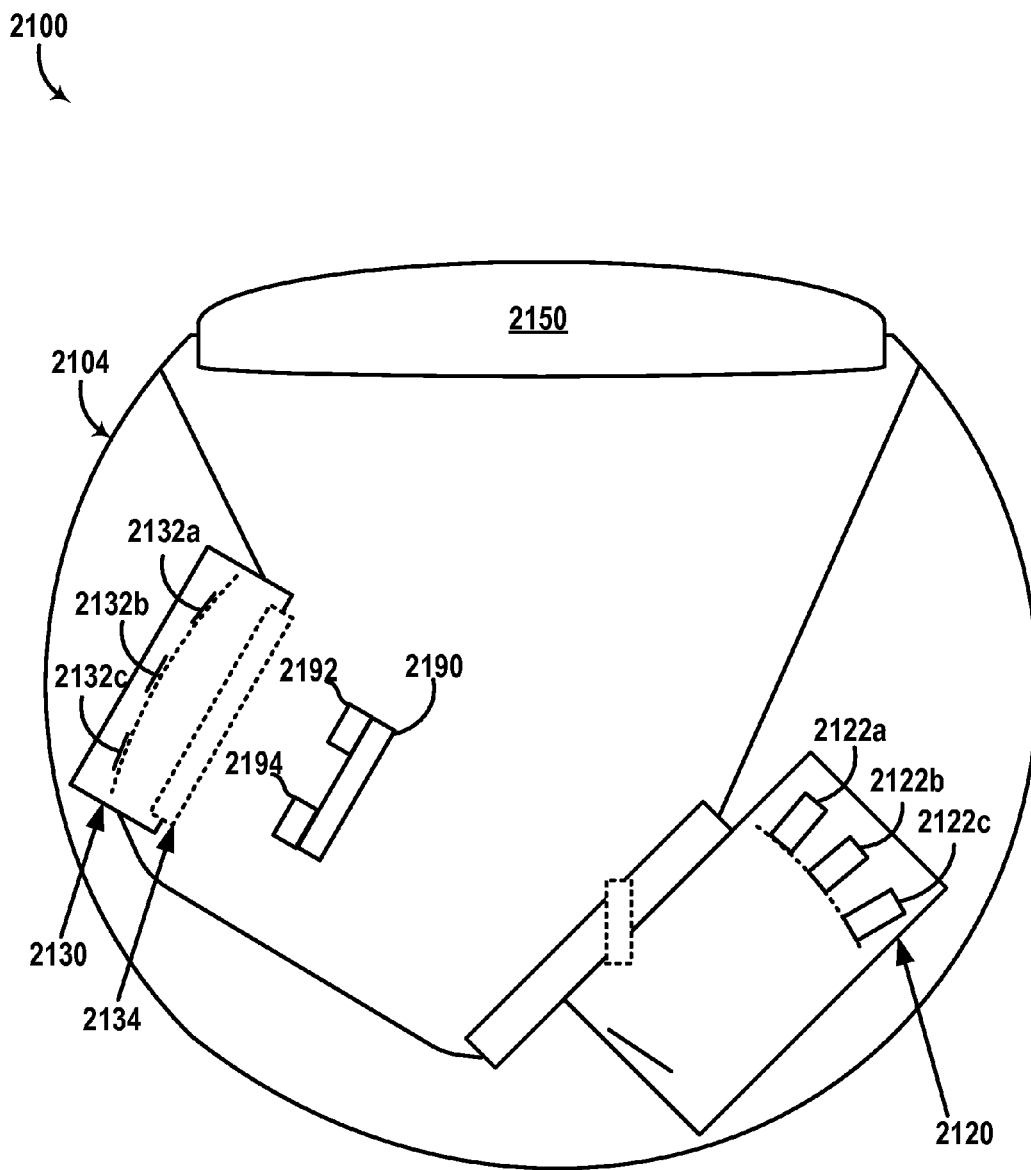


FIG. 21

2206

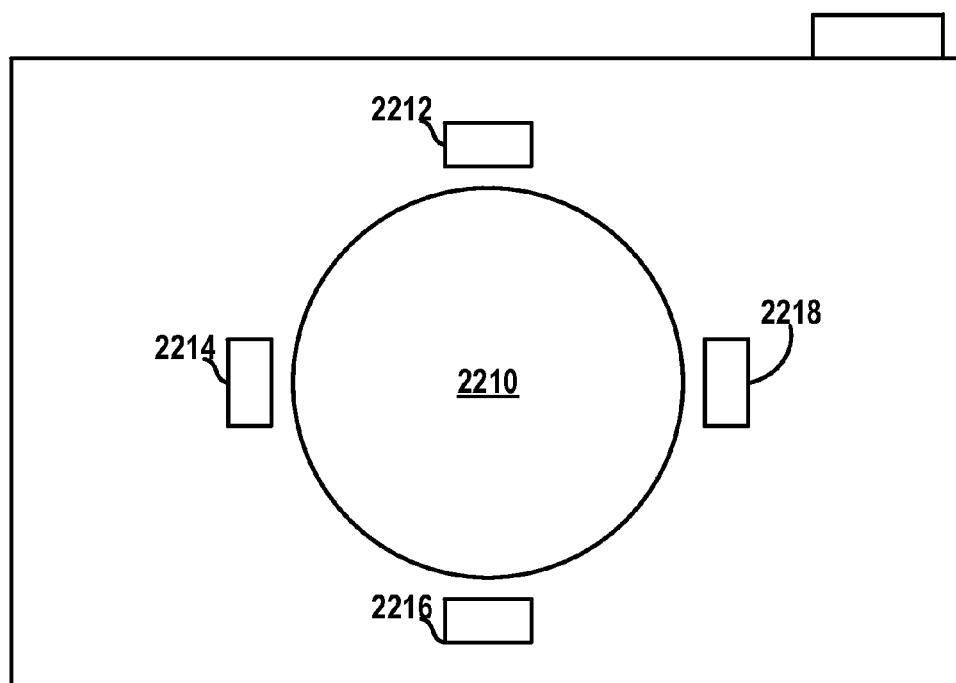


FIG. 22

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METHODS AND SYSTEMS FOR LIDAR OPTICS ALIGNMENT

BACKGROUND

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

A LIDAR can estimate distance to environmental features while scanning through a scene to assemble a “point cloud” indicative of reflective surfaces in the environment. Individual points in the point cloud can be determined by transmitting a laser pulse and detecting a returning pulse, if any, reflected from an object in the environment, and determining the distance to the object according to the time delay between the transmission of the transmitted pulse and the reception of the reflected pulse. A laser, or set of lasers, can be rapidly and repeatedly scanned across a scene to provide continuous real-time information on distances to reflective objects in the scene. Combining the measured distances and the orientation of the laser(s) while measuring each distance allows for associating a three-dimensional position with each returning pulse. In this way, a three-dimensional map of points indicative of locations of reflective features in the environment can be generated for the entire scanning zone.

SUMMARY

In one example, a method is provided that involves mounting a transmit block and a receive block in a light detection and ranging (LIDAR) device to provide a relative position between the transmit block and the receive block. The transmit block may include one or more light sources configured to emit light at a source wavelength. The receive block may include one or more detectors configured to detect light at the source wavelength. The method further involves locating a camera at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors. The method further involves obtaining a first image using the camera located at the given position and focused at infinity. The first image may be indicative of light source positions of the one or more light sources. The method further involves obtaining a second image using the camera located at the given position and focused at infinity. The second image may be indicative of detector positions of the one or more detectors in the receive block. The method further involves determining at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image. The method further involves adjusting the relative position between the transmit block and the receive block based at least in part on the at least one offset.

In another example, a system is provided that includes a mounting platform to mount a light detection and ranging (LIDAR) device that provides a relative position between a transmit block in the LIDAR device and a receive block in the LIDAR device. The transmit block may include one or more light sources configured to emit light at a source wavelength. The receive block may include one or more detectors configured to detect light at the source wavelength. The system also includes a camera located at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors. The system also includes an alignment apparatus configured to adjust the

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relative position between the transmit block and the receive block. The system also includes a controller configured to obtain a first image from the camera located at the given position and focused at infinity. The first image may be indicative of light source positions of the one or more light sources. The controller is also configured to obtain a second image from the camera located at the given position and focused at infinity. The second image may be indicative of detector positions of the one or more detectors in the receive block. The controller is also configured to determine at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image. The controller is also configured to cause the alignment apparatus to adjust the relative position between the transmit block and the receive block based at least in part on the at least one offset.

In yet another example, a system is provided that includes a means for mounting a transmit block and a receive block in a light detection and ranging (LIDAR) device to provide a relative position between the transmit block and the receive block. The transmit block may include one or more light sources configured to emit light at a source wavelength. The receive block may include one or more detectors configured to detect light at the source wavelength. The system also comprises means for locating a camera at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors. The system also comprises means for obtaining a first image using the camera located at the given position and focused at infinity. The first image may be indicative of light source positions of the one or more light sources. The system also comprises means for obtaining a second image using the camera located at the given position and focused at infinity. The second image may be indicative of detector positions of the one or more detectors in the receive block. The system also comprises means for determining at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image. The system also comprises means for adjusting the relative position between the transmit block and the receive block based at least in part on the at least one offset.

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

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a block diagram of a system, according to an example embodiment.

FIG. 2A illustrates a LIDAR device, according to an example embodiment.

FIG. 2B is a cross-section view of the LIDAR device shown in FIG. 2A.

FIG. 2C is a perspective view of the LIDAR device shown in FIG. 2A with various components removed to illustrate an interior of the LIDAR device.

FIG. 3 illustrates a transmit block, according to an example embodiment.

FIG. 4A is a view of a light source, according to an example embodiment.

FIG. 4B is a view of the light source of FIG. 4A in combination with a cylindrical lens, according to an example embodiment.

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FIG. 4C is another view of the light source and cylindrical lens combination of FIG. 4B, according to an example embodiment.

FIG. 5A illustrates a receive block, according to an example embodiment.

FIG. 5B illustrates a side view of three detectors included in the receive block of FIG. 5A.

FIG. 6A illustrates another LIDAR device, according to an example embodiment.

FIG. 6B illustrates a partial cross-section view of the LIDAR device of FIG. 6A.

FIG. 6C illustrates a partial cross-section view of the optics assembly in the LIDAR device of FIG. 6A.

FIG. 7A illustrates a system, according to an example embodiment.

FIG. 7B illustrates an arrangement of the system shown in FIG. 7A where the light filter is not interposed between the LIDAR device and the camera.

FIG. 7C illustrates a partial view of the system shown in FIGS. 7A-7B.

FIG. 8 illustrates another system, according to an example embodiment.

FIG. 9 is a flowchart of a method, according to an example embodiment.

FIG. 10 illustrates an image indicative of light source positions, according to an example embodiment.

FIG. 11 illustrates an image indicative of detector positions, according to an example embodiment.

FIG. 12 illustrates an image in a scenario where light sources and detectors are aligned, according to an example embodiment.

FIG. 13 illustrates an image in a scenario where light sources and detectors have an up/down offset, according to an example embodiment.

FIG. 14 illustrates an image in a scenario where light sources and detectors have a left/right offset, according to an example embodiment.

FIG. 15 illustrates an image in a scenario where light sources and detectors have a forward/backward offset, according to an example embodiment.

FIG. 16 illustrates an image in a scenario where light sources and detectors have a roll offset, according to an example embodiment.

FIG. 17 illustrates an image in a scenario where light sources and detectors have a yaw offset, according to an example embodiment.

FIG. 18 illustrates an image in a scenario where light sources and detectors have a pitch offset, according to an example embodiment.

FIG. 19 illustrates an image indicative of a defect or an aberration, according to an example embodiment.

FIG. 20 is a flowchart of another method, according to an example embodiment.

FIG. 21 illustrates a partial cross-section view of yet another system, according to an example embodiment.

FIG. 22 illustrates a front-view of a camera, according to an example embodiment.

DETAILED DESCRIPTION

The following detailed description describes various features and functions of the disclosed systems, devices and methods with reference to the accompanying figures. In the figures, similar symbols identify similar components, unless context dictates otherwise. The illustrative system, device and method embodiments described herein are not meant to be limiting. It may be readily understood by those skilled in

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the art that certain aspects of the disclosed systems, devices and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

Within examples, a LIDAR device may include a transmit block and a receive block. The transmit block may include one or more light sources that transmit light for propagation away from the LIDAR device toward an environment of the LIDAR device. In turn, the transmitted light may reflect off one or more objects in the environment, and the reflected light may propagate back toward the LIDAR device. Further, the receive block may include one or more detectors to detect the reflected light. Through this process, a computing system may process data from the LIDAR device pertaining to the reflected light to determine positions and/or characteristics of various objects in the environment of the LIDAR device.

To facilitate operation of the LIDAR device, a light beam emitted by a given light source and reflected back toward the LIDAR device is received by a corresponding detector. Within examples, systems and methods are provided for alignment of light source(s) and detector(s) in a LIDAR device.

FIG. 1 is a block diagram of a system 100, according to an example embodiment. The system 100 includes a mounting platform 102, an alignment apparatus 160, and a controller 180. The system 100 may optionally include an auxiliary light source 170.

The mounting platform 102 may provide a platform for mounting some or all of the components of the system 100. As shown, the mounting platform 102 mounts a LIDAR device 104 and a camera 106. In some examples, the mounting platform 102 may also mount a light filter 108. Further, in some examples, the mounting platform 102 may also mount an actuator 112. Accordingly, the mounting platform 102 may be formed from one or more solid materials suitable for supporting the various components, such as plastics or metals among other possibilities. In some examples, some of the components shown to be mounted on the mounting platform 102 may alternatively be mounted to a separate structure (not shown) or otherwise coupled to the system 100. For instance, the camera 106 and/or the light filter 108 may be alternatively positioned and/or mounted outside the mounting platform 102.

The LIDAR device 104 includes a transmit block 120 and a receive block 130. As shown, in some examples, the LIDAR device 104 may optionally include a lens 150.

The transmit block 120 includes one or more light sources 122 that may be configured to emit one or more light beams 124. Although not shown in FIG. 1, the transmit block 120 may include additional components such as a mirror or an exit aperture to condition and/or redirect the light beams 124. The one or more light sources 122 may include laser diodes, light emitting diodes (LEDs), vertical cavity surface emitting lasers (VCSEL), organic light emitting diodes (OLEDs), polymer light emitting diodes (PLED), light emitting polymers (LEP), liquid crystal displays (LCD), micro-electromechanical systems (MEMS), or any other device configured to selectively transmit, reflect, and/or emit light beams 124 at a source wavelength. The source wavelength, for example, may include ultraviolet, visible, and/or infrared portions of the electromagnetic spectrum. In one embodiment, the source wavelength is 905 nm. Additionally, in some examples, the light sources 122 may be configured to emit the light beam(s) 124 in the form of pulses. In some

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examples, the light sources 122 may be disposed on one or more substrates (e.g., printed circuit boards (PCB), flexible PCBs, etc.).

The receive block 130 includes one or more detectors 132 that may be configured to receive light from an environment of the LIDAR device 104. In one example, a given detector of the detectors 132 is configured and arranged to receive a given light beam of the light beams 124 that is reflected off an object in the environment of the LIDAR device 104 toward the given detector. Through this process, for example, the LIDAR device 104 may detect various objects in the environment by emitting light beams 124 using the light sources 122 and detecting reflections of the light beams 124 using the detectors 132. Although not shown, in some examples, the receive block 130 may include additional components such as an inert gas, an entrance aperture (e.g., half-mirror), and/or any other component to filter and/or condition light propagating toward the detectors 132. The detector(s) 132 may comprise photodiodes, avalanche photodiodes, phototransistors, cameras, active pixel sensors (APS), charge coupled devices (CCD), cryogenic detectors, or any other sensor of light. In one embodiment, the detector(s) 132 may be configured to detect light at the source wavelength (e.g., 905 nm, etc.) of the light beams 124 emitted by the light sources 122 and/or reflections thereof.

The lens 150 may be optionally included in the LIDAR device 104 and may be configured to collimate the emitted light beams 124 and/or focus light propagating toward the detectors 132. In one embodiment, the lens 150 may be a single lens having an optical power to both collimate the light beams 124 and focus light onto the detectors 132. In another embodiment, the lens 150 may include two separate lenses. For example, a first lens may collimate the light beam(s) 124 emitted by the light source(s) 122, and a second lens may focus light propagating toward the LIDAR device 104 onto the detector(s) 132. Other lens configurations are possible as well (e.g., multiple lenses for collimation and/or multiple lenses for focus, etc.).

In some examples, the LIDAR device 104 may include additional, fewer, or different components than those shown in FIG. 1. Thus, in some embodiments, the system 100 may be utilized for assembly, manufacture, and/or calibration of various LIDAR devices having various configurations, such as the LIDAR device 104 or any other LIDAR device. Accordingly, in some examples, the LIDAR device 104 may be removably mounted to the mounting platform 102 of the system 100 to facilitate such calibration or assembly.

In some examples, the various components of the LIDAR device 104 such as the transmit block 120, receive block 130, and the lens 150 can be removably mounted in predetermined positions within the LIDAR device 104 to reduce burden of calibrating the arrangement of each component and/or subcomponents included in each component. In these examples, the system 100 may adjust the relative position between the transmit block 120 and the receive block 130 to align the one or more light sources 122 with the one or more detectors 132. Alternatively, in other examples, the system 100 may be configured to adjust the relative position between each of the subcomponents (e.g., each light source of light sources 122, each detector of detectors 132, etc.).

The camera 106 may be any camera (e.g., a still camera, a video camera, etc.) configured to capture images of the LIDAR device 104. In some examples, the camera 106 may be located at a given position at which the camera 106 can image the light beams 124 emitted by the one or more light sources 122, and can image the one or more detectors 132. In one embodiment, the camera may be focused at infinity

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when capturing such images. By way of example, the camera may be mounted to have a field-of-view along the path of the light beams 124 (e.g., facing the lens 150, etc.).

As an example scenario for operation of the camera 106, the LIDAR device 104 may then be configured to cause the light sources 122 to emit the light beams 124 toward the camera 106. In turn, the camera 106 may provide a first image of the light beams 124. The first image, for instance, may indicate light source position(s) (e.g., bright pixels in the first image, etc.) of the light source(s) 122. In the scenario, the camera may also obtain a second image indicative of detector position(s) of the detector(s) 132. Other scenarios are possible as well and are described in greater detail within exemplary embodiments herein.

The light filter 108 may be optionally included in the system 100 to facilitate capture and/or processing of the images described above. For instance, the light filter 108 may be positioned along a path of the light beams 124 between the LIDAR device 104 and the camera 106. In one example, the light filter 108 may be configured to attenuate light within a wavelength range that includes the source wavelength of the light source(s) 122. In this example, the attenuation of the light may facilitate contrasting pixels in the first image that are associated with the light beams 124 against surrounding pixels. Further, in this example, the attenuation of the light may protect the camera 106 from the intensity of the light beams 124. In another example, the light filter 108 may be configured to attenuate light within another wavelength range that does not include the source wavelength of the light source(s) 122. In this example, the images obtained by the camera 106 may represent features of interest (e.g., light source(s) 122, detector(s) 132, etc.) in the LIDAR device 104 more clearly due to the light filter 108 attenuating background light having other wavelengths. Other configurations of the light filter 108 are possible as well and are described in greater detail within exemplary embodiments herein.

The actuator 112 may be optionally included in the system 100. The actuator 112 may be configured to adjust the position of the light filter 108. For instance, the actuator 112 may be configured to actuate the light filter 108 to a first position where the light filter 108 is interposed between the LIDAR device 104 and the camera 106, or to a second position where the light filter 108 is not interposed between the LIDAR device 104 and the camera 106. Example actuators may include motors, stepper motors, pneumatic actuators, hydraulic pistons, relays, solenoids, and piezoelectric actuators among other possibilities.

The alignment apparatus 160 may include any device that couples to one or more of the components in the LIDAR device 104 to adjust the relative position between the transmit block 120 and the receive block 130. By way of example, the alignment apparatus 160 may be a robotic arm that physically couples to the receive block 130 to rotate and/or translate the position of the receive block 130 in the LIDAR 104. Alternatively or additionally, for example, the robotic arm may adjust the position of the transmit block 120. In some examples, the alignment apparatus 160 may adjust the relative position between the transmit block 120 and the receive block 130 based on image(s) obtained by the camera 106. For instance, the alignment apparatus 160 may adjust the relative position to align one or more of the light beams 124 emitted by the light sources 122 with one or more of the detectors 132.

The system 100 may optionally include an auxiliary light source 170 that emits light 174 at the source wavelength to illuminate the receive block 130. The structure and form of

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the auxiliary light source **170** (e.g., LED, etc.) may be similar to the light sources **122**. In one example, where the camera **106** is configured to capture images when focused at infinity for the source wavelength the light sources **122**, the auxiliary light source **170** may illuminate the detectors **132** to facilitate the camera **106** obtaining the second image of the detectors **132** while also focused at infinity for the same source wavelength.

In some examples, the light filter **108** may be configured to remain interposed between the camera **106** and the LIDAR device **104** during capture of the first image (e.g., of the light beams **124**) and during capture of the second image (e.g., of the detectors **132**). In these examples, the illuminating light **174** from the auxiliary light source **170** may allow the camera **106** to capture an image of the detectors **132** while the light filter **108** is interposed.

In other examples, the system **100** may be configured to move the light filter **108** to another position other than the position between the camera **106** and the LIDAR device **104** prior to the camera **106** obtaining the second image of the detectors **132**. For instance, the light filter **108** may be moved by the actuator **112**. In these examples, the camera **106** may rely on background light to obtain the second image of the detectors **132**, or the system **100** may utilize the auxiliary light source **170** to illuminate the receive block **130**.

The controller **180** may include one or more processors configured to operate some or all of the components of the system **100** in line with the discussion above. To that end, the controller **180** may be coupled to the various components via a wired or wireless interface (not shown). In some examples, the controller **180** may execute program functions stored in a computer readable medium (not shown) to cause the system **100** to perform various functions and processes of the present method.

In a first example, the controller **180** may cause a power source (not shown) to provide power to the various components of the system **100**. In a second example, the controller **180** may cause the transmit block **120** of the LIDAR device **104** to emit the light beams **124**. In a third example, the controller **180** may operate an actuator (not shown) to position the light filter **108** between the LIDAR device **104** and the camera **106**, or to position the light filter **108** at any other position. In a third example, the controller **180** may operate the camera **106** to obtain the first image (e.g., of the light beams **124**) and the second image (e.g., of the detectors **132**) in line with the discussion above. In a fourth example, the controller **180** may operate the alignment apparatus **160** to adjust the relative position between the transmit block **120** and the receive block **130**. In a fifth example, the controller **180** may operate the alignment apparatus **160** to mount (or unmounts) various components (e.g., LIDAR device **104**, etc.) to the mounting platform **102**. In a sixth example, the controller **180** may operate the auxiliary light source **170** to illuminate the receive block **130** with light **174**. In a seventh example, the controller **180** may operate the actuator **112** to move the light filter **108**. Other examples are possible as well and are described in greater detail within exemplary embodiments herein.

The system **100** may include additional, fewer, or different components than those shown, and may perform other functions as well. In one example, the system **100** may include a display (not shown) for displaying image(s) obtained using the camera **106**. For instance, the display may have a graphical user interface (GUI) for displaying and/or interacting with images captured by the camera **106**, and a human operator or a computer operator may interact

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with the GUI to adjust the relative position between the transmit block **120** and the receive block **130** by manipulating the images in the GUI. Other procedures are possible as well for controlling the system **100** in accordance with the present disclosure.

FIG. 2A illustrates a LIDAR device **200**, according to an example embodiment. The LIDAR **200** illustrates an example LIDAR device that can be used with a system such as the system **100**. For instance, the LIDAR device **200** may be similar to the LIDAR device **104** of the system **100**, and may be similarly mounted to the mounting platform **104** to adjust the relative position between light sources and detectors of the LIDAR **200**.

As shown, the LIDAR device **200** includes a housing **210** and a lens **250**. Additionally, light beams **204** emitted by the first LIDAR device **200** propagate from the lens **250** along a viewing direction of the first LIDAR **200** toward an environment of the LIDAR device **200**, and reflect off one or more objects in the environment as reflected light **206**.

The housing **210** included in the LIDAR device **200** can provide a platform for mounting the various components included in the LIDAR device **200**. The housing **210** can be formed from any material capable of supporting the various components of the LIDAR device **200** included in an interior space of the housing **210**. For example, the housing **210** may be formed from a solid material such as plastic or metal among other possibilities.

In some examples, the housing **210** can be configured to have a substantially cylindrical shape and to rotate about an axis of the LIDAR device **200**. For example, the housing **210** can have the substantially cylindrical shape with a diameter of approximately 10 centimeters. In some examples, the axis is substantially vertical. By rotating the housing **210** that includes the various components, in some examples, a three-dimensional map of a 360-degree view of the environment of the LIDAR device **200** can be determined without frequent recalibration of the arrangement of the various components of the LIDAR device **200**. Additionally or alternatively, in some examples, the LIDAR device **200** can be configured to tilt the axis of rotation of the housing **210** to control the field of view of the LIDAR device **200**.

The lens **250** mounted to the housing **210** can have an optical power to both collimate the emitted light beams **204**, and focus the reflected light **206** from one or more objects in the environment of the LIDAR device **200** onto detectors in the LIDAR device **200**. In one example, the lens **250** has a focal length of approximately 120 mm. By using the same lens **250** to perform both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

The LIDAR device **200** can be mounted on a mounting structure **260** that rotates about an axis to provide a 360-degree view of the environment surrounding the LIDAR device **200**. In some examples, the mounting structure **260** may comprise a movable platform that may tilt in one or more directions to change the axis of rotation of the LIDAR device **200**.

FIG. 2B is a cross-section view of the first LIDAR **200** shown in FIG. 2A. As shown, the housing **210** houses a transmit block **220**, a receive block **230**, a shared space **240**, and the lens **250**. For purposes of illustration, FIG. 2B shows an x-y-z axis, in which the z-axis is in a substantially vertical direction.

The transmit block **220** includes a plurality of light sources **222a-c** arranged along a curved focal surface **228** defined by the lens **250**. The plurality of light sources **222a-c**

can be configured to emit, respectively, the plurality of light beams **202a-c** having wavelengths within a wavelength range. For example, the plurality of light sources **222a-c** may comprise laser diodes that emit the plurality of light beams **202a-c** having the wavelengths within the wavelength range. The plurality of light beams **202a-c** are reflected by mirror **224** through an exit aperture **226** into the shared space **240** and towards the lens **250**.

The light sources **222a-c** can include laser diodes, light emitting diodes (LED), vertical cavity surface emitting lasers (VCSEL), organic light emitting diodes (OLED), polymer light emitting diodes (PLED), light emitting polymers (LEP), liquid crystal displays (LCD), microelectromechanical systems (MEMS), or any other device configured to selectively transmit, reflect, and/or emit light to provide the plurality of emitted light beams **202a-c**. In some examples, the light sources **222a-c** can be configured to emit the emitted light beams **202a-c** in a wavelength range that can be detected by detectors **232a-c** included in the receive block **230**. The wavelength range could, for example, be in the ultraviolet, visible, and/or infrared portions of the electromagnetic spectrum. In some examples, the wavelength range can be a narrow wavelength range, such as provided by lasers. In one embodiment, the wavelength range includes a source wavelength of 905 nm. Additionally, the light sources **222a-c** can be configured to emit the emitted light beams **202a-c** in the form of pulses. In some examples, the plurality of light sources **222a-c** can be disposed on one or more substrates (e.g., printed circuit boards (PCB), flexible PCBs, etc.) and arranged to emit the plurality of light beams **202a-c** towards the exit aperture **226**.

Although FIG. 2B shows that the curved focal surface **228** is curved in the x-y plane, additionally or alternatively, the plurality of light sources **222a-c** may be arranged along a focal surface that is curved in a vertical plane. For example, the curved focal surface **228** can have a curvature in a vertical plane, and the plurality of light sources **222a-c** can include additional light sources arranged vertically along the curved focal surface **228** and configured to emit light beams directed at the mirror **224** and reflected through the exit aperture **226**. In this example, the detectors **232a-c** may also include additional detectors that correspond to additional light sources of the light sources **222a-c**. Further, in some examples, the light sources **222a-c** may include additional light sources arranged horizontally along the curved focal surface **228**. In one embodiment, the light sources **222a-c** may include 64 light sources that emit light having a wavelength of 905 nm. For instance, the 64 light sources may be arranged in four columns, each comprising 16 light sources, along the curved focal surface **228**. In this instance, the detectors **232a-c** may include 64 detectors that are arranged similarly (e.g., 4 columns comprising 16 detectors each, etc.) along curved focal surface **238**. In other embodiments, the light sources **222a-c** and the detectors **232a-c** may include additional or fewer light sources and/or detectors than those shown in FIG. 2B.

Due to the arrangement of the plurality of light sources **222a-c** along the curved focal surface **228**, the plurality of light beams **202a-c**, in some examples, may converge towards the exit aperture **226**. Thus, in these examples, the exit aperture **226** may be minimally sized while being capable of accommodating vertical and horizontal extents of the plurality of light beams **202a-c**. Additionally, in some examples, the curved focal surface **228** can be defined by the lens **250**. For example, the curved focal surface **228** may correspond to a focal surface of the lens **250** due to shape and composition of the lens **250**. In this example, the

plurality of light sources **222a-c** can be arranged along the focal surface defined by the lens **250** at the transmit block.

The plurality of light beams **202a-c** propagate in a transmit path that extends through the transmit block **220**, the exit aperture **226**, and the shared space **240** towards the lens **250**. The lens **250** collimates the plurality of light beams **202a-c** to provide collimated light beams **204a-c** into an environment of the LIDAR device **200**. The collimated light beams **204a-c** correspond, respectively, to the plurality of light beams **202a-c**. In some examples, the collimated light beams **204a-c** reflect off one or more objects in the environment of the LIDAR device **200** as reflected light **206**. The reflected light **206** may be focused by the lens **250** into the shared space **240** as focused light **208** traveling along a receive path that extends through the shared space **240** onto the receive block **230**. For example, the focused light **208** may be reflected by the reflective surface **242** as focused light **208a-c** propagating towards the receive block **230**.

The lens **250** may be capable of both collimating the plurality of light beams **202a-c** and focusing the reflected light **206** along the receive path **208** towards the receive block **230** due to the shape and composition of the lens **250**. For example, the lens **250** can have an aspheric surface **252** facing outside of the housing **210** and a toroidal surface **254** facing the shared space **240**. By using the same lens **250** to perform both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

The exit aperture **226** is included in a wall **244** that separates the transmit block **220** from the shared space **240**. In some examples, the wall **244** can be formed from a transparent material (e.g., glass) that is coated with a reflective material **242**. In this example, the exit aperture **226** may correspond to the portion of the wall **244** that is not coated by the reflective material **242**. Additionally or alternatively, the exit aperture **226** may comprise a hole or cut-away in the wall **244**.

The focused light **208** is reflected by the reflective surface **242** and directed towards an entrance aperture **234** of the receive block **230**. In some examples, the entrance aperture **234** may comprise a filtering window configured to allow wavelengths in the wavelength range of the plurality of light beams **202a-c** (e.g., source wavelength) emitted by the plurality of light sources **222a-c** and attenuate other wavelengths. In some examples, the entrance aperture **234** may comprise a half-mirror configured to reflect a portion of the focused light **208a-c** and allow another portion of the focused light **208a-c** to propagate toward the detectors **232a-c**. The focused light **208a-c** reflected by the reflective surface **242** from the focused light **208a-c** propagates, respectively, onto a plurality of detectors **232a-c**.

The plurality of detectors **232a-c** can be arranged along a curved focal surface **238** of the receive block **230**. Although FIG. 2B shows that the curved focal surface **238** is curved along the x-y plane (horizontal plane), additionally or alternatively, the curved focal surface **238** can be curved in a vertical plane. The curvature of the focal surface **238** is also defined by the lens **250**. For example, the curved focal surface **238** may correspond to a focal surface of the light projected by the lens **250** along the receive path at the receive block **230**.

The detectors **232a-c** may comprise photodiodes, avalanche photodiodes, phototransistors, cameras, active pixel sensors (APS), charge coupled devices (CCD), cryogenic detectors, or any other sensor of light configured to receive

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focused light **208a-c** having wavelengths in the wavelength range of the emitted light beams **202a-c** (e.g., the source wavelength).

Each of the focused light **208a-c** corresponds, respectively, to the emitted light beams **202a-c** and is directed onto, respectively, the plurality of detectors **232a-c**. For example, the detector **232a** is configured and arranged to receive focused light **208a** that corresponds to collimated light beam **204a** reflected of the one or more objects in the environment of the LIDAR device **200**. In this example, the collimated light beam **204a** corresponds to the light beam **202a** emitted by the light source **222a**. Thus, the detector **232a** receives light that was emitted by the light source **222a**, the detector **232b** receives light that was emitted by the light source **222b**, and the detector **232c** receives light that was emitted by the light source **222c**.

By comparing the received light **208a-c** with the emitted light beams **202a-c**, at least one aspect of the one or more object in the environment of the LIDAR device **200** may be determined. For example, by comparing a time when the plurality of light beams **202a-c** were emitted by the plurality of light sources **222a-c** and a time when the plurality of detectors **232a-c** received the focused light **208a-c**, a distance between the LIDAR device **200** and the one or more object in the environment of the LIDAR device **200** may be determined. In some examples, other aspects such as shape, color, material, etc. may also be determined.

In some examples, the LIDAR device **200** may be rotated about an axis to determine a three-dimensional map of the surroundings of the LIDAR device **200**. For example, the LIDAR device **200** may be rotated about a substantially vertical axis as illustrated by arrow **290**. Although illustrated that the LIDAR device **200** is rotated counter clock-wise about the axis as illustrated by the arrow **290**, additionally or alternatively, the LIDAR device **200** may be rotated in the clockwise direction. In some examples, the LIDAR device **200** may be rotated 360 degrees about the axis. In other examples, the LIDAR device **200** may be rotated back and forth along a portion of the 360 degree view of the LIDAR device **200**. For example, the LIDAR device **200** may be mounted on a platform that wobbles back and forth about the axis without making a complete rotation.

Thus, the arrangement of the light sources **222a-c** and the detectors **232a-c** may allow the LIDAR device **200** to have a particular vertical field-of-view. In one example, the vertical FOV of the LIDAR device **200** is 20°. Additionally, the rotation of the LIDAR device **200** allows the LIDAR device **200** to have a 360° horizontal FOV. Further, the rate of rotation may allow the device to have a particular refresh rate. In one example, the refresh rate is 10 Hz. The refresh rate along with the arrangement of the light sources **222a-c** and the detectors **232a-c** may also allow the LIDAR device **300** to have a particular angular resolution. In one example, the angular resolution is 0.2°×0.3°. However, the various parameters such as the refresh rate and the angular resolution may vary according to the configuration of the LIDAR device **200**. Further, in some examples, the LIDAR device **200** may include additional, fewer, or different components than those shown in FIGS. 2A-2B.

FIG. 2C is a perspective view of the LIDAR device **200** shown in FIG. 2A with various components removed to illustrate an interior of the LIDAR device **200**. As shown, the various components of the LIDAR device **200** can be removably mounted to the housing **210**. For example, the transmit block **220** may comprise one or more printed circuit boards (PCBs) that are fitted in the portion of the housing **210** where the transmit block **220** can be mounted. Although

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FIG. 2C shows the transmit block **220** with one PCB, in some embodiments, the transmit block **320** may include multiple PCBs (not shown) that each include some of the plurality of light sources **322a-c**. In one embodiment, each PCB in the transmit block may include 16 light sources, and the transmit block **220** may include four PCBs. Thus, in this embodiment, the LIDAR device **200** may include 64 light sources. Other embodiments are possible as well where the transmit block **220** includes a different number of light sources. Additionally, the receive block **230** may comprise a plurality of detectors (e.g., detectors **232a-c**, etc.) mounted to a flexible substrate and can be removably mounted to the housing **210** as a block that includes the plurality of detectors. Similarly, the lens **250** can be mounted to another side of the housing **210**.

FIG. 3 illustrates a transmit block **320**, according to an example embodiment. Transmit block **320** may be similar to the transmit blocks **120** and/or **220** described in FIGS. 1-2. For example, the transmit block **320** includes a plurality of light sources **322a-c** similar to the plurality of light sources **222a-c** included in the transmit block **220** of FIGS. 2A-2C. Additionally, the light sources **322a-c** are arranged along a focal surface **328**, which is curved in a vertical plane. The light sources **322a-c** are configured to emit a plurality of light beams **302a-c** that converge and propagate through an exit aperture **326** in a wall **344**.

Although the plurality of light sources **322a-c** can be arranged along a focal surface **328** that is curved in a vertical plane, additionally or alternatively, the plurality of light sources **322a-c** can be arranged along a focal surface that is curved in a horizontal plane or a focal surface that is curved both vertically and horizontally. For example, the plurality of light sources **322a-c** can be arranged in a curved three dimensional grid pattern. For example, the transmit block **320** may comprise a plurality of printed circuit boards (PCBs) vertically mounted such that a column of light sources such as the plurality of light sources **322a-c** are along the vertical axis of each PCB and each of the plurality of PCBs can be arranged adjacent to other vertically mounted PCBs along a horizontally curved plane to provide the three dimensional grid pattern. Alternatively, in some examples, the light sources **322a-c** may be arranged along any other surface such as a linear surface. Further, although the transmit block **320** is shown to include multiple light sources **322a-c**, in some examples, the transmit block **320** may include only one light source or a different number of light sources than those shown in FIG. 3.

As shown in FIG. 3, the light beams **302a-c** converge towards the exit aperture **326** which allows the size of the exit aperture **326** to be minimized while accommodating vertical and horizontal extents of the light beams **302a-c** similarly to the exit aperture **226** described in FIG. 2B.

The light emitted by the light sources **222a-c** may be partially collimated to fit through the exit aperture **224**. FIGS. 4A, 4B, and 4C illustrate an example of how such partial collimation could be achieved. In this example, a light source **400** is made up of a laser diode **402** and a cylindrical lens **404**. As shown in FIG. 4A, laser diode **402** has an aperture **406** with a shorter dimension corresponding to a fast axis **408** and a longer dimension corresponding to a slow axis **410**. FIGS. 4B and 4C show an uncollimated laser beam **412** being emitted from laser diode **402**. Laser beam **412** diverges in two directions, one direction defined by fast axis **408** and another, generally orthogonal direction defined by slow axis **410**. FIG. 4B shows the divergence of laser beam **412** along fast axis **408**, whereas FIG. 4C shows

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the divergence of laser beam **412** along slow axis **410**. Laser beam **412** diverges more quickly along fast axis **408** than along slow axis **410**.

In one specific example, laser diode **402** is an Osram SPL DL90_3 nanostack pulsed laser diode that emits pulses of light with a range of wavelengths from about 896 nm to about 910 nm (a nominal wavelength of 905 nm). In this specific example, the aperture has a shorter dimension of about 10 microns, corresponding to its fast axis, and a longer dimension of about 200 microns, corresponding to its slow axis. The divergence of the laser beam in this specific example is about 25 degrees along the fast axis and about 11 degrees along the slow axis. It is to be understood that this specific example is illustrative only. Laser diode **402** could have a different configuration, different aperture sizes, different beam divergences, and/or emit different wavelengths.

As shown in FIGS. 4B and 4C, cylindrical lens **404** may be positioned in front of aperture **406** with its cylinder axis **414** generally parallel to slow axis **410** and perpendicular to fast axis **408**. In this arrangement, cylindrical lens **404** can pre-collimate laser beam **412** along fast axis **408**, resulting in partially collimated laser beam **416**. In some examples, this pre-collimation may reduce the divergence along fast axis **408** to about one degree or less. Nonetheless, laser beam **416** is only partially collimated because the divergence along slow axis **410** may be largely unchanged by cylindrical lens **404**. Thus, whereas uncollimated laser beam **412** emitted by laser diode has a higher divergence along fast axis **408** than along slow axis **410**, partially collimated laser beam **416** provided by cylindrical lens **404** may have a higher divergence along slow axis **410** than along fast axis **408**. Further, the divergences along slow axis **410** in uncollimated laser beam **412** and in partially collimated laser beam **416** may be substantially equal.

In one example, cylindrical lens **404** is a microrod lens with a diameter of about 600 microns that is placed about 250 microns in front of aperture **406**. The material of the microrod lens could be, for example, fused silica or a borosilicate crown glass, such as Schott BK7. Cylindrical lens **404** could also be used to provide magnification along fast axis **408**. For example, if the dimensions of aperture **406** are 10 microns by 200 microns, as previously described, and cylindrical lens **404** is a microrod lens as described above, then cylindrical lens **404** may magnify the shorter dimension (corresponding to fast axis **408**) by about 20 times. This magnification effectively stretches out the shorter dimension of aperture **406** to about the same as the longer dimension. As a result, when light from laser beam **416** is focused, for example, onto a detector, the focused spot could have a substantially square shape instead of the rectangular slit shape of aperture **406**.

FIG. 5A illustrates a receive block **530**, according to an example embodiment. FIG. 5B illustrates a side view of three detectors **532a-c** included in the receive block **530** of FIG. 5A. Receive block **530** may be similar to the receive block **130** of FIG. 1 and/or the receive block **230** of FIGS. 2B-2C. For example, the receive block **530** includes a plurality of detectors **532a-c** arranged along a curved surface **538** defined by a lens **550** similarly to the receive block **230**, the detectors **232a-c**, and the curved plane **238** described in FIG. 2B. Focused light **508a-c** from lens **550** propagates along a receive path that includes a reflective surface **542** onto the detectors **532a-c** similar, respectively, to the focused light **208a-c**, the lens **250**, the reflective surface **242**, and the detectors **232a-c** described in FIG. 2B.

The receive block **530** comprises a flexible substrate **580** on which the plurality of detectors **532a-c** are arranged

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along the curved surface **538**. The flexible substrate **580** conforms to the curved surface **538** by being mounted to a receive block housing **590** having the curved surface **538**. As illustrated in FIG. 5B, the curved surface **538** includes the arrangement of the detectors **532a-c** curved along a vertical and horizontal axis of the receive block **530**.

In some embodiments, the number and arrangement of the detectors **532a-c** may be different than those shown in FIGS. 5A-5B. For instance, the detectors **532a-c** may be alternatively arranged along a linear surface, or may alternatively only include one detector, among other possibilities.

As noted above in the description of FIG. 1, the system **100** may be used with various LIDAR devices having various configurations, such as the LIDAR device **200** of FIGS. 2A-2C. FIG. 6A illustrates another LIDAR device **600** that may be used with the system **100**, according to an example embodiment.

As shown, the LIDAR device **600** includes an optics assembly **610**, a transmit lens **652**, a receive lens **654**, a mirror **620**, a pin **622**, and a motor **670**. For purposes of illustration, FIG. 6A shows an x-y-z axis, in which the z-axis is pointing out of the page, and the x-axis and y-axis define a horizontal plane along the surface of the page.

In some examples, the LIDAR device **600** may emit light that propagates away from the mirror **660** along a viewing direction of the LIDAR device **600** (e.g., parallel to z-axis shown in FIG. 6A, etc.) toward an environment of the LIDAR device **600**, and may receive reflected light from one or more objects in the environment.

Accordingly, the optics assembly **610** may be configured to emit light pulses towards the mirror **660** that are then reflected by the mirror **660** towards the environment. Further, the optics assembly **610** may be configured to receive reflected light that is reflected off the mirror **660**. In one embodiment, the optics assembly **610** may include a single laser emitter that is configured to provide a narrow beam having a wavelength of 905 nm. In other embodiments, the optics assembly **610** may include multiple light sources similarly to the LIDAR device **200** of FIGS. 2A-2C. As shown, the optics assembly **610** includes the transmit lens **652** for collimation and/or focusing of emitted light from the optics assembly **610** onto the mirror **620**, and a receive lens **654** for focusing reflected light from the mirror **660** onto one or more detectors (not shown) of the optics assembly **610**. However, in some examples, the optics assembly **610** may alternatively include a single lens for both collimation of emitted light and focusing of reflected light similarly to the lens **250** of the LIDAR device **200**.

As shown, the mirror **660** may be arranged to steer emitted light from the transmit lens **652** towards the viewing direction of the LIDAR device **600**. Further, for example, the mirror **660** may be arranged to steer reflected light from the mirror **660** towards the receive lens **654**. In some examples, the mirror **660** may be a triangular mirror that performs complete rotations about an axis defined by the pin **622**. In one embodiment, the vertical FOV of the LIDAR device **600** is 110°.

The pin **662** may be configured to mount the mirror **660** to the LIDAR device **600**. In turn, the pin **662** can be formed from any material capable of supporting the mirror **660**. For example, the pin **662** may be formed from a solid material such as plastic or metal among other possibilities. In some examples, the LIDAR device **600** may be configured to rotate the mirror **660** about the pin **662** for complete rotations to steer emitted light from the optics assembly **610** vertically. In other examples, the LIDAR device **600** may be configured to rotate the mirror **660** about the pin **662** over a

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given range of angles to steer the emitted light. Thus, in some examples, various vertical FOVs are possible by adjusting the rotation the mirror 660 about the pin 662.

The motor 670 may include any motor such as a stepper motor, an electric motor, a combustion motor, a pancake motor, and/or a piezoelectric actuator among other possibilities. In some examples, the motor 670 may be configured to rotate various components of the LIDAR device 600 (e.g., optics assembly 610, mirror 660, pin 662, etc.) about an axis of the LIDAR device 600. For example, the axis may be substantially vertical similarly to the y-axis shown in FIG. 6A. By rotating the various components of the LIDAR device 600 about the axis, in some examples, the motor 670 may steer the emitted light that is reflected off the mirror 660 horizontally, thus allowing the LIDAR device 600 to have a horizontal FOV. In one embodiment, the motor 670 may rotate for a defined amount of rotation such as 270°. In this embodiment, the LIDAR device 600 may thus have a horizontal FOV of 270. However, other amounts of rotation are possible as well (e.g., 360°, 8°, etc.) thereby allowing a different horizontal FOV for the LIDAR device 600. Thus, in some examples, the LIDAR device 600 may provide an alternative device for scanning the environment or a portion thereof to the LIDAR device 104 of FIG. 1, and/or the LIDAR device 200 of FIGS. 2A-2C.

FIG. 6B illustrates a partial cross-section view of the LIDAR device 600 shown in FIG. 6A. It is noted that some of the components of the LIDAR device 600 are omitted from the illustration of FIG. 6B for convenience in description.

As shown, the optics assembly 610 comprises a transmit block 620 that includes one light source 622. In some examples, the transmit block 620 may alternatively include more than one light source similarly to the transmit block 220 of the LIDAR device 200. However, for the sake of example, the transmit block 620 includes one light source 622. The light source 622 may be configured to emit one or more light pulses (e.g., laser beams, etc.) towards the transmit lens 652. For example, as shown, emitted light 602a propagates away from the light source 622 towards the transmit lens 652. In some examples, the light source 622 may be similar to the light sources 222a-c of the LIDAR device 200 of FIGS. 2A-2C. In one embodiment, the light source 622 may be configured to emit light pulses having a wavelength of 905 nm. In other embodiments, the light source 622 may be configured to emit light having any other wavelength.

In line with the discussion above, the transmit lens 652 may be configured to collimate the emitted light 602a into one or more collimated light beams 602b and/or may be configured to focus the emitted light 602a as the focused light 602b onto the mirror 660.

As shown, the mirror 660 may be a triangular mirror that has three reflective surfaces 660a, 660b, 660c. However, in other examples, the mirror 660 may alternatively include a greater or fewer number of reflective surfaces. As shown, the collimated light 602b may then reflect off the reflective surface 660a and into the environment of the LIDAR 600 as emitted light 602c. For example, a direction of the emitted light 602c is illustrated by arrow 604. In practice, as the mirror 660 is rotated about an axis defined by the pin 662, the emitted light 602c may be steered to have a different direction than that illustrated by arrow 604. For example, the direction 604 of the emitted light 602c may instead correspond to a different direction along arrow 606. Thus, by rotating the mirror 660 about the pin 662, the LIDAR device 600 may be configured to have a vertical FOV, for example,

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Consider by way of example a scenario where the mirror 660 is configured to rotate about an axis defined by the pin 662 continuously in a clock-wise direction. In this scenario, the direction 604 of the emitted light 602c may thereby be adjusted also in a clock-wise direction as illustrated by the arrow 606 until the focused light 602b is reflecting off an edge of the reflective surface 660a. At this point, the emitted light 602c would be directed towards a maximum extent of the vertical FOV of the LIDAR device 600. Continuing with the scenario, as the mirror 660 continues to rotate, the collimated light 602b may then be focused onto the reflective surface 660b instead of the reflective surface 660a. At this point, the reflected light 602c may be steered to a direction that is towards a minimum extent of the vertical FOV of the LIDAR device 600. Continuing with the scenario, as the mirror 660 continues to rotate, the direction of the emitted light 602c may then be adjusted in a clock-wise direction towards the maximum extent of the vertical FOV that corresponds to the light 602b being focused onto another edge of the reflective surface 660b. Similarly, continuing with the scenario, the direction of the emitted light 602c may then be adjusted to scan the vertical FOV of the LIDAR device 600 by reflecting the light 602b off the reflective surface 660c instead of the reflective surface 660b. Through this process, for example, the LIDAR device 600 may continuously scan the vertical FOV. As a variation of the scenario above by way of example, the mirror 660 may be alternatively configured to rotate within a given range of angles (e.g., wobble, etc.) to define a narrower vertical field-of-view than that of the scenario described above. Other configurations for rotation of the mirror 660 are possible as well.

FIG. 6C illustrates a partial cross-section view of the optics assembly 610 in the LIDAR device 600 of FIG. 6A. For purposes of illustration, FIG. 6C shows an x-y-z axis, in which the z-axis is pointing out of the page, and the x-axis and y-axis define a horizontal plane along the surface of the page.

As shown, the optical assembly 610 comprises transmit block 620 that includes one light source 622. The light source 622 may be similar to the light sources 222a-c of the LIDAR device 200. In line with the discussion above, in some examples, the transmit block 620 may alternatively include more than one light source. The light source 622 is configured to emit light 602a toward the transmit lens 652. Further, the optical assembly 610 comprises receive block 630 that includes one detector 632. The detector 632 may be similar to the detectors 232a-c of the LIDAR device 200. Again, in some examples, the receive block 630 may alternatively include more than one detector. The detector 632 may be configured to receive light 608 focused by the receive lens 654.

As shown, the optics assembly 610 also includes an optical shield 612. The optical shield 612 may be configured to provide optical shielding between the transmit block 620 and the receive block 630, at least for the light having the source wavelength of the emitted light 602a. In turn, the optical shield 612 may mitigate interference with light 608 detected by the detector 632 of the receive block 630. The optical shield 612 may be formed, for example, as a wall coated by a metal, metallic ink, or metallic foam to provide the shielding. Example metals may include copper or nickel. Other configurations and/or materials are possible as well for the optical shield 612.

As noted in the description of the system 100 of FIG. 1, in some examples, the present method allows alignment of the detector 632 with light originating at the light source

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622. By way of example, an alignment apparatus (e.g., apparatus 160) may couple to the transmit block 620 and/or the receive block 630, and may then adjust the relative position between the transmit block 620 and the receive block 630 to perform the alignment.

The optical components (i.e., the transmit block 620 and the receive block 630) of the optical assembly 610 may each have six degrees of freedom (DOF). Three of the six DOF are translational: forward/backward (e.g., linearly along an axis of the optical component that is parallel to the y-axis shown in FIG. 6C), up/down (e.g., linearly along an axis of the optical component that is parallel to the z-axis), and left/right (e.g., linearly along an axis of the optical component that is parallel to the x-axis). Further, three of the six DOF are rotational: pitch (e.g., rotation about the axis of the optical component that is parallel to the x-axis), yaw (e.g., rotation about the axis of the optical component that is parallel to the z-axis), and roll (e.g., rotation about the axis of the optical component that is parallel to the y-axis). In accordance with the present disclosure, the alignment apparatus (not shown) may adjust the relative position between the transmit block 620 and the receive block 630 shown in FIG. 6C by adjusting some or all of the six DOF described above for one or both of the transmit block 620 and the receive block 630.

In line with the discussion above, systems and methods herein allow optics alignment for LIDAR devices having various different configurations. Thus, the configurations of the LIDAR devices 200 and 600 are presented for exemplary purposes only. Other configurations and LIDAR devices are possible as well for the systems and methods herein.

FIG. 7A illustrates a system 700, according to an example embodiment. The system 700 may be similar to the system 100 of FIG. 1. For example, as shown, the system 700 includes a mounting platform 702, a LIDAR device 704, a camera 706, a light filter 708, and an alignment apparatus 760 that can be similar, respectively, to the mounting platform 102, the LIDAR device 104, the camera 106, the light filter 108, and the alignment apparatus 160 of the system 100. As shown, the system 700 also includes a mounting structure 710, an actuator 712, and a manipulator 762.

The mounting structure 710 may be formed from any solid material (e.g., metal, plastic, etc.) similarly to the mounting platform 702, and may be shaped to facilitate coupling one or more of the components of the system 700 to the mounting platform 702. As shown, for example, the mounting structure 710 couples the camera 706 and the light filter 708 to the mounting platform 702. However, in some examples, a separate mounting structure may be utilized for each of the camera 706 and the light filter 708.

The actuator 712 may be configured to adjust a position of the light filter 708. Example actuators may include motors, stepper motors, pneumatic actuators, hydraulic pistons, relays, solenoids, and piezoelectric actuators among other possibilities.

The manipulator 762 may include any structure configured to couple the alignment apparatus 702 with one or more components of the LIDAR device 704. In line with the discussion above, the system 700 may adjust a relative position between a transmit block (not shown) and a receive block (not shown) of the LIDAR device 704. For instance, the alignment apparatus 760 (e.g., robotic arm, etc.) may adjust the relative position between the transmit block and the receive block by adjusting the position of the manipulator 762 or changing the orientation of the manipulator 762, among other possibilities.

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As shown, the mounting platform 702 includes a plurality of holes, exemplified by holes 702a and 702b. In some embodiments, the various components such as the LIDAR device 704, the camera 706, and/or the light filter 708 may be mounted to the mounting platform by coupling the various components to such holes in the mounting platform (e.g., by fastening a bolt through the holes). In other embodiments, the various components may be mounted to the mounting platform 702 via other processes or devices. In one example, the various components may be mounted to the mounting platform 702 via an application of an adhesive among other possibilities. In another example, a mounting structure may couple one or more of the components to the mounting platform 702. For instance, as shown in FIG. 7A, the mounting structure 710 may be coupled to the mounting platform 702 (e.g., by fastening a bolt to one of the holes, etc.), and may also be coupled the camera 706 and the light filter 708 to provide the particular positions of the camera 706 and the light filter 708 relative to the mounting platform 702. Other configurations and shapes of the mounting structure 710 are possible as well.

Further, as shown, the LIDAR device 704 has a configuration similar to the LIDAR device 200 of FIGS. 2A-2C. However, in some examples, other configurations are possible for the LIDAR device 704, such as the configuration of the LIDAR device 600 of FIGS. 6A-6C among other possibilities.

An example scenario for operation of the system 700 is as follows. First, as shown, the LIDAR device 704 may be mounted to the mounting platform 702 to have a field-of-view (FOV) through which light emitted by a transmit block (not shown) of the LIDAR device 704 and light received by a receive block (not shown) of the LIDAR device 704 propagates. For instance, the LIDAR device 704 may be mounted to the mounting platform 702 using the alignment apparatus 760 (e.g., robotic arm, etc.) or any other device (e.g., mechanical tool, etc.). Next, the camera 706 may be located at a given position relative to the LIDAR device 704 such that the camera 706 may obtain images of the receive block (not shown) of the LIDAR device 704 and/or light emitted by the transmit block (not shown) of the LIDAR device 704.

Continuing with the scenario, the camera 706 may then be focused to infinity for the source wavelength (e.g., 905 nm) of the light emitted by the LIDAR device 704. Next, the light filter 708 may be positioned at a first position to be interposed between the LIDAR device 704 and the camera 706 along the FOV of the LIDAR device 704. For instance, the actuator 712 may be configured to move the light filter 708 to the first position shown in FIG. 7A.

Continuing with the scenario, the system 700 may then cause the transmit block (not shown) of the LIDAR device 704 to emit one or more light beams through the light filter 708 and toward the camera 706. Referring back to FIG. 2B by way of example, the light beams may correspond to the light beams 204a-c propagating out of the lens 250. Next, the camera 706 may obtain a first image of the light beams emitted by the LIDAR device 704. Continuing with the example of FIG. 2B, the first image may indicate light source positions of light sources 222a-c in the LIDAR device 200. At this point in the scenario, the system may then cause the LIDAR device 704 to stop emitting the light beams.

Continuing with the scenario, the system may then cause the actuator 712 to move the light filter 708 to a second position where the light filter 708 is not interposed between the camera 706 and the LIDAR 704. FIG. 7B illustrates the

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light filter **708** at the second position described above. In turn, the camera **706** may obtain a second image. The second image may indicate detector positions of detectors in a receive block (not shown) of the LIDAR device **704**. Referring back to FIG. 2B by way of example, the second image may represent the detector positions of detectors **232a-c** that are viewable to the camera **706** via mirror **242** and lens **250**.

Continuing with the scenario, the system **700** may then determine at least one offset based on the first image and the second image. In one instance, the at least one offset may include distances between adjacent light sources and/or adjacent detectors of the LIDAR device **704**. In another instance, the at least one offset may include distances between light beams emitted by light sources in the LIDAR device **704** and corresponding detectors of the LIDAR device **704**. Other offsets are possible as well and are described in greater detail within exemplary embodiments herein.

In line with the discussion above, the alignment apparatus **760** (e.g., robotic arm, etc.) may couple to the transmit block (not shown) and/or the receive block (not shown) of the LIDAR device **704** via the manipulator **762**. Thus, in the scenario, the alignment apparatus **760** may then adjust the relative position between the transmit block and the receive block in accordance with the determined at least one or more offset.

FIG. 7C illustrates a partial view of the system **700** shown in FIGS. 7A-7B. It is noted that some of the components of the system **700** are omitted from the illustration of FIG. 7C for convenience in description. For purposes of illustration, FIG. 7C shows an x-y-z axis, in which the z-axis is pointing out of the page, and the x-axis and y-axis define a horizontal plane along the surface of the page.

As shown in FIG. 7C, the manipulator **762** includes protrusions **762a-d** that may be configured to couple with receive block **730**. The receive block **730** may be included in the LIDAR device **704** shown in FIGS. 7A-7B. It is noted that other components of the LIDAR device **704** (e.g., transmit block, etc.) are omitted from the illustration of FIG. 7C for convenience in description. The receive block **730** may be similar to the receive block **230** of the system **200**. However, in some embodiments, the receive block **730** may take any other form such as the configuration of the receive block **630** among other possibilities.

Similarly to the description of the receive block **630** of FIG. 6C, the receive block **730** has six degrees of freedom (DOF). Three of the six DOF are translational: forward/backward (e.g., linearly along an axis of the receive block **730** that is parallel to the z-axis shown in FIG. 7C), up/down (e.g., linearly along an axis of the receive block **730** that is parallel to the y-axis), and left/right (e.g., linearly along an axis of the receive block **730** that is parallel to the x-axis). Further, three of the six DOF are rotational: pitch (e.g., rotation about the axis of the receive block **730** that is parallel to the x-axis), yaw (e.g., rotation about the axis of the optical component that is parallel to the y-axis), and roll (e.g., rotation about the axis of the optical component that is parallel to the z-axis).

Continuing with the scenario, the system **700** may adjust the position of the receive block **730**, when coupled to the manipulator **762**, by adjusting the forward/backward position, the up/down position, the left/right position, the pitch, the yaw, and/or the roll of the receive block **730** in line with the discussion above. In turn, the system **700** may adjust the relative position between the transmit block (not shown) of the LIDAR **704** and the receive block **730**. In some embodiments, additionally or alternatively to the adjustments to the

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position/orientation of the receive block **730**, the manipulator **762** may adjust the position/orientation of the transmit block (not shown) of the LIDAR device **704** in a similar manner. Through this process, for example, the system **700** may align one or more light sources of the LIDAR device **704** with one or more detectors of the LIDAR device **704**.

In some embodiments, the system **700** may then decouple the manipulator **762** from the receive block **730** (or the transmit block), and the receive block **730** may be configured to remain at the alignment (e.g., relative position) performed by the alignment apparatus **760**. By way of example, the system **700** may apply an epoxy or other adhesive to a periphery of the receive block **730** to maintain the receive block **730** at the aligned relative position to the transmit block of the LIDAR device **704**. In one instance, the manipulator **762** may remain coupled to the receive block **730** until the adhesive is cured. However, other processes are possible as well for maintaining the relative position between the transmit block and the receive block **730** of the LIDAR device **704**. For instance, the receive block **730** may be fastened to a housing of the LIDAR device **704** using bolts, screws, or any other device among other possibilities.

It is noted that the scenario presented above is for exemplary purposes only. Other scenarios are possible as well that may include some or all of the components of the system **700**, or may include other processes than those described. A non-exhaustive list of example variations of the scenario is presented below.

In a first example, the system **700** may not include the light filter **708**. For instance, the camera **706** may be configured to obtain the first image and the second image without the light filter **708** being interposed between the camera **706** and the LIDAR device **704**.

In a second example, the camera **706** and the light filter **708** may be mounted separately from the LIDAR device **704**. For instance, the system **700** may be implemented in an assembly line where multiple LIDAR devices such as the LIDAR device **704** are located on an assembly belt. In this instance, the camera **706**, the light filter **708** and the robotic arm **760** may be mounted independently adjacent to the assembly belt, and may perform similar functions to the scenario described above to calibrate each LIDAR device in the assembly line.

In a third example, the receive block **730** may be illuminated by an auxiliary light source (not shown) similar to the auxiliary light source **170**. For instance, the light filter **708** may remain interposed between the LIDAR device **704** and the camera **706** while the first image of the laser beams emitted by the LIDAR device **704** is captured by the camera **706**, and while the second image of the receive block **730** is captured as well. In this instance, the receive block **730** would be visible to the camera **706** through the light filter **708** due to the illumination by the auxiliary light source with light at the source wavelength that is viewable through the light filter **708**.

In a fourth example, the LIDAR device **704** may be configured to continue emitting light while the camera **106** captures the first image and the second image. For instance, the light filter **708** may alternatively attenuate the light beams having the source wavelength emitted by light sources of the LIDAR device **704**. Thus, in this instance, the light filter **708** may be positioned as shown in FIG. 7B while the camera **706** is capturing the first image indicative of the light source positions. Further, in this instance, the light filter **708** may be positioned as shown in FIG. 7A while the camera **706** is capturing the second image indicative of the detector positions. Thus, various configurations of the light

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filter **708** may therefore affect the operation of the system **700** in line with the discussion above.

In a fifth example, the camera **706** may be configured to capture a single image instead of the first image and the second image. The single image may be indicative of both the light source positions of light sources in the LIDAR device **704**, and the detector positions of detectors in the receive block **730**. Referring back to FIG. 2B by way of example, the single image may capture both the light beams **204a-c** and light reflected off the detectors **232a-c**. As in the third example above, the receive block **730** in this example may be illuminated by an auxiliary light source such that the detectors **232a-c** are viewable through the light filter **708**. Other example scenarios are possible as well.

FIG. 8 illustrates another system **800**, according to an example embodiment. The system **800** may be similar to the systems **100** and **700**. For example, the system **800** includes a mounting platform **802**, a camera **806**, a light filter **808**, and an alignment apparatus **860** that are similar, respectively, to the mounting platform **702**, the camera **706**, the light filter **708**, and the alignment apparatus **760** of the system **700**. The system **800** also includes a LIDAR device **804** that is similar to the LIDAR device **104** of the system **100**. The system **800** also includes a manipulator **862** shaped and configured to couple the alignment apparatus **860** with one or more components of the LIDAR device **804**. The system **800** also includes an auxiliary light source **870** that is similar to the auxiliary light source **170** of the system **100**.

As shown, the LIDAR device **804** has a configuration similar to the LIDAR device **600** of FIGS. 6A-6C. However, in some examples, other configurations are possible as well, such as the configuration of the LIDAR device **200** among other possibilities.

As shown, the light filter **808** is interposed between the LIDAR device **804** and the camera **806**. Additionally, the camera **806** is located at a given position at which the camera **806** can image light beam(s) emitted by the LIDAR device **804** and can image detector(s) (not shown) in the LIDAR device **804**. Referring back to FIG. 6A by way of example, the camera **806** may be positioned to have a field-of-view facing the mirror **660** of the LIDAR device **600**.

However, as shown, the system **800** does not include an actuator (e.g., actuator **712** of system **700**) to move the light filter **808**. Instead, the system **800** includes the auxiliary light source **870** to illuminate a receive block (not shown) of the LIDAR device **804** with light having the source wavelength of light emitted by light source(s) (not shown) in the LIDAR device **804**. For instance, such illumination may allow detectors in the receive block of the LIDAR device **804** to be viewable by the camera **806** through the light filter **808**. Although the auxiliary light source **870** is shown to be mounted separately from other components of the system **800**, in some examples, the auxiliary light source **870** may be alternatively mounted to any of the components of the system **800**, such as the alignment apparatus **860**, the light filter **808**, the mounting platform **802**, etc. In one example, the auxiliary light source **870** may be alternatively mounted inside the LIDAR device **804**. Referring back to FIG. 6C by way of example, the auxiliary light source may be alternatively mounted to a wall of the optics assembly **610**. Other configurations of the auxiliary light source **870** are possible as well.

As shown, the manipulator **862** has a different shape and structure than the manipulator **762** of the system **700**. Referring back to FIG. 6C by way of example, the manipu-

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lator **862** may have any shape suitable for adjusting position/orientation of the transmit block **620** and/or the receive block **630**.

Thus, in some examples, the system **800** may perform similar functions as those described for the system **100** and the system **700**, but may include some variations suitable for other LIDAR device configurations, such as the configuration of the LIDAR device **804**.

FIG. 9 is a flowchart of a method **900**, according to an example embodiment. Method **900** shown in FIG. 9 presents an embodiment of a method that could be used with any of the systems **100**, **700**, **800**, the LIDAR devices **200**, **600**, the transmit block **320**, the light source **400**, and/or the receive block **530**, for example. Method **900** may include one or more operations, functions, or actions as illustrated by one or more of blocks **902-912**. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

In addition, for the method **900** and other processes and methods disclosed herein, the flowchart shows functionality and operation of one possible implementation of present embodiments. In this regard, each block may represent a module, a segment, a portion of a manufacturing or operation process, or a portion of program code, which includes one or more instructions executable by a processor for implementing specific logical functions or steps in the process. The program code may be stored on any type of computer readable medium, for example, such as a storage device including a disk or hard drive. The computer readable medium may include non-transitory computer readable medium, for example, such as computer-readable media that stores data for short periods of time like register memory, processor cache and Random Access Memory (RAM). The computer readable medium may also include non-transitory media, such as 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 may also be any other volatile or non-volatile storage systems. The computer readable medium may be considered a computer readable storage medium, for example, or a tangible storage device.

In addition, for the method **900** and other processes and methods disclosed herein, each block in FIG. 9 may represent circuitry that is wired to perform the specific logical functions in the process.

At block **902**, the method **900** involves mounting a transmit block and a receive block in a light detection and ranging (LIDAR) device to provide a relative position between the transmit block and the receive block. The transmit block may include one or more light sources configured to emit light at a source wavelength. The receive block may include one or more detectors configured to detect light at the source wavelength. In one embodiment, the source wavelength is 905 nm. In other embodiments, the source wavelength may be any other wavelength (e.g., infrared, ultraviolet, x-ray, visible, etc.).

By way of example, the transmit block and the receive block may be mounted by a robotic arm (e.g., alignment apparatuses **160**, **760**, **860**, etc.) into a housing (e.g., housing **210**, optics assembly **610**, etc.) to provide the relative position. In this example, the relative position may be similar to the relative position between transmit block **220** and receive block **230** of FIG. 2B, or the relative position between transmit block **620** and receive block **630** of FIG.

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6C, among other possibilities. However, in other examples, the mounting at block 902 may be performed by a device other than the alignment apparatus. For instance, the mounting at block 902 may correspond to an alignment (e.g., adjustment of the relative position) by a system performing the method 900 for a transmit block and a receive block that are already mounted in a LIDAR device.

In some examples, the LIDAR device may include a lens configured to (i) collimate light emitted from the one or more light sources and (ii) focus light onto the one or more detectors, similarly to the lens 250 of the LIDAR device 200. In other examples, the LIDAR device may include a transmit lens for collimation of emitted light and a receive lens for focusing received light, similarly to the transmit lens 652 and the receive lens 654 of the LIDAR device 600.

At block 904, the method 900 involves locating a camera at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors. By way of example, the given position may be similar to the position of the camera 706 of the system 700. For instance, a field-of-view of the camera may be aligned with a FOV of the LIDAR device where light emitted from the one or more light sources propagates away from the LIDAR device.

At block 906, the method 900 involves obtaining a first image indicative of light source positions of the one or more light sources. The first image, for example, may be obtained using the camera located at the given position and focused at infinity. Referring back to FIG. 2B by way of example, the light source positions of the light sources 222a-c may vary according to the particular orientation and position of the transmit block 220. In turn, the direction of propagation of the light beams 204a-c may also vary, and such variation may be represented by pixels in the first image obtained by the camera.

In some examples, the method 900 may also involve obtaining the first image while the one or more light sources are emitting light at the source wavelength. For instance, a system performing the method 900 may provide power and/or instructions to the LIDAR device to emit the light at the source wavelength, and may provide instructions to the camera to capture the first image while the one or more light sources are emitting the light. Further, in some instances, the system may provide instructions to the camera to adjust the focus to infinity for the source wavelength. Alternatively, for instance, the camera may be configured to have the focus prior to capturing the first image.

In some examples, the method 900 may also involve obtaining the first image while a light filter is interposed between the camera and the one or more light sources. The light filter may be similar to the light filters 108, 708, or 808. In one example, the light filter may be configured to attenuate light having wavelengths other than the source wavelength. In this example, the first image may be more suitable for representing features of the emitted light beams at the source wavelength. In another example, the light filter may be configured to attenuate light within a wavelength range that includes the source wavelength. In this example, the light filter may reduce the intensity of the emitted light to protect components of the camera. Additionally or alternatively, in this example, the light filter may reduce an amount of light propagating toward the camera that has wavelengths proximal to the source wavelength. In turn, for instance, pixels in the first image representing the emitted light beams having the source wavelength may be easily contrasted from surrounding pixels having proximal wavelengths.

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In some examples, the method 900 may also involve detecting a defect in a light source based on the first image. In one example, the first image may indicate that one or more of the light sources in the transmit block has a different intensity, brightness, color, or other characteristic compared to other light sources. For instance, a system performing method 900 may compare pixel properties (e.g., brightness, intensity, color, etc.) associated with one light source against other pixel properties in the first image associated with another light source. Alternatively, for instance, the system may compare the pixel properties of the light source with pre-determined pixel properties or pixel properties in a stored image among other possibilities.

In some examples, the method 900 may also involve detecting an aberration in an optical element optically coupled to a light source based on the first image. Referring back to FIGS. 4A-4C by way of example, the light source may be coupled to an optical element such as the cylindrical lens 404. In this example, the system performing the method 900 may detect the aberration in such optical element by examining the shape or other properties of pixels in the first image that are associated with a light beam from the light source (e.g., compare with other pixels, compare with stored parameters/image, etc.). Thus, in some embodiments, the method 900 may allow diagnosis of light source(s) in the LIDAR device.

At block 908, the method 900 involves obtaining a second image indicative of detector positions of the one or more detectors. Similarly to the first image, the second image may be obtained using the camera located at the given position and focused at infinity. Referring back to FIG. 2B by way of example, the second image may represent the detectors 232a-c that are viewable to the camera via the lens 250 and the mirror 242. Referring back to FIGS. 6A-6C as another example, the second image may represent the detector 632 that is viewable to the camera via the lens 654 and the mirror 660. Thus, in some embodiments, the camera may obtain the first image and the second image while the camera is located at the same given position.

In some examples, the method 900 may also involve obtaining the second image while the one or more light sources are not emitting light at the source wavelength. For instance, a system performing the method 900 may reduce power to the one or more light sources and/or provide instructions to the LIDAR device to stop emitting light beams.

However, in other examples, the method 900 may involve obtaining the second image while the one or more light sources are emitting the light at the source wavelength. In one instance, a light filter may be interposed between the camera and the LIDAR device while the camera is capturing the second image, and the light filter may be configured to attenuate light at the source wavelength emitted by the one or more light sources. In this instance, the system performing the method 900 may then obtain the second image indicative of the detector positions while the light filter attenuates the light beams emitted by the one or more light sources. In another instance, the second image may indicate both the light source positions and the detector positions since the one or more light sources are emitting the light at the source wavelength when the second image is obtained. Other examples are possible as well.

In some examples, the method 900 may also involve obtaining the second image while the one or more detectors are illuminated with light at the source wavelength from an auxiliary light source. The auxiliary light source may be similar to the auxiliary light sources 170 and 870 included,

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respectively, in the systems **100** and **800**. In one example, the camera may be focused at infinity for the source wavelength. In another example, a light filter interposed between the camera and the LIDAR device may be configured to attenuate light having wavelengths other than the source wavelength. In both examples, the auxiliary light source may illuminate the one or more detectors such that reflections of the illuminating light having the source wavelength are viewable by the camera when capturing the second image.

At block **910**, the method **900** involves determining at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image. In one example, the at least one offset may include distances between adjacent regions of the first image that are associated with particular light sources. In another example, the at least one offset may include distances between adjacent regions of the second image that are associated with particular detectors. In yet another example, the at least one offset may include an offset between a region of the first image associated with a given light source, and a corresponding region of the second image associated with a given detector. The offset in the third example may have a horizontal component and a vertical component, or may just be a distance between the respective regions (e.g., number of pixels). As a variation of the third example, the offset may also include a depth component where the camera is configured to obtain 3D images, for instance. Other offsets are possible as well.

In some examples, the method **900** may also involve generating a composite image based on overlaying the first image and the second image. In these examples, the at least one offset may be determined based on separation between one or more pixels in the composite image associated with a light source and one or more pixels in the composite image associated with a corresponding detector.

At block **912**, the method **900** includes adjusting a relative position between the transmit block and the receive block based at least in part on the at least one offset. By way of example, a robotic arm or other device (e.g., alignment apparatuses **160**, **760**, **860**, etc.) may couple to the transmit block and/or the receive block to adjust the relative position. The robotic arm, for instance, may translate the coupled component linearly and/or rotate the coupled component about an axis in line with the discussion for the systems **100**, **700**, and **800**.

Accordingly, in some examples, the method **900** may also involve adjusting the relative position between the transmit block and the receive block by rotating the receive block about an axis. Further, in some examples, the method **900** may also involve adjusting the relative position by rotating the transmit block about an axis.

In some examples, adjusting the relative position between the transmit block and the receive block at block **912** reduces the at least one offset. For instance, where the at least one offset includes an offset between a light source and a corresponding detector, the adjustment of the relative position may reduce the offset to align the light source with the detector. In other examples, adjusting the relative position between the transmit block and the receive block at **912** causes the at least one offset to correspond to a particular offset. For instance, where the at least one offset includes an offset between two adjacent light sources, the adjustment of the relative position may cause the offset to correspond to the particular offset.

FIG. **10** illustrates an image **1000** indicative of light source positions of light sources in a transmit block of a

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LIDAR device, according to an example embodiment. The image **1000** may be similar to the first image described at block **906** of the method **900**. For instance, dark pixels in the image **1000** may represent light beams emitted by one or more light sources in a transmit block. Referring back to FIG. **3** by way of example, each of regions **1002**, **1004**, **1006** in the image **1000** may correspond, respectively, to light beams **302a**, **302b**, **302c** emitted by light sources **322a**, **322b**, **322c** of the transmit block **320**.

FIG. **11** illustrates an image **1100** indicative of detector positions of detectors in a receive block, according to an example embodiment. The image **1100** may be similar to the second image described at block **908** of the method **900**. Referring back to FIG. **5A** by way of example, regions **1102**, **1104**, **1106** in the image **1100** may correspond, respectively, to the detectors **532a**, **532b**, **532c** of the receive block **530**.

FIG. **12** illustrates an image **1200** in a scenario where light sources in a transmit block and detectors in a receive block of a LIDAR device are aligned, according to an example embodiment. For example, the image **1200** may correspond to a composite image generated by overlaying the image **1000** and the image **1100**, in line with the discussion at block **910** of the method **900**.

However, in some examples, light sources and detectors in a LIDAR device may not be aligned with one another due to manufacturing/assembly variability or other factors.

FIG. **13** illustrates an image **1300** in a scenario where the light sources and the detectors of a LIDAR device are misaligned along the up/down DOF described in the discussion of FIG. **7C**, according to an example embodiment. Image **1300** may be a composite image determined similarly to the image **1200**. For instance, region **1302** may correspond to region **1006** of the image **1000**, and region **1304** may correspond to region **1106** of the image **1100**. In turn, the at least one offset determined at block **910** of the method **900** may correspond to a distance (e.g., pixel distance, etc.) between the region **1302** and the region **1304**, and a system (e.g., system **700**, etc.) may perform the adjustment of the relative position between the transmit block and the receive block to align the light source associated with region **1302** with the detector associated with region **1304**. By way of example, the system may adjust the up/down position of the transmit block and/or the up/down position of the receive block to reduce the determined offset, in line with the discussion above.

FIG. **14** illustrates an image **1400** in a scenario where the light sources and the detectors of the LIDAR device are misaligned along the left/right DOF described in the discussion of FIG. **7C**, according to an example embodiment. As a variation of the discussion for image **1300**, an offset in the LIDAR device of image **1400** may correspond to the distance between the regions **1402** (e.g., associated with a light source) and **1404** (e.g., associated with a corresponding detector).

FIG. **15** illustrates an image **1500** in a scenario where the light sources and the detectors are misaligned along the forward/backward DOF, according to an example embodiment. For instance, as shown in image **1500**, the regions that correspond to light source positions appear smaller and closer to one another, than the regions that correspond to detector positions. Similarly here, one or more offsets according to block **910** of the method **900** may be determined. An example offset may be a ratio between: (i) the distance between region **1502** and **1504** (e.g., particular detector positions), and (ii) the distance between regions **1506** and **1508** (e.g., corresponding light source positions). However, other offsets are possible as well such as offsets

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determined by various image processing algorithms to detect differences in sizing or depth among other possibilities.

FIG. 16 illustrates an image 1600 in a scenario where the light sources and the detectors are misaligned along the roll DOF described in FIG. 7C, according to an example embodiment. Similarly here, the offset between the roll position of the light sources and the roll position of the detectors may be determined. For instance, an image processing algorithm may determine such offset, and a system of the present method may adjust the relative position between the transmit block and the receive block accordingly. Alternatively, for instance, manual operation of a robotic arm may be employed by visual inspection of the image 1600 (e.g., video feed, etc.) to adjust the relative position between the transmit block and the receive block, among other possibilities.

FIG. 17 illustrates an image 1700 in a scenario where the light sources and detectors are misaligned along the yaw DOF described in FIG. 7C, according to an example embodiment. For instance, as shown, light beams from light sources at a right side of the image 1700 (e.g., associated with regions 1702 and 1704) are at a greater distance (e.g., offset) to one another than light sources at a left side of the image 1700 (e.g., associated with regions 1706 and 1708). This variation may be due to the yaw of the transmit block. In contrast, distances between adjacent corresponding detectors (e.g., associated with regions 1710 and 1712) do not exhibit the same variation, due to the receive block having a different yaw. Thus, in some examples, the present method may adjust the yaw of the receive block to correspond to the yaw of the transmit block. Alternatively or additionally, in some examples, the present method may adjust the yaw of the transmit block to correspond to the yaw of the receive block.

FIG. 18 illustrates an image 1800 in a scenario where the light sources and detectors are misaligned along the pitch DOF described in FIG. 7C, according to an example embodiment. Similarly to the discussion above for the yaw misalignment in image 1700, the transmit block in this scenario has a pitch orientation that is different from the pitch orientation of the receive block. For instance, a distance (e.g., offset) between light beams indicated by regions 1802 and 1804 is different from the distance between light beams indicated by regions 1806 and 1808, due to the pitch of the transmit block. Further, corresponding detectors for those light beams are not similarly separated in the image 1800, which indicates that the receive block has a different pitch than the pitch of the transmit block. In turn, similarly to the discussion above for image 1700, the present method may adjust the pitch of the transmit block, the receive block, or both, to align the transmit block with the receive block, in line with the discussion at block 912 of the method 900.

Although images 1200-1800 illustrate composite images overlaying a first image (e.g., image 1000, etc.) with a second image (e.g., image 1100), in some examples, the present method may determine the various offsets described above for images 1200-1800 without overlaying the two images. For instance, a computing device herein may determine the various offsets by comparing pixel locations in the first image 1000 with corresponding pixel locations in the second image 1100. Other image processing techniques are possible as well (e.g., filtering, transforms, etc.) for determining the at least one offset described at block 910 of the method 900.

Further, although images 1300-1800 illustrate scenarios where the light sources and the detectors are offset in only one DOF, in some examples, the light sources and the

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detectors may be offset in more than one DOF. For instance, a LIDAR device may have light sources and detectors that are offset in both the forward/backward DOF described in image 1500 and the roll DOF described in image 1600. Other offset combinations are possible as well.

Further, although images 1000-1800 represent light sources and detectors of a LIDAR device having a similar configuration to the LIDAR device 200, in some examples, similar images may be generated for any other LIDAR device configuration, such as the configuration of the LIDAR device 600 among other possibilities.

In addition to alignment of light sources and detectors of a LIDAR device, in some examples, the present method may facilitate diagnosis of the various components of the LIDAR device. As an example, FIG. 19 illustrates an image 1900 indicative of a defect or an aberration. Image 1900 is an example image of light beams from a transmit block, similarly to the image 1000. For instance, region 1902 of image 1900 may correspond to a light beam from a light source, similarly to region 1002 of the image 1000. In one example, region 1904 may represent a light beam from a defective light source. For instance, pixels in region 1904 may have a different color, brightness, intensity, or any other characteristic than pixels in other similar regions (e.g., region 1902), due to a defect in the light source associated with region 1904. In another example, region 1906 may be a region where a light beam from a light source is expected, and therefore the associated light source may also be defective. In yet another example, regions 1908 and 1910 appear distorted compared to similar regions (e.g., region 1902). In turn, for instance, such distortions may indicate that optical elements (e.g., cylindrical lens 404 of FIGS. 4B-4C, etc.) coupled to light sources associated with regions 1908 and 1910 may have aberrations, and the present method may therefore detect the aberrations. Other example defects and aberrations are possible as well. In some examples, the present method may detect the various defects/aberrations described above by comparing the various regions 1904-1910 with similar regions in the image 1900 (e.g., region 1902, etc.). Additionally or alternatively, in some examples, the present method may detect the various defects/aberrations by comparing the image 1900 with a stored image (e.g., image 1000).

FIG. 20 is a flowchart of another method 2000, according to an example embodiment. Method 2000 shown in FIG. 20 presents an embodiment of a method that could be used with any of the systems 100, 700, 800, the LIDAR devices 104, 200, 600, 704, 804, the transmit block 320, the light source 400, and/or the receive block 530, for example. Method 2000 may include one or more operations, functions, or actions as illustrated by one or more of blocks 2002-2004. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

At block 2002, the method 2000 involves obtaining one or more images using a camera located at a given position at which the camera can image light beams emitted by one or more light sources in a transmit block of a LIDAR device and can image one or more detectors in a receive block of the LIDAR device. In some examples, the one or more images may include a single image that indicates both light source positions of the one or more light sources and detector positions of the one or more detectors. For instance, the single image may be similar to images 1200-1800 shown

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in FIGS. 12-18. In other examples, the one or more images may include a first image indicative of the light source positions and a second image indicative of the detector positions, similarly to the first image and the second image described, respectively, at blocks 906 and 908 of the method 900.

In some examples, the method 2000 may also involve causing an actuator to move a light filter to a first position where the light filter is interposed between the camera and the LIDAR device, obtaining a first image indicative of light source positions of the one or more light sources while the light filter is at the first position, causing the actuator to move the light filter to a second position where the light filter is outside a field-of-view of the camera, and obtaining a second image indicative of detector positions of the one or more detectors while the light filter is at the second position. Referring back to FIGS. 7A and 7B by way of example, the actuator, the light filter, and the camera may correspond, respectively, to the actuator 712, the light filter 708, and the camera 706. Thus, in this example, the method 2000 may adjust the position of the light filter 708 to the first position illustrated in FIG. 7A to obtain the first image, and to the second position illustrated in FIG. 7B to obtain the second image.

At block 2004, the method 2000 involves adjusting a relative position between the transmit block and the receive block based on the one or more images. For instance, the adjustment at block 2004 may be similar to the adjustments described at block 912 of the method 900, along some or all the six DOF (e.g., up/down, left/right, forward/backward, roll, yaw, pitch) of the transmit block, the receive block, or both. Through this process, for instance, the present method may align the one or more light sources with the one or more detectors.

In some scenarios, the process described for yaw or pitch alignment in the description of images 1700 and 1800 is less suitable than other methods herein. As an example, the variation in distances between adjacent light sources indicated by a first image (e.g., image 1000) and the variation in distances between adjacent detectors indicated by a second image (e.g., image 1100) may be insufficient for detection of yaw or pitch offsets between the transmit block and the receive block. For instance, the one or more detectors (or the one or more light sources) may be arranged closely to one another. As another example, the transmit block and the receive block may only include, respectively, one light source and one detector, similarly to the transmit block 620 and the receive block 630 shown in FIG. 6C. Thus, in this example, there may be no adjacent light sources or adjacent detectors for the determination of the offsets described in the description of images 1700 and 1800. Accordingly, in some embodiments, alternative or additional processes for rotational position alignment (e.g., yaw, pitch, roll) are presented below.

In one embodiment, the receive block may be coupled to a half-mirror positioned along a receive path of the receive block. Referring back to FIG. 2B by way of example, the half-mirror may correspond to the entrance aperture 234 and may be configured to reflect at least a portion of light incident on the half-mirror, and the receive path may correspond to receive path 208. Further, in this embodiment, the camera may be coupled to at least two light sources positioned along a periphery of a camera lens of the camera. The at least two light sources may be configured to emit light toward the LIDAR device. Further, in this embodiment, the method 2000 may also involve causing the at least two light sources to emit light pulses, and obtaining a third image

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from the camera indicative of reflections of the emitted light pulses off the half-mirror. In one instance, the method 2000 may also involve determining offsets between the reflections indicated by the third image, and determining the rotational position adjustment accordingly. In another instance, the method 2000 may alternatively involve comparing the third image with a stored image, and adjusting the relative position based on the comparison. For example, the stored image may indicate particular pre-determined offsets between the reflected light pulses that correspond to a particular yaw, pitch, or roll of the receive block. In this example, the method 2000 may adjust the relative position to achieve the particular offsets.

In another embodiment, the method 2000 may additionally or alternatively involve actuating at least two probes adjacent to the receive block toward the receive block. A given probe (e.g., force sensor, proximity sensor, etc.) may be configured to provide a signal indicative of contact (or proximity) between the given probe and the receive block. In this embodiment, adjusting the relative position may comprise rotating the receive block (e.g., adjusting yaw, pitch, or roll of the receive block) such that at least two signals from the at least two probes are provided at a substantially same time. For instance, the at least two probes may have a particular yaw or pitch substantially similar to the yaw or pitch of the transmit block, and thus by providing the at least two signals at the substantially same time, the yaw or pitch of the receive block may also correspond to the yaw or pitch of the transmit block.

FIG. 21 illustrates a partial cross-section view of yet another system 2100, according to an example embodiment. The system 2100 may be similar to any of the systems 100, 700, or 800. For instance, as shown, the system 2100 includes a LIDAR device 2104 that is similar to the LIDAR devices 104 and 704 the systems 100 and 700. It is noted that some components of the system 2100 (e.g., alignment apparatus, mounting platform, etc.) are omitted from the illustration of FIG. 21 for convenience in description.

As shown, the LIDAR device 2104 has a configuration similar to the LIDAR device 200. For instance, as shown, the LIDAR device 2104 includes a transmit block 2120, light sources 2122a-c, receive block 2130, detectors 2132a-c, an exit aperture 2134, and a lens 2150 that are similar, respectively, to the transmit block 220, the light sources 222a-c, the receive block 230, the detectors 232a-c, the exit aperture 234, and the lens 250 of the LIDAR device 200. However, in some examples, the system 2100 may be adapted for use with other LIDAR device configurations such as the configuration of the LIDAR device 600, etc. Further, as shown, the system 2100 includes an actuator 2190 and probes 2192-2194.

The actuator 2190 may be configured to move the probes 2192 and 2194 toward the receive block 2130 in line with the discussion above at block 2004 of the method 2000. Example actuators may include motors, pneumatic actuators, hydraulic pistons, relays, solenoids, and piezoelectric actuators among other possibilities.

The probes 2192 and 2194 may include any probes suitable for detection of the receive block 2130 in line with the discussion above at block 2004 of the method 2000. In one example, the probes 2192-2194 may include force sensors that provide a signal if the probes 2192-2194 contact the receive block 2130. In another example, the probes 2192-2194 may include proximity sensors (e.g., IR range sensors, etc.) that provide a signal if the probes 2192-2194 are within a threshold distance to the receive block 2130.

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In the illustration of FIG. 21, a yaw of a component corresponds to an amount of rotation of the component about an axis of the component pointing out of the page. Further, a pitch of the component corresponds to an amount of rotation of the component about an axis of the component pointing away from the component. For instance, a pitch of the transmit block 2120 may be the amount of rotation of the transmit block 2120 about an axis perpendicular to one of the light sources 2122a-c, a pitch of the receive block 2130 may be the amount of rotation of the receive block 2130 about an axis perpendicular to the exit aperture 2134, and a pitch of the probe 2192 may be the amount of rotation of the probe 2192 about an axis perpendicular to the probe 2192 that is pointing toward the receive block 2130, etc.

In line with the discussion above, the system 2100 provides an example embodiment for the rotational position alignment described at block 2004 of the method 2000. Consider an example scenario where the probes 2192-2194 have a particular yaw (i.e., amount of rotation about axis pointing out of page) as shown in FIG. 21. In some examples, the particular yaw may be substantially similar to the yaw of the transmit block 2120. In one example, the probes 2192-2194 may be mounted via a mounting apparatus (not shown) to the transmit block 2120. In this example, the mounting apparatus may have a particular structure that causes the probes 2192-2194 to have a substantially similar yaw to the yaw of the transmit block 2120. In another example, the probes 2192-2194 may be mounted to an alignment apparatus (e.g., alignment apparatus 160, 760, 860, etc.) that provides the particular yaw. For instance, the system 2100 may determine the yaw of the transmit block 2120 by processing an image from a camera (not shown) in line with the description of the image 1700 of FIG. 17. In turn, for instance, the system 2100 may adjust the particular yaw of the probes 2192-2194 by utilizing a robotic arm or other device coupled to the probes 2192-2194 among other possibilities.

Continuing with the example scenario, the actuator 2190 may move the probes 2192-2194 toward the receive block 2130 in line with the discussion at block 2004 of the method 2000. On one hand, if the two probes 2192-2194 detect the receive block 2130 (e.g., provide a signal, etc.) at a substantially similar time, then the system 2100 may determine that the yaw of the receive block 2130 corresponds to the yaw of the probes 2192-2192, and therefore also corresponds to the yaw of the transmit block 2120. On the other hand, if the two probes 2192-2194 detect the receive block 2130 at substantially different times, then the system 2100 may determine that the yaw of the receive block 2130 does not correspond to the yaw of the probes 2192-2194, and therefore does not correspond to the yaw of the transmit block 2120. In this case, the system 2100 may then perform the adjustment of the relative position between the transmit block 2120 and the receive block 2130 in line with the discussion at block 912 of the method 900. Through this process, for example, the transmit block 2120 and the receive block 2130 may be aligned with one another, at least with regard to the yaw DOF.

As a variation of the example scenario, the probes 2192-2194 may be arranged vertically (e.g., along an axis pointing out of the page) instead of the arrangement shown in FIG. 21, or the system 2100 may include two additional probes (not shown) that are arranged vertically. In either case, the probes in this scenario may have a particular pitch (e.g., amount of rotation about an axis pointing away from the probes 2192-2194 toward the receive block 2130). Similarly to the previous scenario, the particular pitch may also

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correspond to a pitch of the transmit block 2120. Thus, in this scenario, a similar process to the previous scenario may be performed by the system 2100 to align the pitch of the receive block 2130 with the pitch of the transmit block 2120.

As a further variation of the example scenarios above, the probes 2192-2194 may be alternatively moved by the actuator 2192 toward the transmit block 2120 instead of the receive block 2130. In this scenario, the system 2100 may adjust the position of the transmit block 2120 to align the pitch and/or yaw of the transmit block 2120 with the pitch and/or yaw of the receive block 2130.

FIG. 22 illustrates a front-view of a camera 2206, according to an example embodiment. The camera 2206 may be similar to the cameras 106, 706, and 806 included, respectively, in the systems 100, 700, and 800. For instance, the camera 2206 may be located at a given position where the camera can capture images of light beams emitted by a LIDAR device and can capture images of detectors in the LIDAR device, similarly to the cameras 106, 706, and 806. However, in some examples, the camera 2206 may be located in other positions such as inside the housing of a LIDAR device, similarly to the probes 2192-2194 of the system 2100. In these examples, the camera 2206 may be configured to only capture images of the detectors in the LIDAR device, or may be configured to only capture images of light beams emitted by the LIDAR device, among other possibilities.

As shown, the camera 2206 includes a lens 2210 and light sources 2212, 2214, 2216, and 2218. However, in some examples, the camera 2206 may include additional, fewer, or different components than those shown. In one example, the camera 2206 may alternatively not include the lens 2210. For instance, the camera 2206 in this example may be an image sensor configured to capture images without use of the lens 2210, among other possibilities. In another example, the camera 2206 may be alternatively configured not to include the light sources 2212-2218, or may be configured to include additional or fewer light sources than the four light sources 2212-2218 shown, in accordance with the discussion at block 2004 of the method 2000.

The lens 2210 may include one or more optical element (e.g., convex lens, concave lens, Fresnel lens, mirror, etc.) arranged to modify, condition, focus, and/or redirect light incident on the lens 2210 toward imaging sensors (not shown) of the camera 2206. In some examples, the lens 2210 may be configured to provide an infinity focus for incident light having a source wavelength. In one embodiment, the source wavelength is 905 nm. However, other source wavelengths are possible as well (e.g., infrared, ultraviolet, x-ray, visible, etc.).

The light sources 2212-2218 may include laser diodes, light emitting diodes (LEDs), vertical cavity surface emitting lasers (VCSEL), organic light emitting diodes (OLEDs), polymer light emitting diodes (PLED), light emitting polymers (LEP), liquid crystal displays (LCD), micro-electromechanical systems (MEMS), filament light sources, or any other device configured to selectively transmit, reflect, and/or emit light propagating away from the camera 2206. In some examples, the light sources 2212-2218 may be configured to emit light at the source wavelength of light emitted by the LIDAR device (not shown) imaged by the camera 2206. Referring back to FIG. 7A by way of example, the camera 2206 may correspond to the camera 706 of the system 700. Thus, in this example, the light sources 2212-2218 may emit light having the source wavelength that can propagate through the light filter 708 similarly to light emitted by the LIDAR device 704. However, in other

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examples, the light sources **2212-2218** may be configured to emit light at other wavelengths. For instance, the light filter may allow propagation of the light from the light sources **2212-2218** even if the light has other wavelengths, or the light filter may not be interposed between the camera **2206** and the LIDAR device, similarly to the configuration shown in FIG. 7B, among other possibilities.

As shown, the light sources **2212-2218** are positioned along a periphery of the camera lens **2210**. However, in some examples, the light sources **2212-2218** may be alternatively positioned at a different location. In one example, referring back to FIG. 7A, the light sources **2212-2218** may be alternatively positioned along a periphery of the light filter **708**. In another example, referring back to FIG. 21, the light sources **2212-2218** may be alternatively positioned within a housing of the LIDAR device **2104** similarly to the probes **2192-2194**. As a variation of the previous example, the camera **2206** may be alternatively positioned inside the housing of the LIDAR device **2104** as well similarly to the actuator **2190**. In yet another example, referring back to FIG. 21, the light sources **2212-2218** may be alternatively positioned at a periphery of the transmit block **2120** or at a periphery of the receive block **2130**. Other positions for the light sources **2212-2218** are possible as well.

Thus, in some examples, the light sources **2212-2218** may be utilized by a system of the present method to determine the at least one offset in line with the discussion at block **910** of the method **900**, and therefore facilitate the adjustment of the relative position between a transmit block and a receive block of a LIDAR device in line with the discussion at block **912** of the method **900**. In one example, the light sources **2212-2218** may facilitate alignment of the rotational position (e.g., yaw, pitch, roll) of a transmit block and a receive block in line with the discussion at block **2004** of the method **2000**.

As an example scenario for rotational position alignment using the camera **2206**, suppose that the camera **2206** corresponds to the camera **706** of the system **700**. In the scenario, the light sources **2212-2218** may be configured to emit light that propagates through the light filter **708** (e.g., if the light filter **708** is interposed between the camera **2206** and the LIDAR device **704** as illustrated in FIG. 7A). Suppose that, for the sake of example, the LIDAR device **704** has the configuration of the LIDAR device **200** shown in FIG. 2B. In this example, the light from the light sources **2212-2218** may propagate through the lens **250**, and then reflect off mirror **242** onto the entrance aperture **234**. Further, suppose that, in this example, the entrance aperture **234** includes a half-mirror that reflects at least a portion of the light from the light sources **2212-2218**. In turn, the reflected light may reflect off the half-mirror, then reflect off the mirror **242**, then propagate through the lens **250** of the LIDAR device, and then propagate into the lens **2210** of the camera **2206**. At this point in the scenario, the camera **2206** may capture an image of the reflected light in line with the discussion at block **2004** of the method **2000**.

Continuing with the scenario, a system of the present method may then analyze the image, in line with the discussion for images **1700-1800**, using the properties (e.g., position, shape, intensity, etc.) of the light beams originating from the light sources **2212-2218** to determine yaw or pitch offsets between the transmit block and the receive block.

As a variation of the scenario above, suppose that the light sources **2212-2218** are alternatively positioned along a periphery of the transmit block **220** of the LIDAR device **200**. In this scenario, four mirrors may be positioned at the positions shown for the light sources **2212-2218**. In turn, the

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four mirrors may reflect the light from the light sources **2212-2218** towards the receive block **230** of the LIDAR device **200**, and the camera **2206** may capture an image of reflections of that light off the entrance aperture **234** (e.g., half-mirror) to determine a possible yaw/pitch offset between the transmit block **220** and the receive block **230**.

As another variation of the scenario, suppose that the light sources **2212-2218** are alternatively positioned along a periphery of the receive block **230** of the LIDAR device **200**. In this scenario, a system of the present method may analyze an image of light from the light sources **2212-2218** in line with the discussion for images **1600-1800** to determine the rotational position (e.g., roll, yaw, pitch) of the receive block.

As yet another variation of the scenario, the light sources **2212-2218** may be alternatively positioned along a periphery of the transmit block **220** of the LIDAR device **200**, and four additional similar light sources may be positioned along the periphery of the receive block **230** of the LIDAR device **200**. Similarly here, one or more images of the light from the light sources **2212-2218** and the four additional light sources may be obtained from the camera **2206** and analyzed by the system of the present method to determine rotational offsets (e.g., roll, yaw, pitch) between the transmit block and the receive block. Thus, various configurations and positions are possible for the light sources **2212-2218** to facilitate optics alignment in line with the discussion above.

It should be understood that arrangements described herein are for purposes of example only. As such, those skilled in the art will appreciate that other arrangements and other elements (e.g. machines, interfaces, functions, orders, and groupings of functions, etc.) can be used instead, and some elements may be omitted altogether according to the desired results. Further, many of the elements that are described are functional entities that may be implemented as discrete or distributed components or in conjunction with other components, in any suitable combination and location, or other structural elements described as independent structures may be combined.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

What is claimed is:

1. A method comprising:

mounting a transmit block and a receive block in a light detection and ranging (LIDAR) device to provide a relative position between the transmit block and the receive block, wherein the transmit block includes one or more light sources configured to emit light at a source wavelength, and wherein the receive block includes one or more detectors configured to detect light at the source wavelength;

locating a camera at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors;

obtaining a first image using the camera located at the given position and focused at infinity, wherein the first image is indicative of light source positions of the one or more light sources;

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obtaining a second image using the camera located at the given position and focused at infinity, wherein the second image is indicative of detector positions of the one or more detectors in the receive block;

comparing the first image with the second image to determine separation between one or more pixels associated with a light source and one or more pixels associated with a corresponding detector;

based on at least the comparison, determining at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image; and

adjusting the relative position between the transmit block and the receive block based at least in part on the at least one offset.

2. The method of claim 1, wherein the LIDAR device further includes a lens configured to (i) collimate light emitted from the one or more light sources and (ii) focus light onto the one or more detectors, and wherein the given position is such that the camera can image light beams emitted by the one or more light sources via the lens and can image the one or more detectors via the lens.

3. The method of claim 1, wherein adjusting the relative position between the transmit block and the receive block comprises:

rotating the receive block about an axis.

4. The method of claim 1, wherein obtaining the first image comprises:

obtaining the first image while the one or more light sources are emitting light at the source wavelength.

5. The method of claim 4, wherein obtaining the first image further comprises:

obtaining the first image while a light filter is interposed between the camera and the one or more light sources, wherein the light filter is configured to attenuate light within a wavelength range that includes the source wavelength.

6. The method of claim 1, wherein obtaining the second image comprises:

obtaining the second image while the one or more light sources are not emitting light at the source wavelength and the one or more detectors are illuminated with light at the source wavelength from an auxiliary light source.

7. The method of claim 1, wherein comparing the first image with the second image comprises generating a composite image based on overlaying the first image and the second image, and

wherein the composite image includes the one or more pixels associated with the light source and the one or more pixels associated with the corresponding detector.

8. The method of claim 1, wherein adjusting the relative position between the transmit block and the receive block reduces the at least one offset.

9. The method of claim 1, wherein adjusting the relative position between the transmit block and the receive block causes the at least one offset to correspond to a particular offset.

10. The method of claim 1, further comprising:

detecting a defect in a light source based on the first image.

11. The method of claim 1, further comprising:

detecting an aberration in an optical element optically coupled to a light source based on the first image.

12. The method of claim 1, wherein the receive block is coupled to a half-mirror positioned along a receive path of the receive block, wherein the camera is coupled to at least two light sources positioned along a periphery of a camera

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lens of the camera and configured to emit light toward the LIDAR device, the method further comprising:

causing the at least two light sources to emit light pulses; obtaining a third image from the camera indicative of reflections of the emitted light pulses off the half-mirror coupled to the receive block; and

comparing the third image with a stored image, wherein adjusting the relative position between the transmit block and the receive block is further based on the comparison.

13. The method of claim 1, further comprising actuating at least two probes positioned adjacent to the receive block toward the receive block, wherein a given probe is configured to provide a signal indicative of contact between the given probe and the receive block, wherein adjusting the relative position between the transmit block and the receive block comprises rotating the receive block such that at least two signals from the at least two probes are provided at a same time.

14. A system comprising:

a mounting platform to mount a light detection and ranging (LIDAR) device that provides a relative position between a transmit block in the LIDAR device and a receive block in the LIDAR device, wherein the transmit block includes one or more light sources configured to emit light at a source wavelength, wherein the receive block includes one or more detectors configured to detect light at the source wavelength;

a camera located at a given position at which the camera, when focused at infinity, can image light beams emitted by the one or more light sources and can image the one or more detectors;

an alignment apparatus configured to adjust the relative position between the transmit block and the receive block; and

a controller configured to:

obtain a first image from the camera located at the given position and focused at infinity, wherein the first image is indicative of light source positions of the one or more light sources;

obtain a second image from the camera located at the given position and focused at infinity, wherein the second image is indicative of detector positions of the one or more detectors in the receive block;

compare the first image with the second image to determine separation between one or more pixels associated with a light source and one or more pixels associated with a corresponding detector;

based on at least the comparison, determine at least one offset based on the light source positions indicated by the first image and the detector positions indicated by the second image; and

cause the alignment apparatus to adjust the relative position between the transmit block and the receive block based at least in part on the at least one offset.

15. The system of claim 14, wherein the LIDAR device further includes a lens configured to (i) collimate light emitted from the one or more light sources and (ii) focus light onto the one or more detectors, and wherein the given position is such that the camera can image light beams emitted by the one or more light sources via the lens and can image the one or more detectors via the lens.

16. The system of claim 14, further comprising:

a light filter configured to attenuate light within a wavelength range that includes the source wavelength; and an actuator coupled to the light filter, wherein the controller is further configured to:

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cause the actuator to move the light filter to a first position where the light filter is interposed between the camera and the one or more light sources; obtain the first image while the light filter is at the first position; 5
 cause the actuator to move the light filter to a second position where the light filter is outside a field-of-view of the camera; and
 obtain the second image while the light filter is at the second position. 10

17. The system of claim **14**, further comprising:
 at least two light sources positioned along a periphery of a camera lens of the camera and configured to emit light toward the LIDAR device, wherein the receive block is coupled to a half-mirror positioned along a receive path of the receive block, and wherein the controller is further configured to: 15
 cause the at least two light sources to emit light pulses;
 obtain a third image from the camera indicative of reflections of the emitted light pulses off the half-mirror coupled to the receive block; and 20

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adjust the relative position between the transmit block and the receive block based also on the third image.

18. The system of claim **14**, further comprising:
 at least two probes positioned adjacent to the receive block, wherein a given probe is configured to provide a signal indicative of contact between the given probe and the receive block, and wherein the controller is further configured to:
 control an actuator to move the at least two probes toward the receive block; and
 cause the alignment apparatus to rotate the receive block such that at least two signals from the at least two probes are provided at a same time.

19. The system of claim **14**, wherein causing the alignment apparatus to adjust the relative position between the transmit block and the receive block reduces the at least one offset.

20. The system of claim **14**, wherein the controller is further configured to:
 detect an aberration in an optical element optically coupled to a light source based on the first image.

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