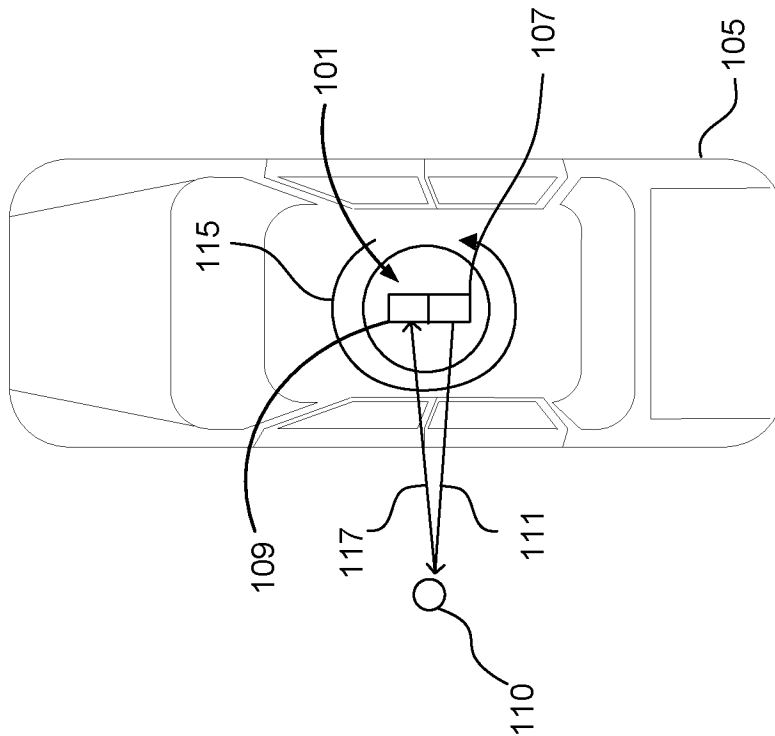
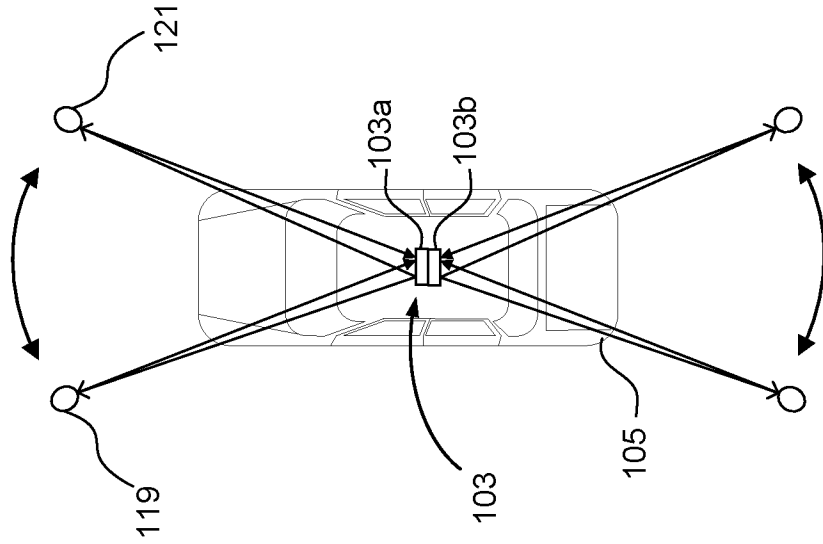




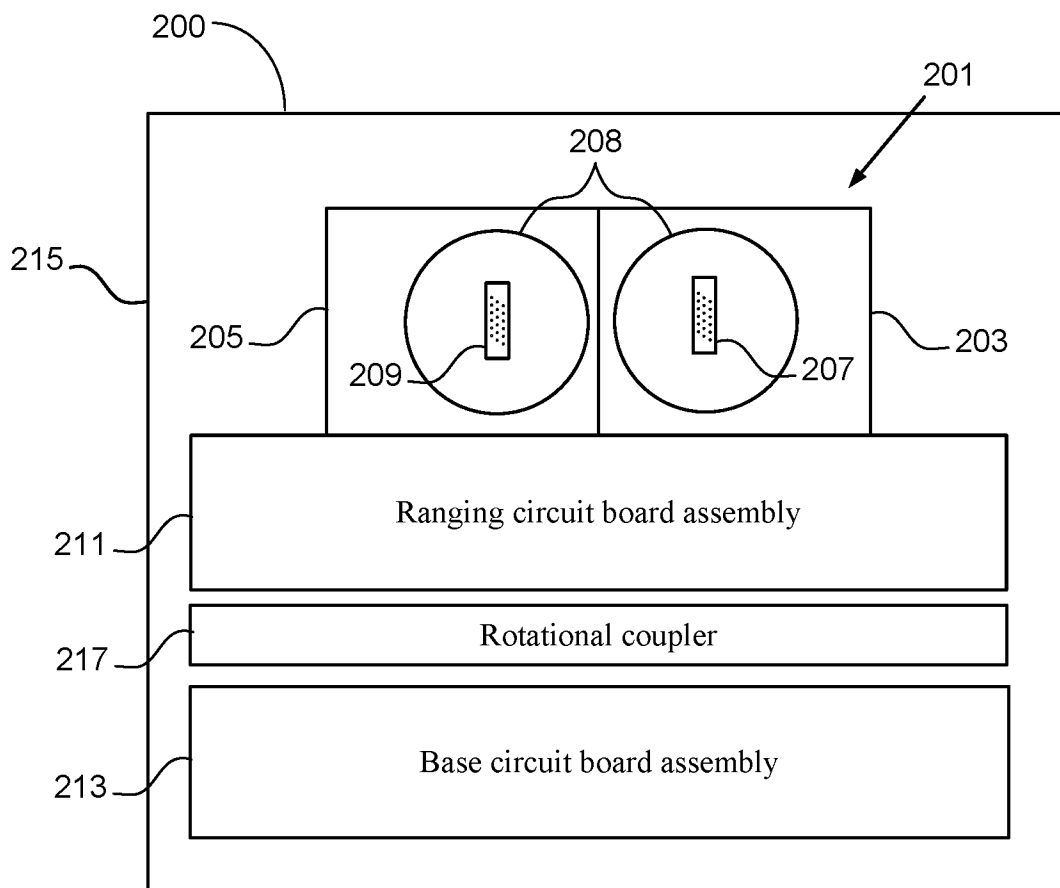


FIG. 2A

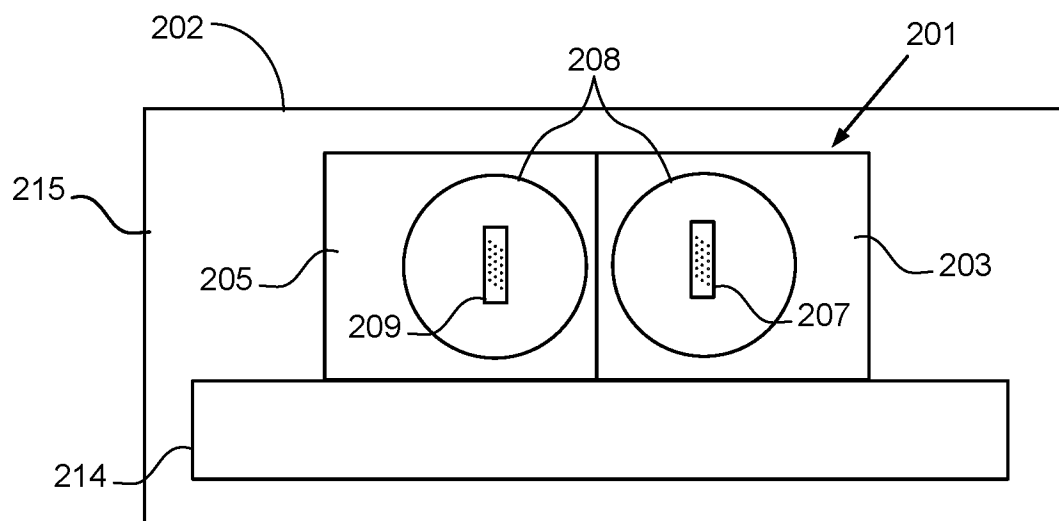


FIG. 2B

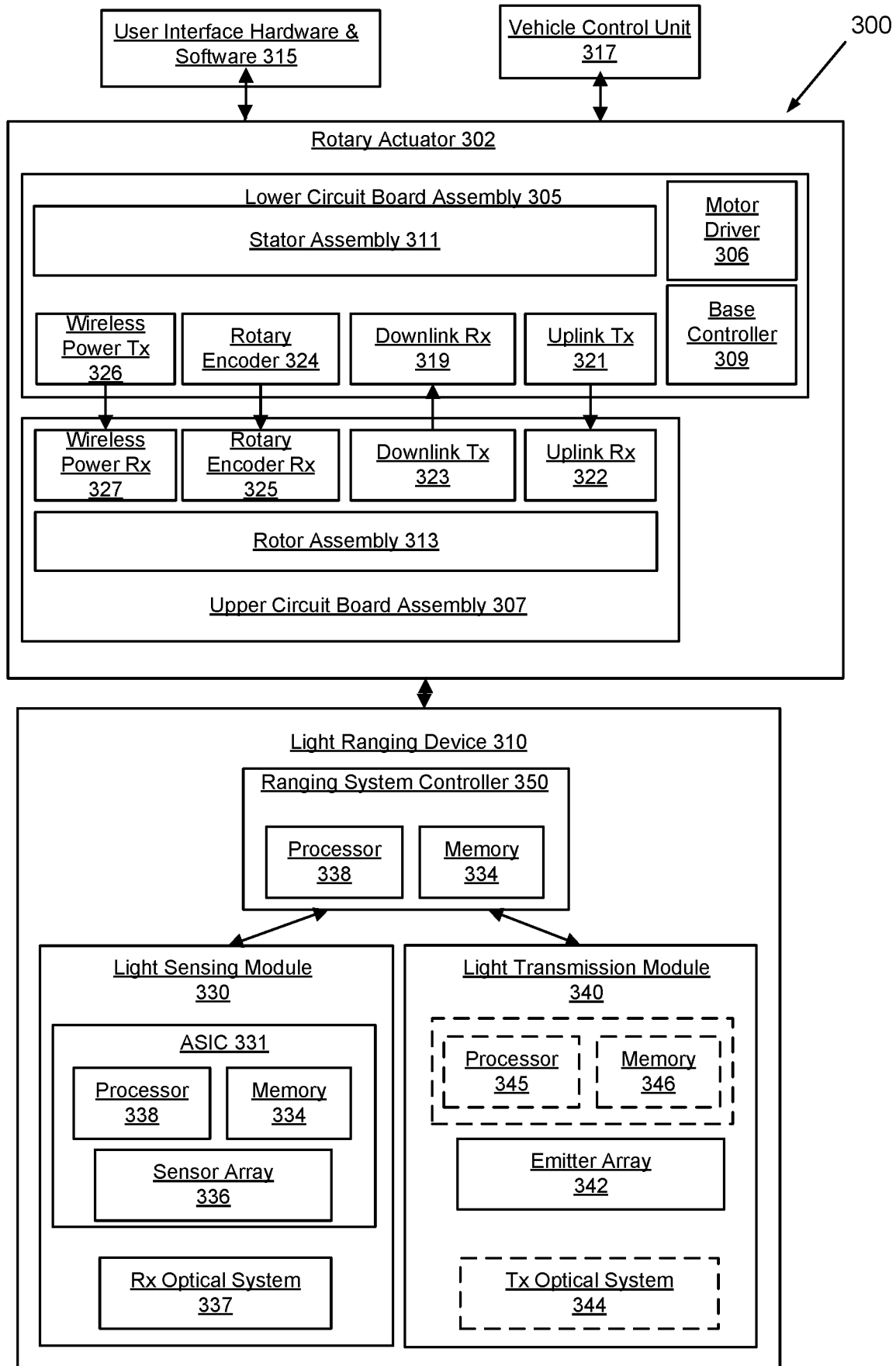
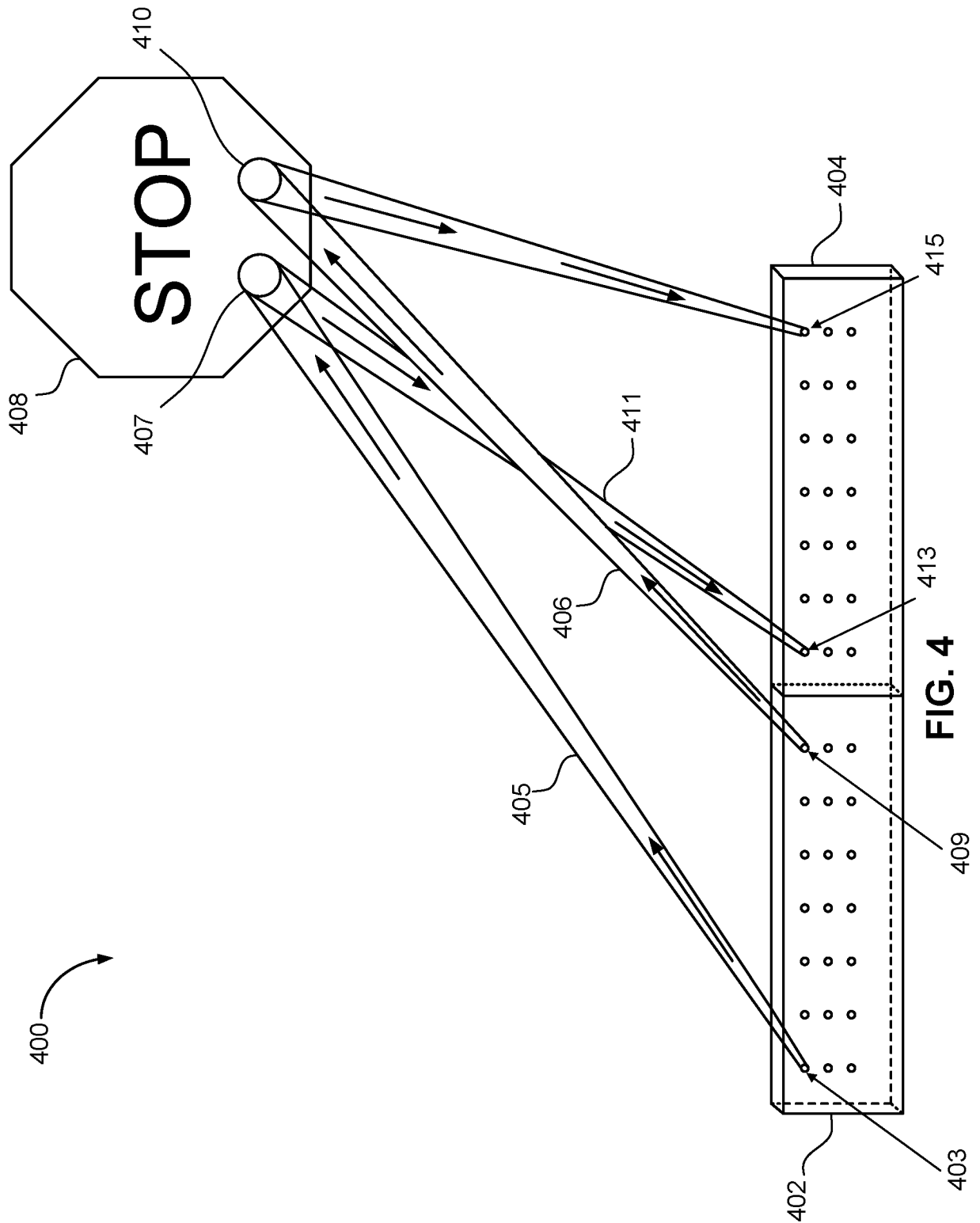


FIG. 3

IPR2023-01422

Ouster

Ex. 2002 - 3



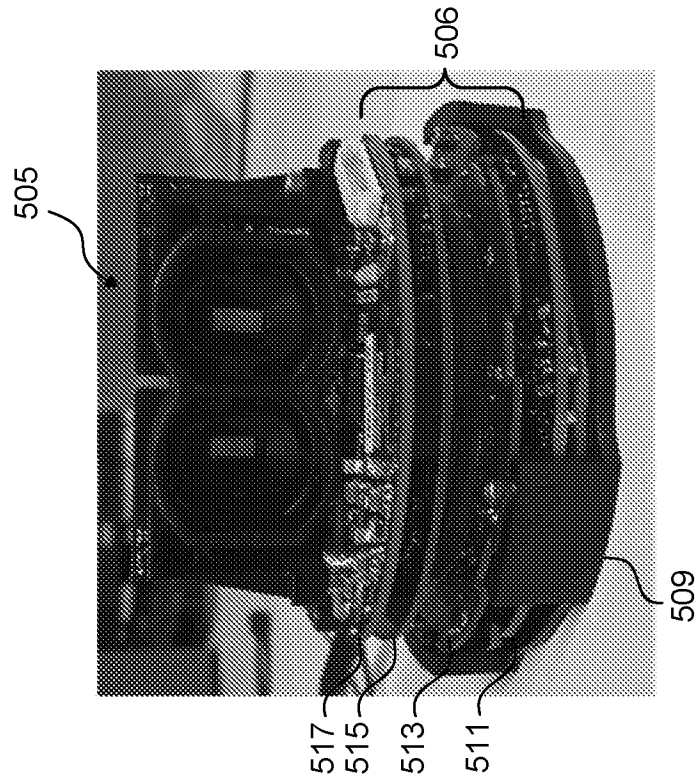


FIG. 5B

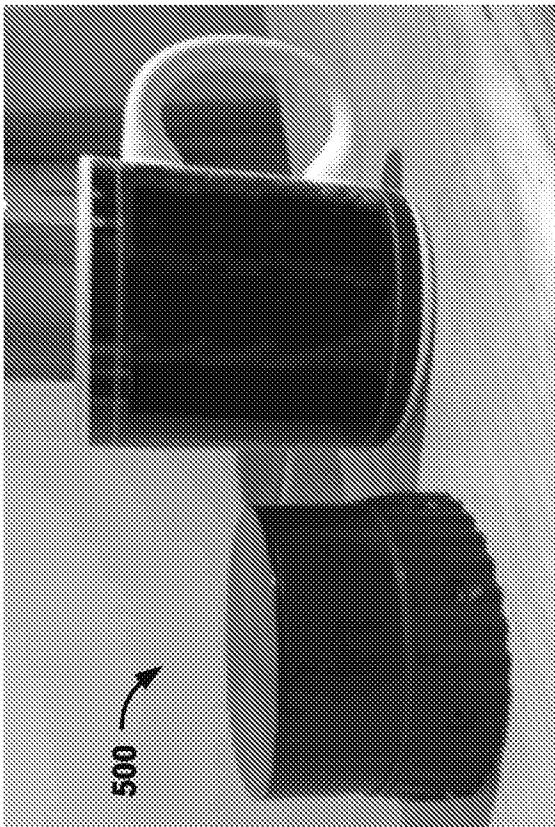
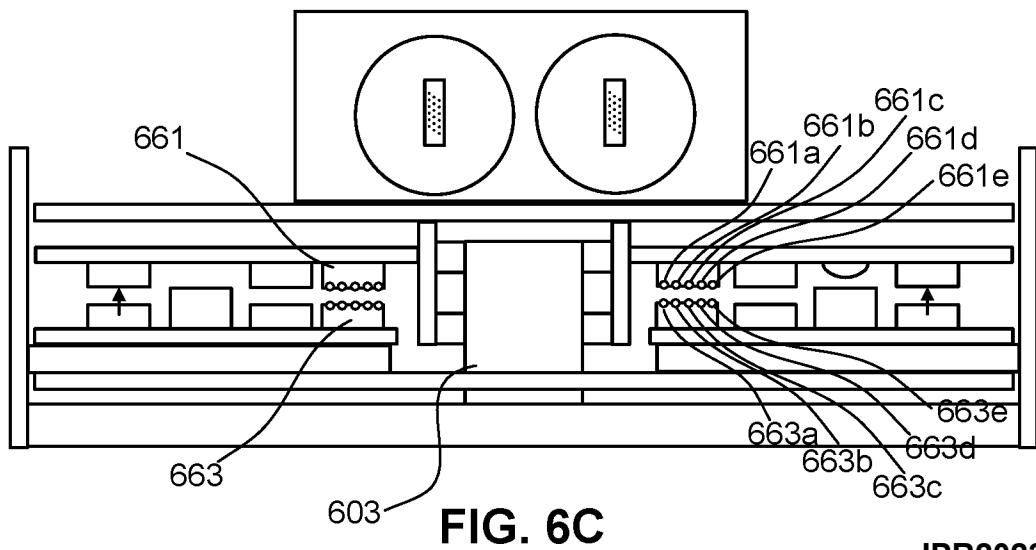
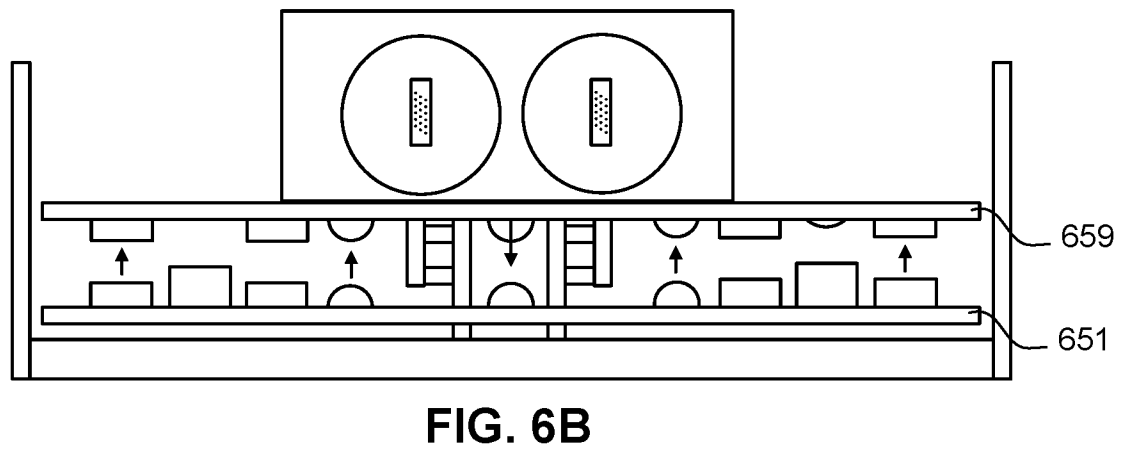
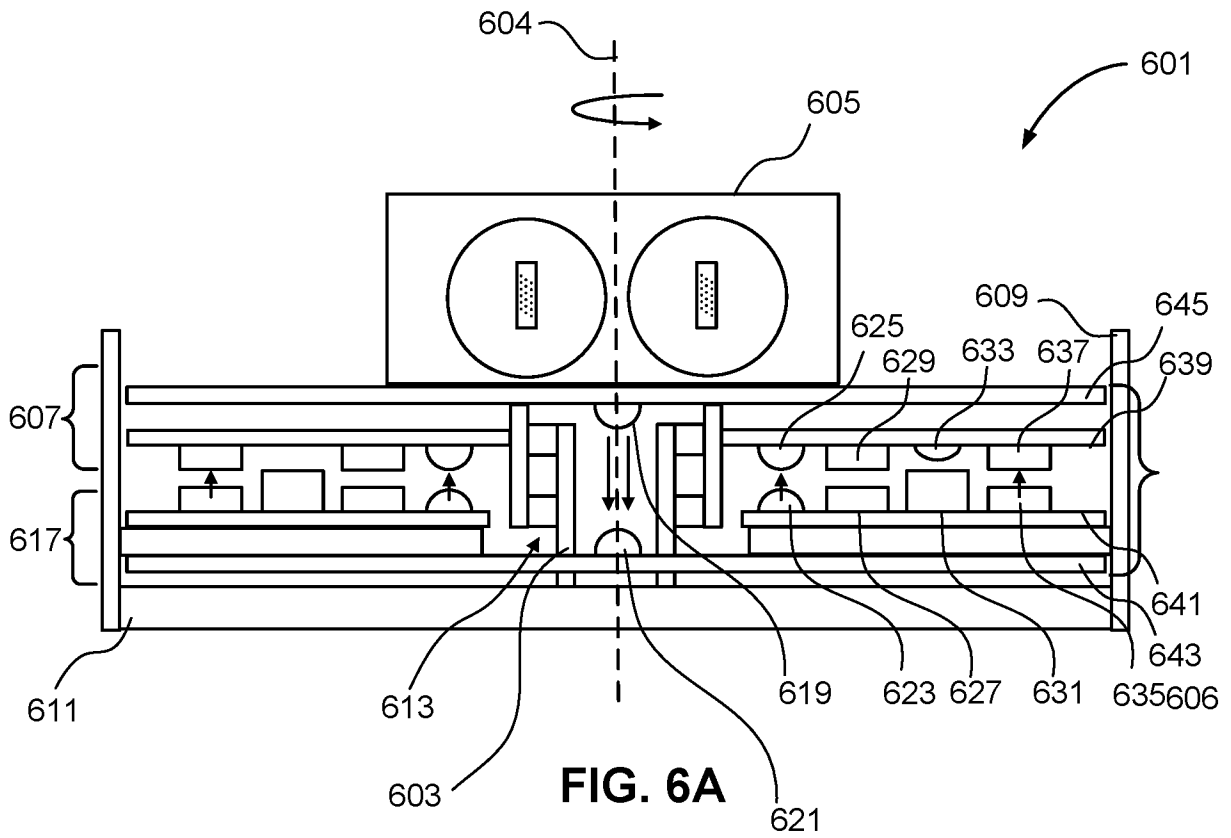


FIG. 5A



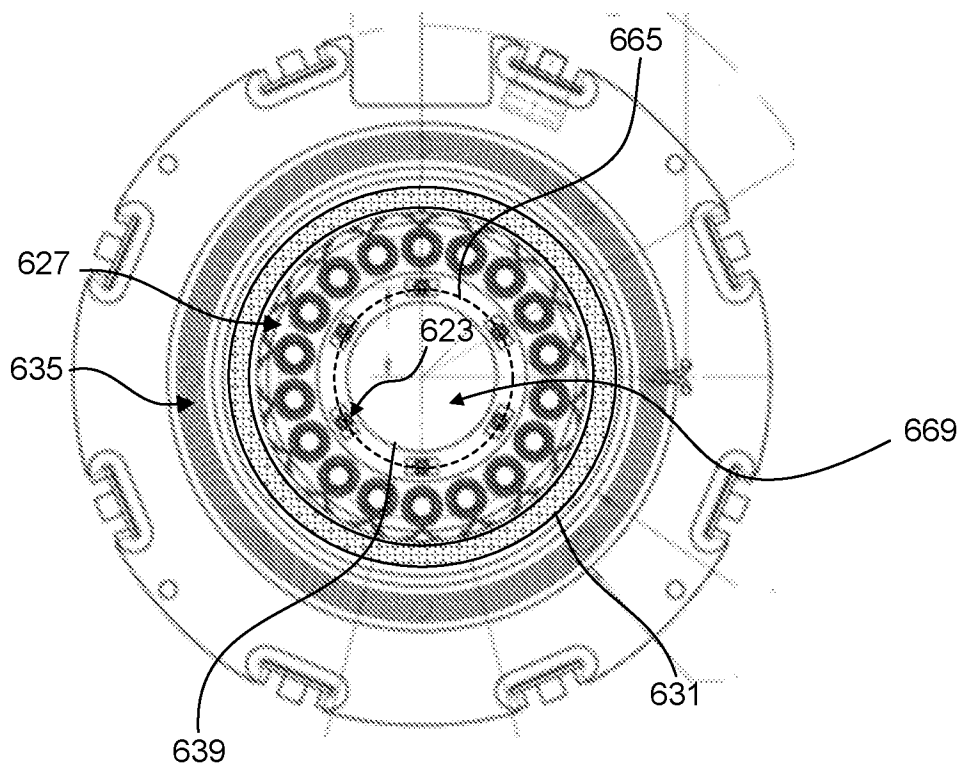


FIG. 6D

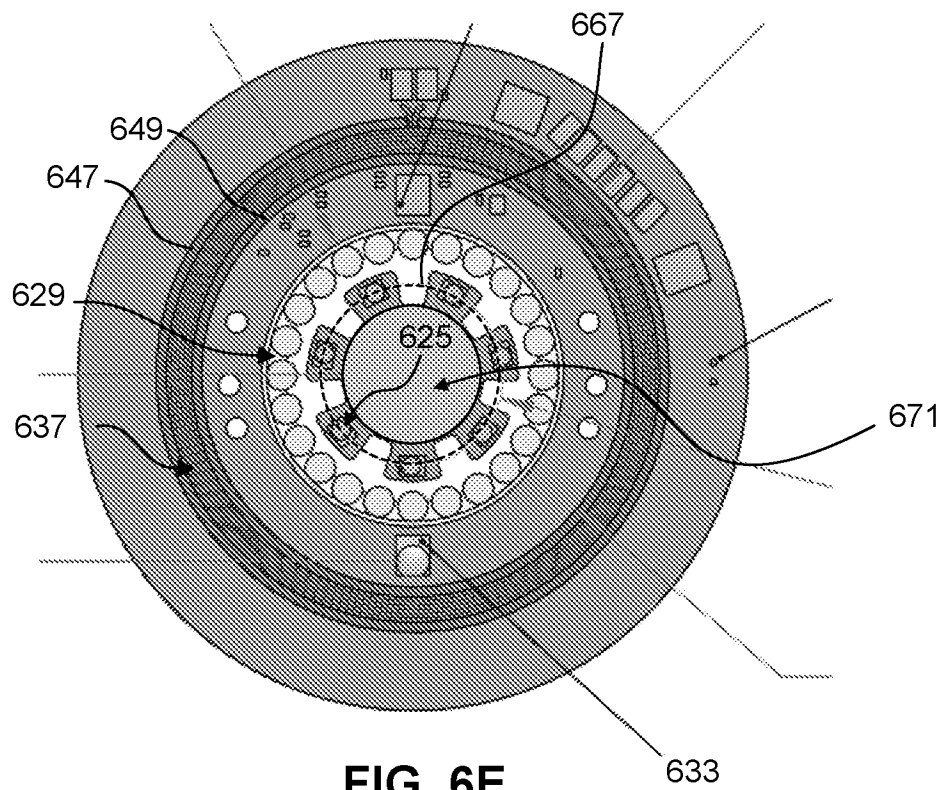


FIG. 6E

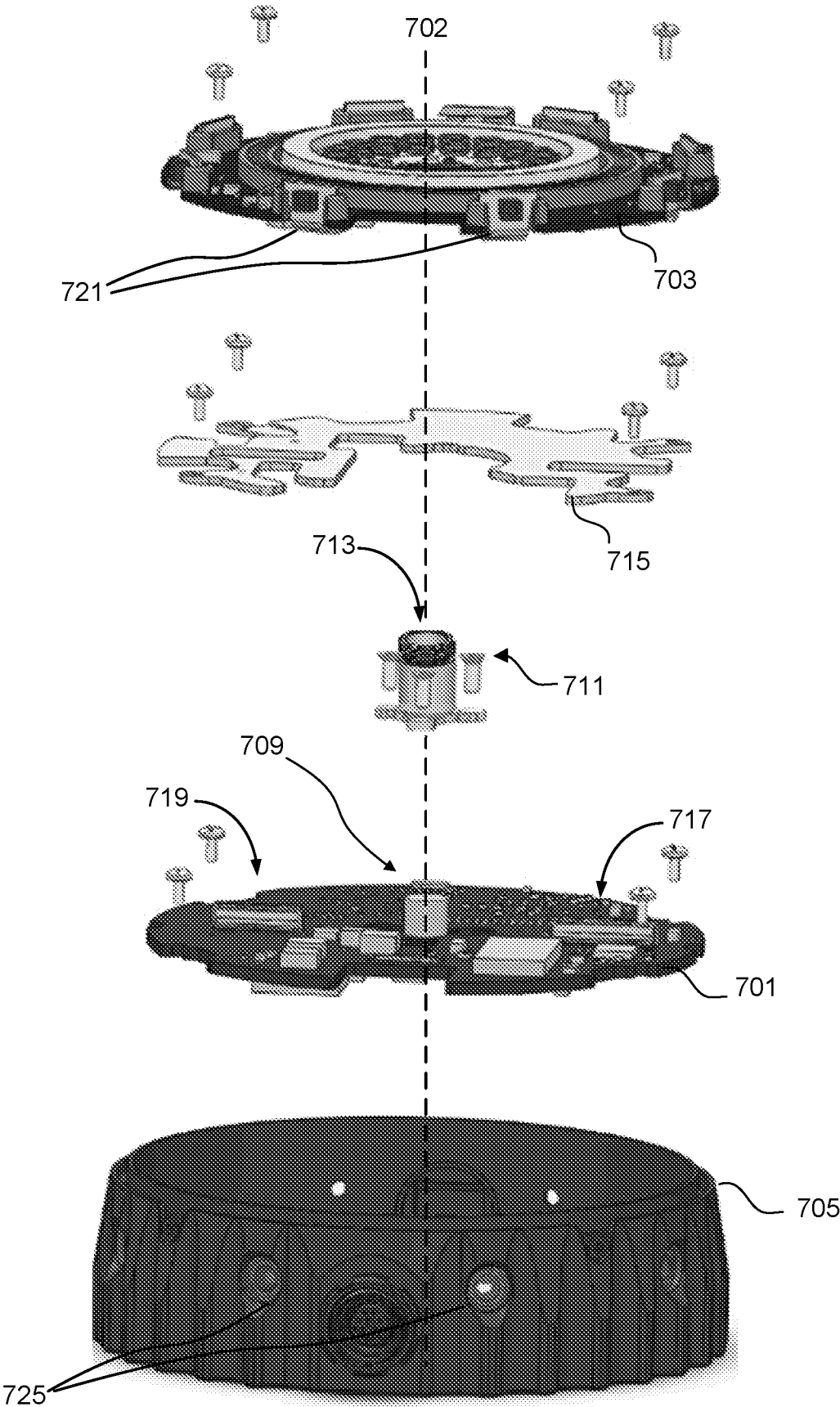


FIG. 7

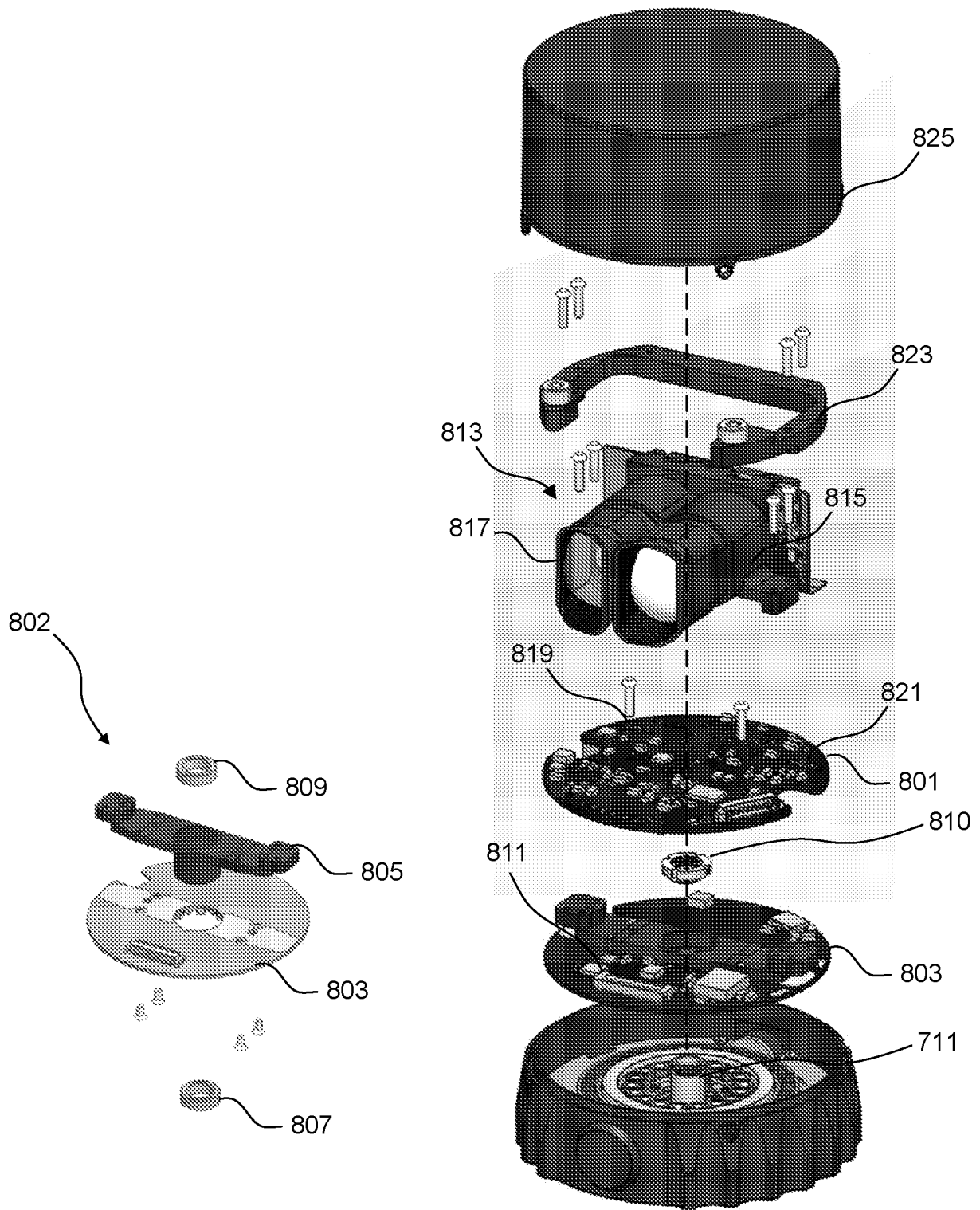
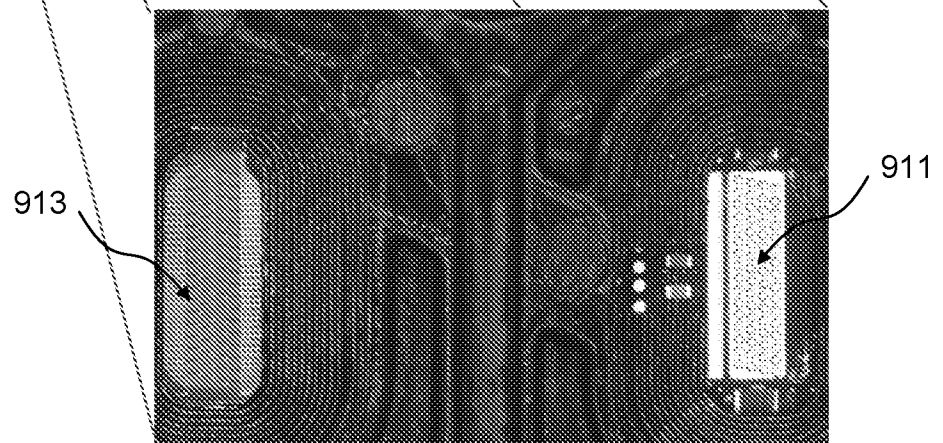
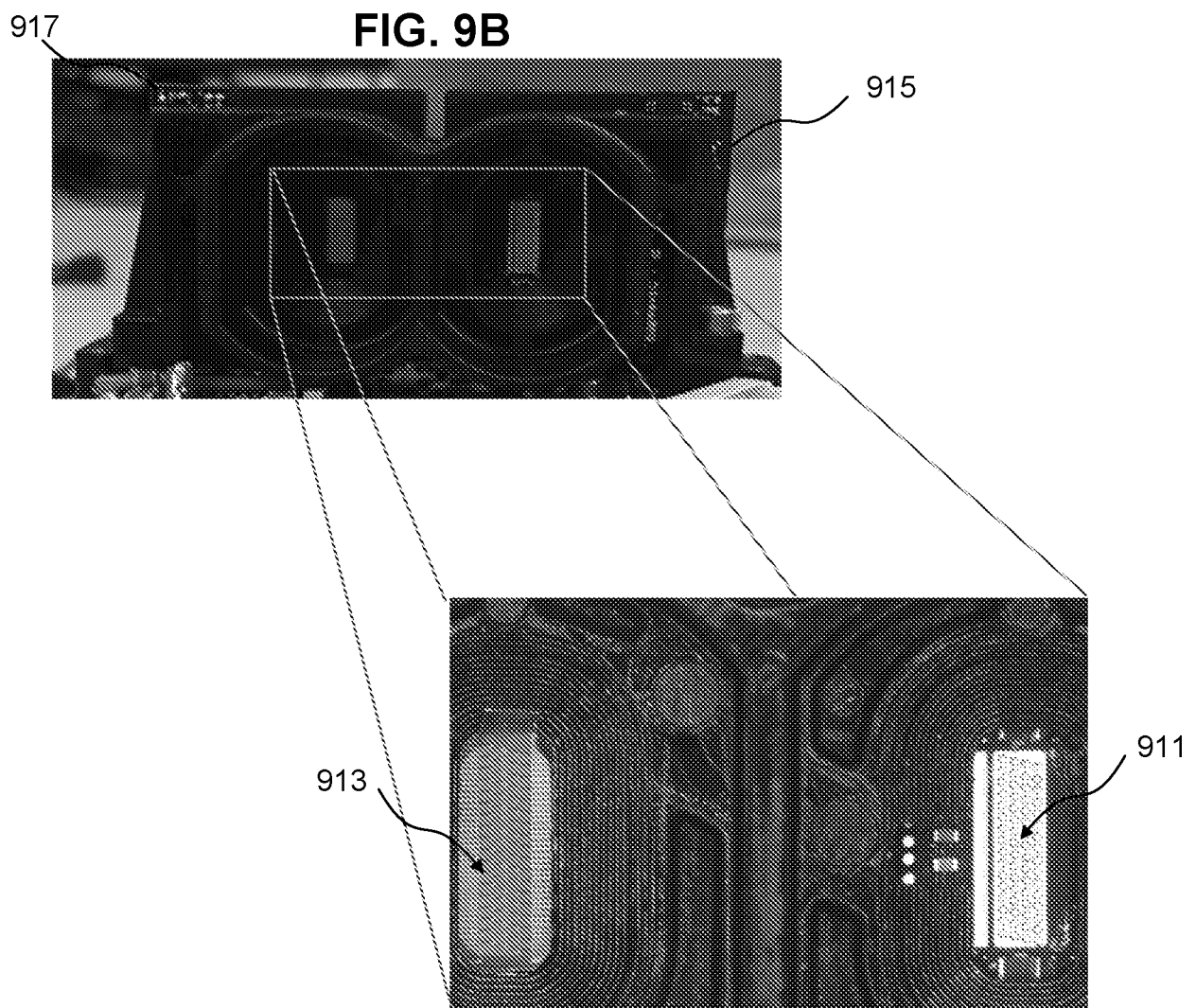
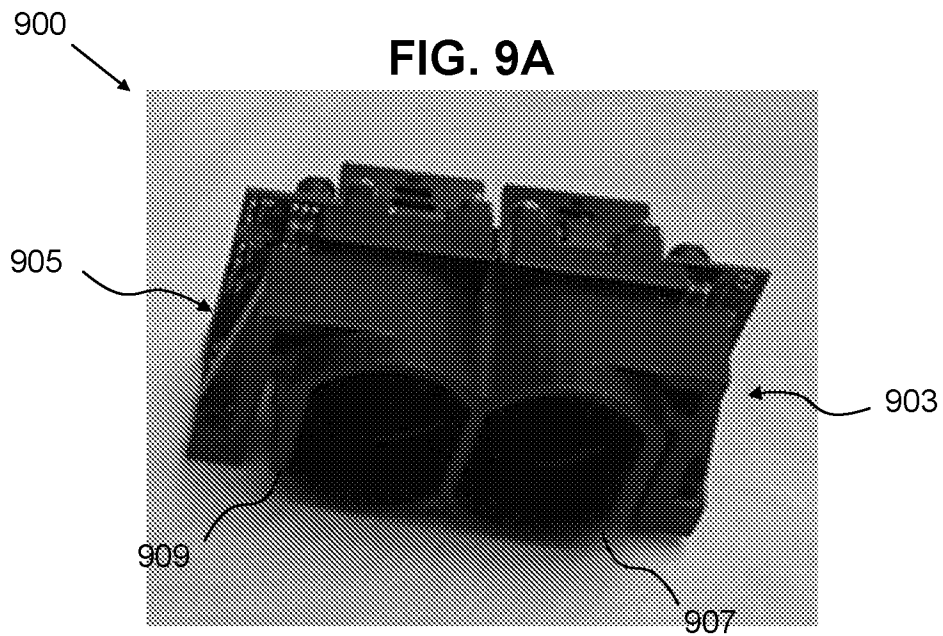


FIG. 8



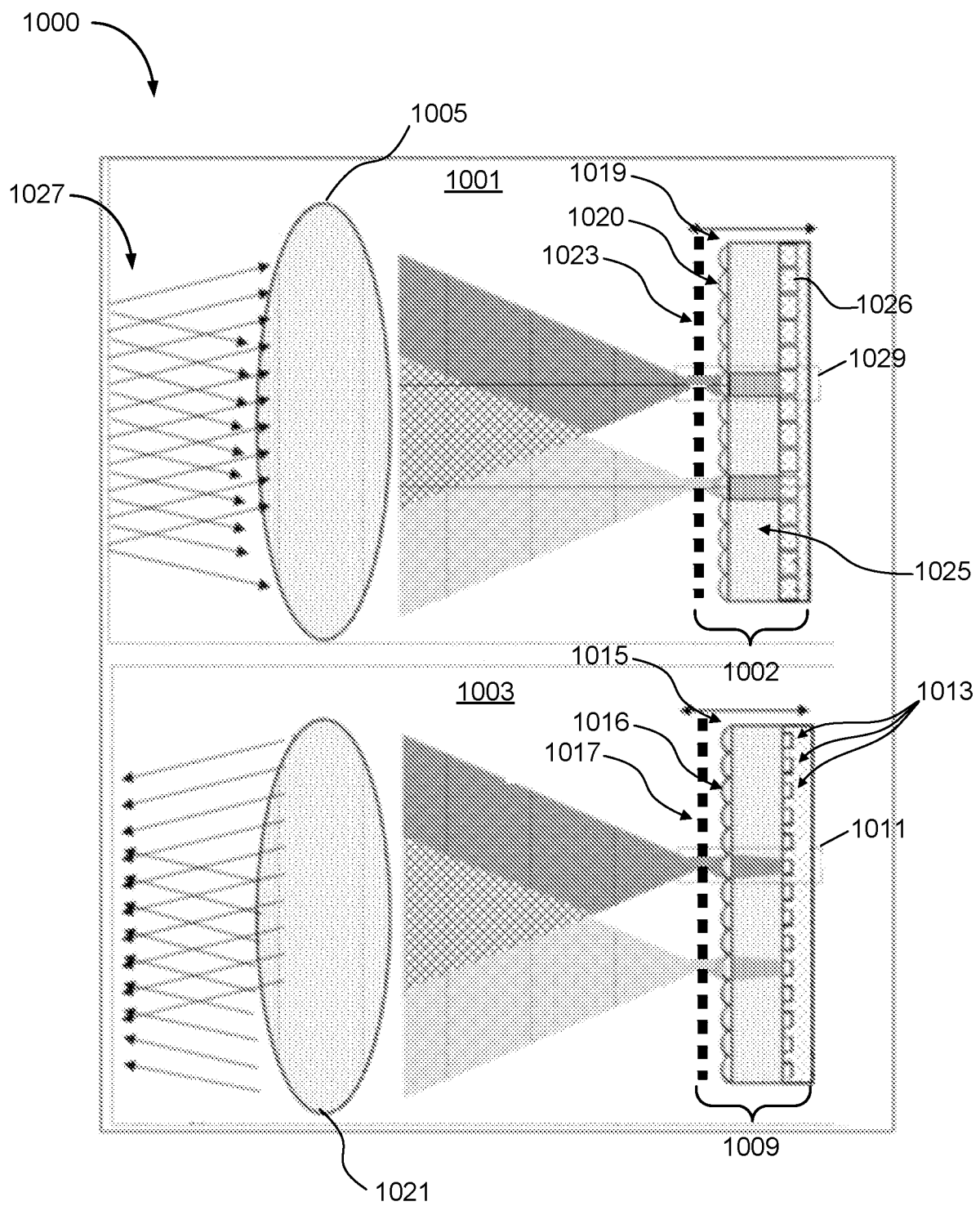


FIG. 10

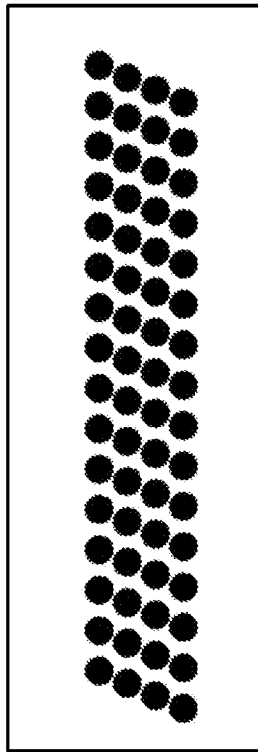


FIG. 11A

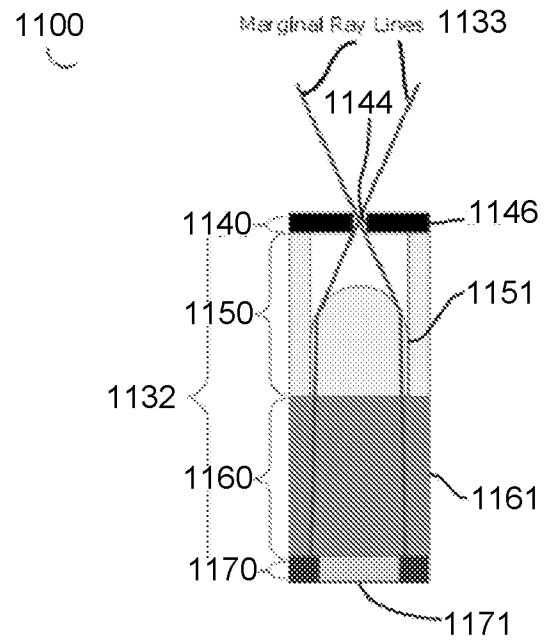


FIG. 11B

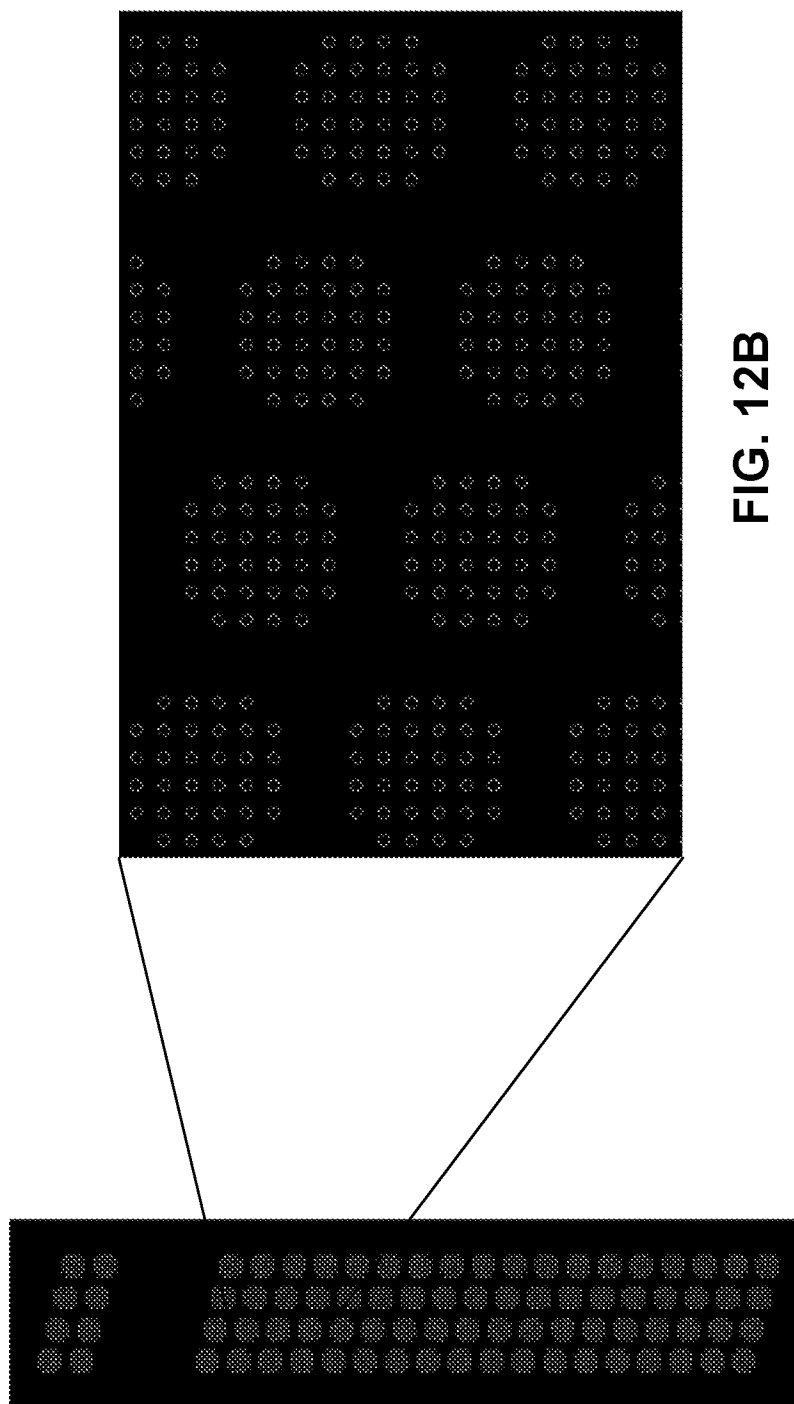


FIG. 12B

FIG. 12A

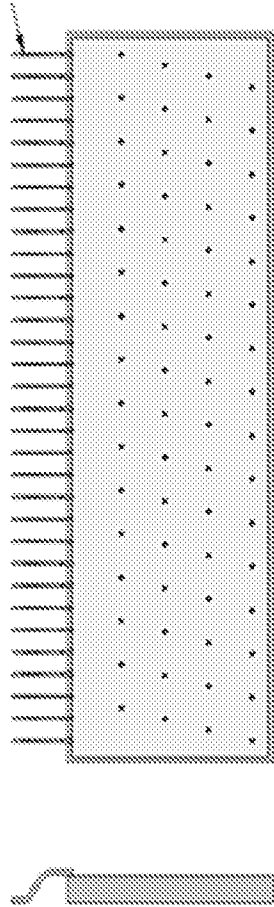
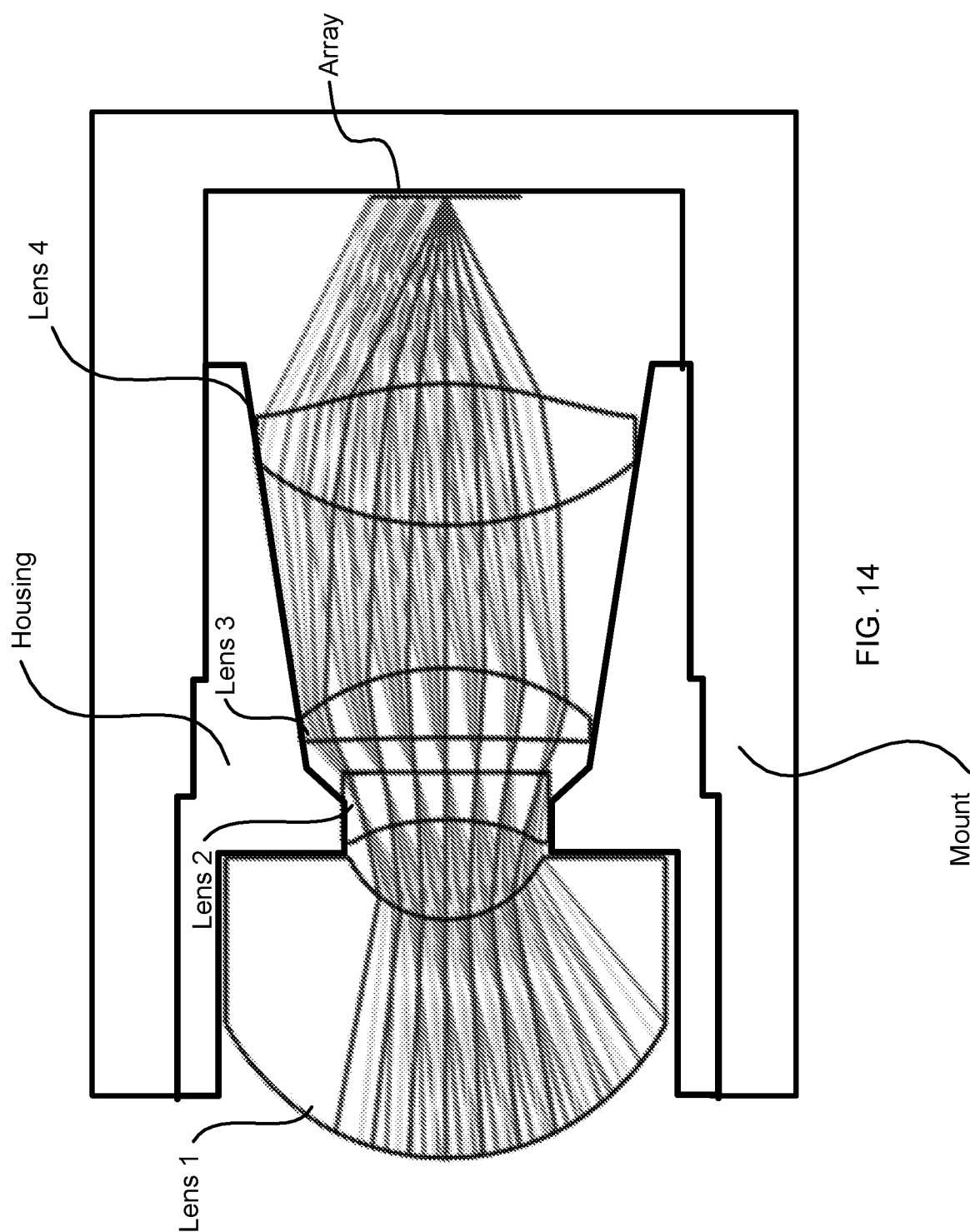


FIG. 13



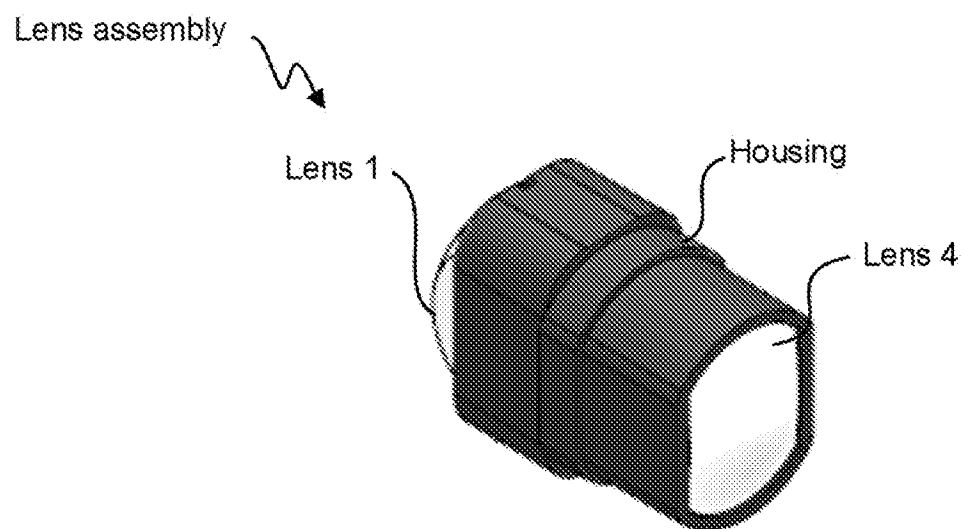


FIG. 15A

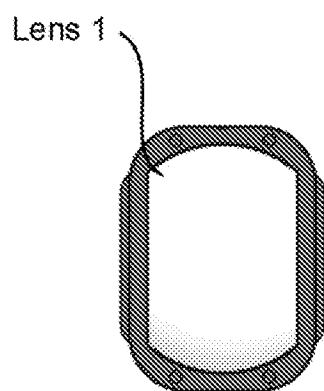


FIG. 15B

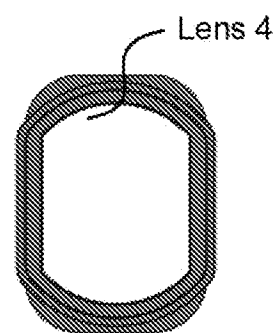


FIG. 15C

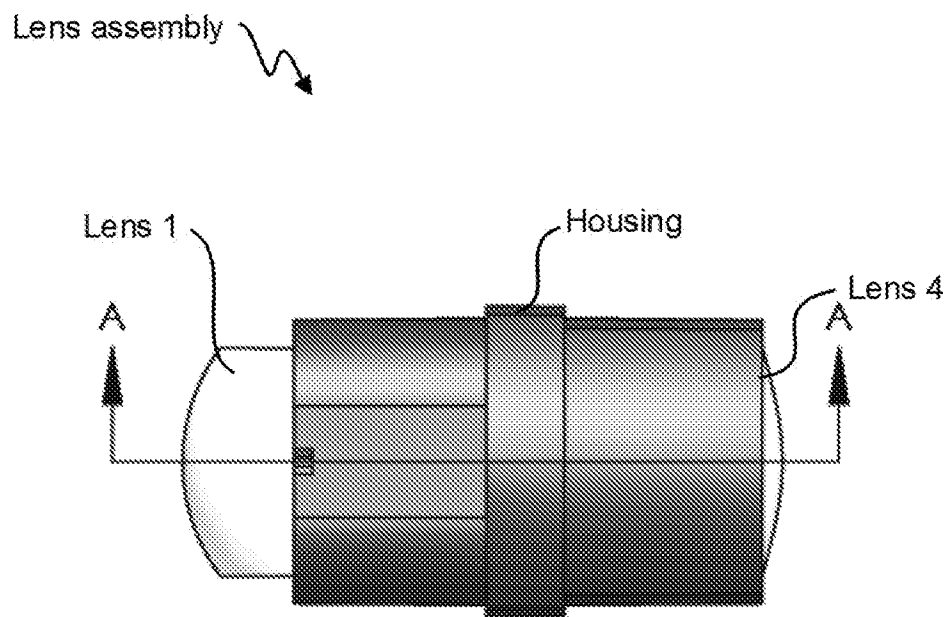


FIG. 16A

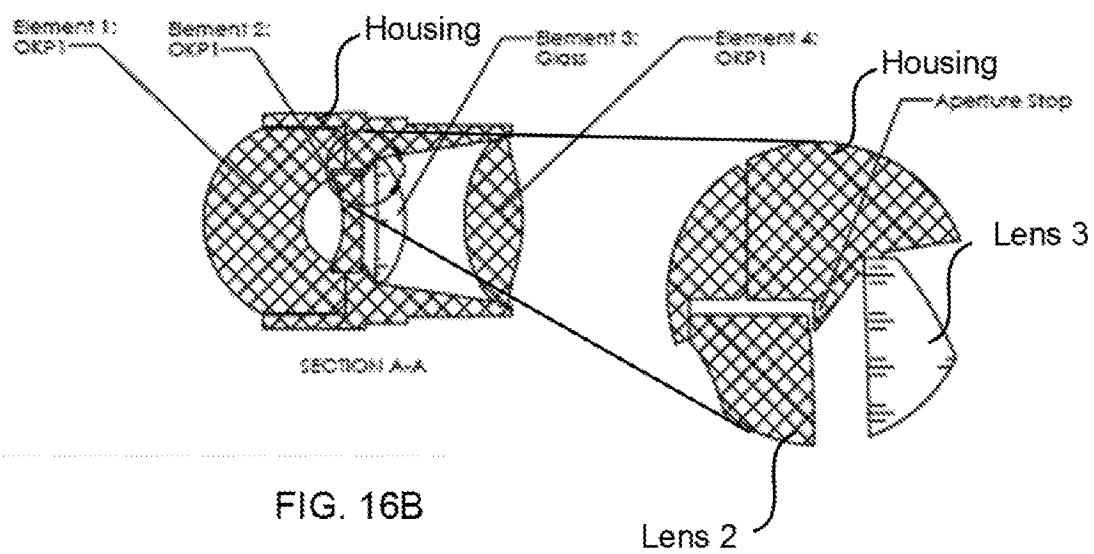


FIG. 16B

FIG. 16C

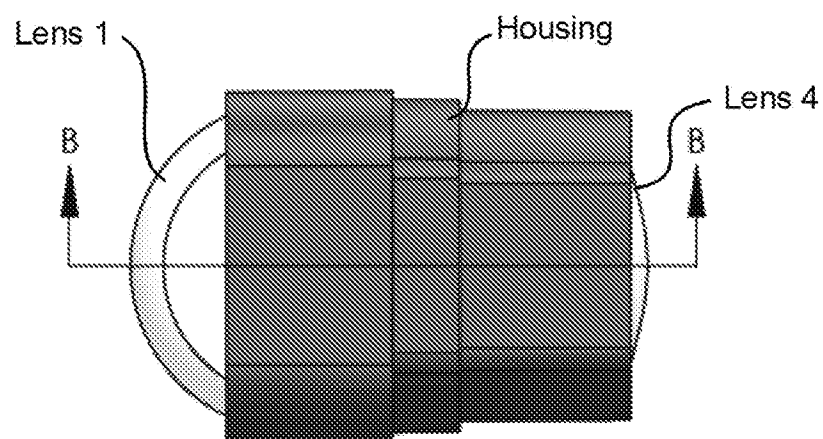
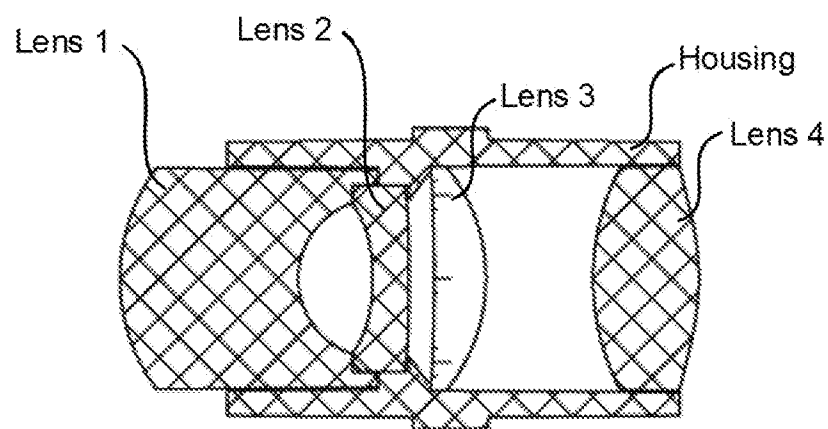


FIG. 16D



SECTION B-B

FIG. 16E

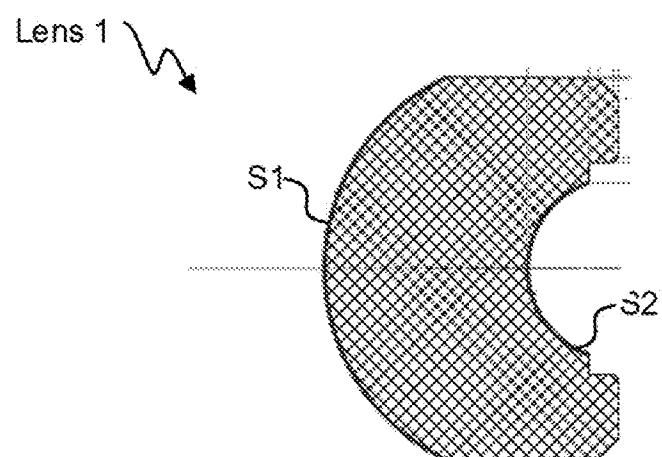


FIG. 17A

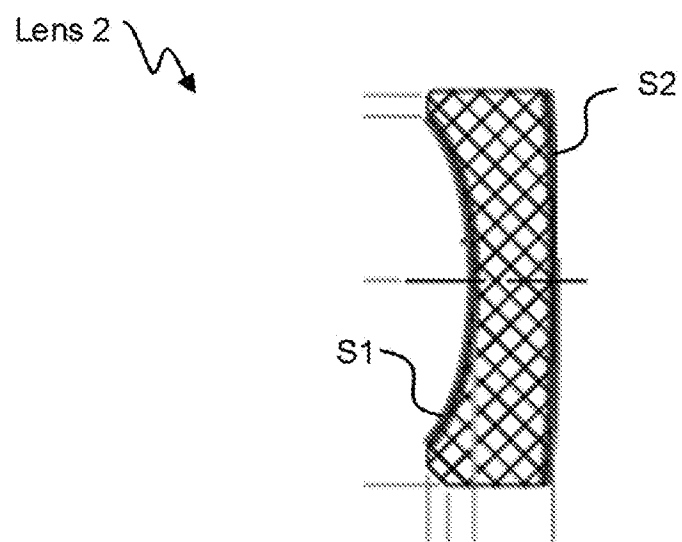


FIG. 17B

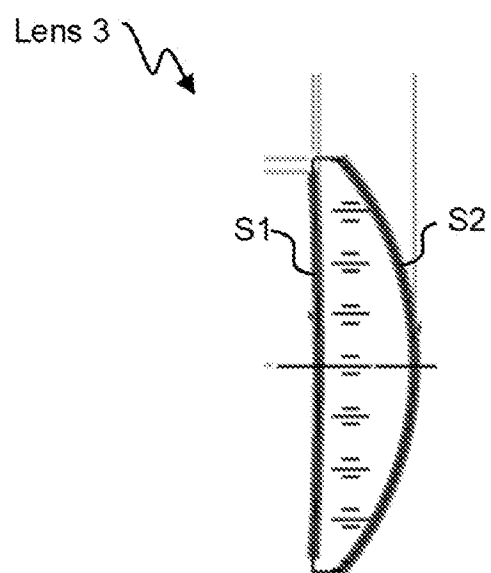


FIG. 17C

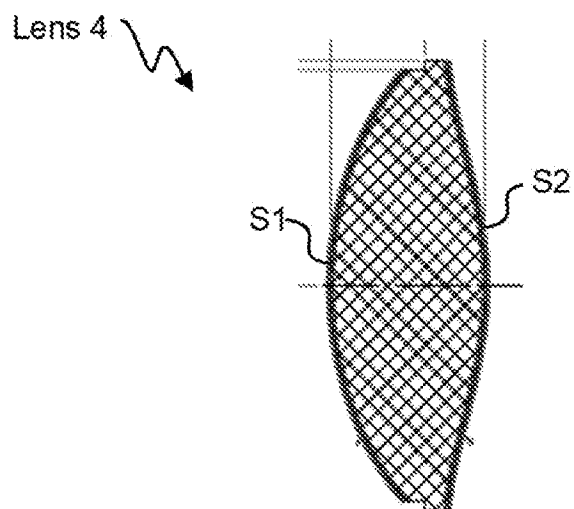


FIG. 17D

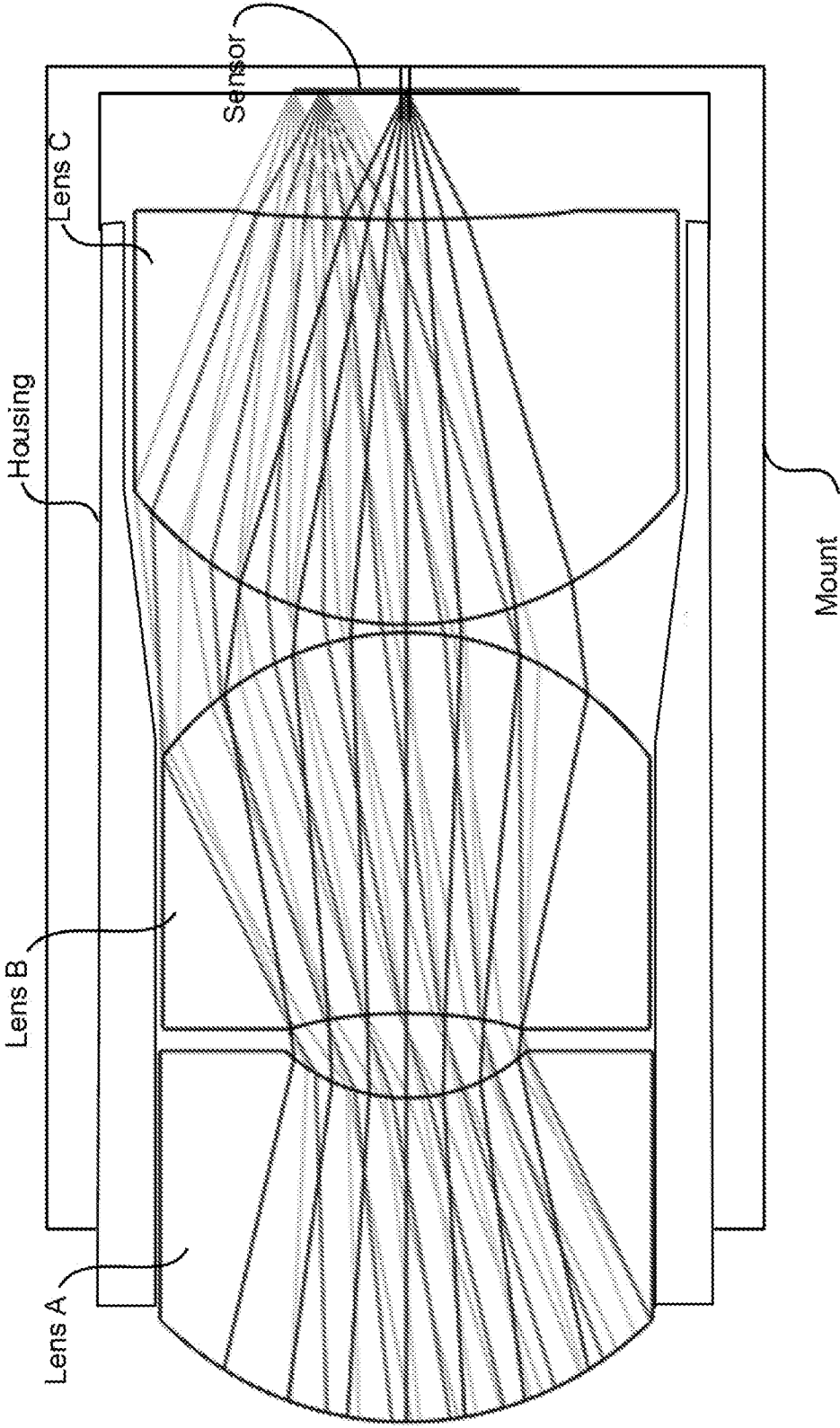


FIG. 18

**PROVISIONAL
PATENT APPLICATION
COMPACT LIDAR SYSTEM**

Inventors: Angus Pacala, residing in San Francisco, CA; and
Mark Frichtl, residing in San Francisco, CA.

Assignee: Ouster, Inc.
2741 16th St
SAN FRANCISCO, CA 94103

Entity: Small

KILPATRICK TOWNSEND & STOCKTON LLP
Two Embarcadero Center, Suite 1900
San Francisco, California 94111-3834
Tel: 415 576 0200

COMPACT LIDAR SYSTEM

BRIEF SUMMARY OF THE INVENTION

[0001] In autonomous vehicle navigation and automotive safety systems, light detection and ranging (LIDAR) systems can be used for hazard detection (e.g., for self-driving cars), mapping, and other general machine vision needs. However, current LIDAR sensors are both technologically complex and costly to manufacture, and industry is struggling to keep pace as demand for units rapidly increases. Current LIDAR units are still too costly to allow for wide deployment within any burgeoning consumer fleet of autonomous vehicles, with current unit prices likely needing to be reduced by a factor of 10x or more before widespread adoption is economically feasible.

[0002] Overall component cost and manufacturing complexity are now driven by the underlying complexities in the architecture of the LIDAR units themselves. This is further exacerbated by modern LIDAR sensors being a conglomeration of different internal sub-systems, which are themselves quite complex, e.g., optoelectronic systems, electromechanical systems, computer control systems, high-speed communication systems, data processing systems, and the like. To achieve the high positional accuracy, long distance range, and low power consumption that modern sensing applications require, stringent technical requirements for each one of these sub-systems have led to considerations like ease of assembly and overall systems integration being de-emphasized in favor of optimizing primarily for performance considerations. Such trade-offs have led to architectures and designs that are exceedingly complex and difficult to build, most requiring expensive calibration and alignment procedures before products can be shipped to the customer.

[0003] For example, some LIDAR systems have internal architectures that employ one or more large motherboards and bulky, heavy optical systems that are mounted on a counter-balanced structural member, all within a turret that rotates at rates on the order of 1,000 RPM. In these systems, separate laser emitter/detector pairs may be mounted to individual, separate circuit boards. For example, each emitter board and receiver board can be required to be separately mounted to the motherboard, with each emitter/detector pair precisely aligned along a particular direction to ensure that the field of view of every detector overlaps with the field of view of the

detector's respective emitter. As a result of the above architecture, precision alignment techniques are typically required during assembly to align each emitter board and each receiver board separately. This architecture becomes increasingly problematic when one desires to scale the resolution of the device because increasing the resolution requires the addition of more laser emitter/detector pairs, again, each mounted on their own circuit board. Consequently, scaling the resolution linearly with this type of architecture can lead to exponential increases in manufacturing costs and also exponential reductions in reliability due to the sheer number of individual parts and boards involved. Once assembly and alignment is complete, great care must be taken that the precisely aligned multi-board arrangement is not disturbed or jolted out of alignment during shipping or at some other point over the design life of the system.

[0004] In addition to the complexities of alignment and assembly of the optical systems, most LIDAR systems have a low degree of system integration with most control and drive circuits being their own separate modules that are mounted to their own custom boards. These custom boards may need to be mounted to the motherboard or may be mounted somewhere else on a structural element by way of one or more mounting brackets. In some cases, each board can have one or more electrical interconnects that need to be routed through one or more internal volumes or passages within the enclosure to eventually connect with the motherboard.

[0005] For rotating LIDAR systems, even more additional specialized mounts and interconnects may be required for both the electric motor rotor and stator. In addition to power connections, data uplink and downlink lines are needed and usually accomplished by one or more inductive, capacitive, and/or metal slip ring rotary couplers, which can be difficult to implement and/or lead to low rates of data transfer. Some systems employ metal brushes within the rotary coupler and are thus inherently unreliable due to the requirement of mechanical contact of the brushes within the rotary mechanism. Other slip ring-type connectors can employ hazardous substances, such as mercury, causing these types of couplers to be non-compliant under the Restriction of Hazardous Substances Directive 2002/95/EC (ROHS) and thus severely disfavored or even banned in some jurisdictions.

[0006] With respect to the optoelectronic systems, the industry has experienced challenges in incorporating more cost-effective single photon photodetectors such as CMOS-based single

photon avalanche diodes (SPADs) due to their low quantum efficiency in the near IR and their low dynamic range.

[0007] The low dynamic range inherent to SPADS is due, in part, to the physics of how a SPAD detects a photon (they are so-called Geiger mode devices that, for each photon detection event, produce a binary signal (photon detected or not detected) in the form of an avalanche current pulse). To provide a useful signal, each SPAD is backed by an analog front end composed of a quenching circuit that can sense the leading edge of the avalanche current, generate a standard output pulse synchronous with the avalanche build-up, quench the avalanche by lowering the bias back down to the breakdown voltage, and then restore the photodiode to the operative level. The quenching process takes time, leading to some amount of dead time between subsequent photon detections and, accordingly, an upper limit to the photon flux (or intensity in photons per second) that a single SPAD can detect. In addition, the need to quench the SPAD increases cost and complexity because each SPAD should be backed by dedicated circuitry, which also limits the resolution of SPAD arrays due to the large combined size of the SPADs and their required circuitry.

[0008] To improve quantum efficiency, some SPAD-based detectors employ InGaAs technology but such systems cannot be integrated to the degree that CMOS devices can. Therefore the external/supporting circuitry must be fabricated separately from the SPAD array, e.g., in a package that is external to the SPAD array. Thus, in InGaAs systems, the required detector electronics cannot all be integrated on the same substrate. In addition, the InGaAs substrate is relatively expensive and the associated manufacturing processes have a much lower yield than silicon further compounding the costs increase. To complicate matters further, InGaAs substrates need to be actively cooled in order to reduce dark currents to suitable levels, which increases the amount of energy consumed during runtime, increasing cost and complexity even further.

[0009] Rather than employing SPAD-based detectors, most commercially available LIDAR solutions employ avalanche photodiodes (APDs). APDs are not binary detection devices, but rather, output an analog signal, e.g., a current, that is proportional to the light intensity incident on the detector and have high dynamic range as a result. However, APDs must be backed by

several additional analog circuits including, e.g., analog circuits such as transimpedance amplifiers, differential amplifiers, high-speed A/D converters, one or more digital signal processors (DSPs) and the like. Traditional APDs also require high reverse bias voltages not possible with standard CMOS processes. Without mature CMOS, it is difficult to integrate all this analog circuitry onto a single chip with a compact form factor and multiple external circuit modules located on a printed circuit board are usually employed which contributes to the high cost of these existing units. By comparison, if the limitations of SPADs are overcome, advanced timing, and digital signal processing circuitry can be directly implemented on the CMOS die which provides significant improvement in reliability, cost, power consumption, size, system complexity, and the feasibility of future resolution scaling.

[0010] Accordingly, to support growing markets for 3D sensing systems, there remains a need for more cost effective but still high performing LIDAR systems. Furthermore, there remains a need for improved and more elegant system architectures that enable streamlined assembly processes that can be effectively employed at scale.

[0011] Various embodiments can address one or more of the above problems with LIDAR system. For example, a spinning light ranging system can have a light ranging device (e.g., which emits light pulses and detects reflected pulses) that is connected to an upper circuit board assembly that rotates about an axis defined by a shaft. The upper circuit board assembly can cooperate with a lower circuit board assembly, e.g., to provide power, data, or encoded positions, via respective circuit elements. The inclusion of cooperating wireless circuit elements on the rotating upper board assembly and the lower board assembly (e.g., as opposed to external, physical connections) can provide for a more compact design. Further, specific circuit elements (e.g., optical or power) can be positioned in a manner to enable efficient communication or to increase flux. For example, a wireless power receiver can be provided at a ring at an outer edge of the upper circuit board assembly, maximizing the amount of magnetic flux captured by an inductive ring or maximizing the area available in a capacitive system.

[0012] According to some embodiments, an optical communications subsystem can provide an optical communications channel between a rotating light ranging device and a base subsystem that does not rotate about a shaft. The optical communications channel can provide for fast

communications, but also can provide for a compact and inexpensive design. For instance, a turret optical communication component can be positioned on a rotating assembly to communicate data (e.g., ranging data from the light ranging device) with a base optical communication component. Such positioning can alleviate the need for more bulky

5 communication mechanisms. For example, downlink transmitter can be positioned to transmit optical ranging data through a hollow shaft used for rotation. As another example, one or more uplink transmitters of the base subsystem can communicate can transmit uplink signals to one or more uplink receivers that rotate on a rotating assembly, e.g., where these uplink elements are positioned in rings that align.

10 **[0013]** According to some embodiments, a rotation of an upper circuit board assembly can be driven by a motor integrated on an upper and lower circuit board, thereby making the light ranging system compact. For example, the upper circuit board assembly can include a plurality of rotor elements symmetrically arranged about a rotation shaft, and a lower circuit board assembly can include a plurality of stator elements symmetrically arranged about the shaft. A
15 driver circuit can drive the stator elements. Having such motor and stator elements built onto the circuit boards themselves provides various advantages over products that use bulkier motors (e.g., stepper motors, brushed motors or unintegrated brushless motors).

[0014] These and other embodiments of the invention are described in detail below. A better understanding of the nature and advantages of embodiments of the present invention may be
20 gained with reference to the following detailed description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Illustrative embodiments are described with reference to the following figures.

[0016] FIGS. 1A-1B show automotive light ranging devices, also referred to herein as LIDAR
25 systems, according to some embodiments.

[0017] FIGS. 2A-2B show high level block diagrams of rotating and solid-state LIDAR systems, respectively, according to some embodiments.

[0018] FIG. 3 illustrates a more detailed block diagram of a rotating LIDAR system 300 according to some embodiments like those described above in reference to FIG. 2A.

[0019] FIG. 4 shows an illustrative example of the light transmission and detection process for a light ranging system according to some embodiments, with a focus on the emitter array and sensor array that form an arrangement of emitter-sensor channels, as introduced above in reference to FIG. 2.

[0020] FIGS. 5A-5B show a rotating LIDAR system 500 in accordance with one or more embodiments.

[0021] FIGS. 6A-6C show cross-sectional views of a LIDAR system in accordance with one or more embodiments.

[0022] FIG. 6D shows a top view of a stator board in accordance with one or more embodiments.

[0023] FIG. 6E shows a bottom view of a rotor board in accordance with one or more embodiments.

[0024] FIG. 7 shows an exploded view of the lower circuit board assembly to illustrate the assembly process of the compact LIDAR system according to certain embodiments.

[0025] FIG. 8 shows the assembled lower circuit board assembly, an exploded view of the upper circuit board assembly, the light ranging system, and the enclosure to illustrate the assembly process of the compact LIDAR system according to certain embodiments.

[0026] FIGS. 9A-9C show a perspective view, a front view, and a zoomed front view, respectively, of a light ranging device 900 according to certain embodiments.

[0027] FIG. 10 shows an optical block diagram of a light ranging device 1000 showing both the optical systems for a Rx module 1001 and a Tx module 1003 according to certain embodiments.

[0028] FIG. 11A shows a top view of a micro-optics package according to certain embodiments.

[0029] FIG. 11B shows a cross-section of a single micro-optic receiver channel according to some embodiments.

[0030] FIG. 12A-12B shows top views of a SPAD-based detector according to some embodiments.

5 **[0031]** FIG. 13 shows top views of a VCSEL chip transmitter according to some embodiments.

[0032] FIG. 14 depicts a simplified schematic of an embodiment of a LIDAR bulk optical system.

[0033] FIGS. 15A, 15B, and 15C depict an embodiment of a bulk optics lens assembly.

[0034] FIGS. 16A-16E depicts various views of an embodiment of a lens assembly.

10 **[0035]** FIG. 17A-17D, depict a cross sections of embodiment of the lenses of a lens assembly.

[0036] FIG. 18 depicts an embodiment of a lens assembly with three lenses.

TERMS

15 **[0037]** Unless defined otherwise, technical and scientific terms used herein have the same meaning as commonly understood by a person of ordinary skill in the art. Methods, devices, and materials similar or equivalent to those described herein can be used in the practice of disclosed techniques. The following terms are provided to facilitate understanding of certain terms used frequently and are not meant to limit the scope of the present disclosure. Abbreviations used herein have their conventional meaning within the relevant arts.

20 **[0038]** The term *ranging data* may refer to any data that can be transmitted from a laser ranging device, e.g., a turret component of a rotating LIDAR system. Examples of ranging data include range information, e.g. distance to a given target point at a certain angle (azimuth and/or zenith), range-rate or velocity information, e.g. the derivative of the ranging data with respect to time, and also operational information such as signal-to-noise ratio (SNR) of return or signal
25 intensity, target reflectivity, ambient NIR levels coming from each pixel field of view, diagnostic information including temperature, voltage levels, etc. In some embodiments, ranging data can

include RGB information from an RGB camera that is located in the turret, e.g., a high speed read-out camera such as a line scan camera or thermal imager.

[0039] The term *turret* may refer to the rotating part or portion of a rotating LIDAR system.

Turret components include any rotating component or circuit boards in the turret portion of the LIDAR system and can include one or more components located in a light ranging device and/or one or more components located on a rotating circuit board of a rotary actuator.

[0040] In the context of a rotating LIDAR system, the term *base* may refer to the non-rotating part or portion of the rotating LIDAR system. *Base components* include any non-rotating component or circuit boards in the base portion of the LIDAR system and can include one or more components located in a base assembly and/or one or more components located on a non-rotating circuit board of a rotary actuator.

[0041] The terms *upper* and *lower* refer to the position, or relative position, of components along the axis of rotation of a LIDAR system. In some embodiments, *upper* components, also referred to as *turret* components, are located on the turret of the LIDAR system while *lower* components, also referred to as *base* components, are located on the base of the LIDAR system. In some embodiments, the term *upper* is used to describe elements or surfaces that face the turret while the term *lower* is used to describe elements or surfaces that face the base.

[0042] The term *ring* includes not just circular shapes but also shapes that are slightly non-circular, e.g., elliptical, and arranged circumferentially around a central axis, including perturbations or oscillations (e.g., wavy) at a circumference.

[0043] One or more shapes that are referred to as *symmetric* may include both perfectly symmetric shapes as well as shapes that are generally but not perfectly symmetric. Arrangements of electronic components described herein may operate most efficiently in a symmetric configuration, however, the term symmetric does not exclude those configurations that are slightly asymmetric, or have a slight deviation from symmetric even if those configurations do not result in the optimal operational configuration.

[0044] The term *parallel* is not limited to perfectly parallel but includes also those geometrical arrangements and configurations that are substantially parallel as a result of manufacturing

variations, e.g., two elements that are referred to herein as being *parallel* may have an angle between -5 and 5 degrees or -1 and 1 degrees between the two elements depending on the manufacturing tolerance employed..

[0045] The term *perpendicular* is not limited to perfectly perpendicular but includes also those geometrical arrangements and configurations that are substantially perpendicular as a result of manufacturing variations, e.g., two elements that are referred to herein as being *perpendicular* may have an angle between 85 and 95 degrees between the two elements.

[0046] The term *photosensor* (or just *sensor*) can convert light into an electrical signal, as may be done with an avalanche photodiode (APD). A photosensor may include a plurality of “*photodetectors*,” e.g., single-photon avalanche diodes (SPADs). The term *sensor array* may refer to a sensor chip that includes an array of multiple sensors.

[0047] The term *transmitter* may refer to a structure that includes one or more light transmitting elements, e.g., LED, laser, VCSEL, and the like. The term *transmitter* may also include a transmitter chip that includes an array of transmitters, also referred to as an emitter array.

[0048] The term *bulk optic(s)* refers to single lenses and/or lens assemblies that include one or more macroscopically-sized optics, e.g., with diameters on the order of centimeters or greater, such as those used in commercially available camera lenses and microscope lenses. In this disclosure, the term *bulk optics* is contrasted with the term *microoptics* which refers to optical elements or arrays of optical elements having individual element diameters that are on the order of a few micrometers to a few millimeters in size or smaller.

[0049] As used herein, the term *image space telecentric optics module* refers to an optical system (bulk or otherwise) where, at the image plane, all (or substantially all) of the chief rays from within the aperture of the lenses are incident on the image plane “straight on”, or at a zero angle of incidence, within a specified tolerance (e.g., +/- 2 degrees).

DETAILED DESCRIPTION

[0050] According to certain embodiments, methods and systems disclosed herein relate to a compact light ranging and detection (LIDAR) system and methods of assembly of a compact

LIDAR system. The LIDAR system can include a modular light ranging device and an optional highly compact and integrated rotary actuator. The modular light ranging device can operate as a stand-alone non-rotating solid state LIDAR or, if connected to the integrated rotary actuator, can operate as part of a turret of a rotating LIDAR. The light ranging device can include a light transmission module for illuminating objects in a field located around the light ranging module and also includes a light sensing module for sensing reflected or scattered portions of the illuminating light pulses for use in computing a 3D depth image. The light ranging module can also include a detector chip that include an array of photosensors, e.g., an array of SPADS fabricated.

[0051] In some embodiments, the rotary actuator includes an upper circuit board assembly (also referred to herein as a turret, or rotating circuit board assembly) and a base circuit board assembly (also referred to herein as a stationary circuit board assembly). The various circuit boards of the rotary actuator can be highly integrated in the sense that many of the functional and/or supporting electronic and optical components of the LIDAR system can be mounted directly to one or more boards of the rotary actuator. For example, the base controller of the LIDAR system that can control various emission parameters of the light transmission module can be mounted on a board of the base circuit board assembly of the rotary actuator.

Furthermore, power can be provided to the light ranging module by way of a wireless power transmission system that is also integrated onto a board of the rotary actuator. Communication between the base controller and the light ranging module and vice versa is enabled by way of an optical uplink channel and an optical downlink channel where the electrical and optical components that support the optical uplink/downlink channels are also integrated onto one or more circuit boards of the rotary actuator.

[0052] In some embodiments, these same boards include electric motor components, also integrated onto one or more surfaces of the upper and lower circuit board assemblies of the rotary actuator. For example, an electric motor stator can be bonded directly to a surface of the lower circuit board assembly of the rotary actuator along with other electrical components, e.g., a group of optical uplink transmitters, an optical downlink receiver, and a wireless power transmitter. Likewise, an electric motor rotor can be bonded directly to a surface of the upper circuit board assembly of the rotary actuator along with other electrical components, e.g., a group

of optical uplink receivers, an optical downlink transmitter, an optical or magnetic rotary encoder reader, and a wireless power receiver.

[0053] In some embodiments, the upper circuit board assembly can include one or more connectors, also bonded to a surface of the upper circuit board assembly, to connect the light ranging module to the upper circuit board assembly. Additionally, the rotary actuator can also include additional computational resources, one or more FPGAs, ASICs, microprocessors, and the like, that can be used by the light ranging module to perform data processing on the acquired data.

[0054] In view of the high level of systems integration in the compact LIDAR disclosed herein, a fully functioning system can be assembled by simply attaching the light ranging module to the rotary actuator. There is no need for a separate electric motor module, separate communications module, separate power modules, etc.

[0055] In some embodiments, the architecture of the rotary actuator lends itself to an elegant method of assembly. For example, the system can be architected such that the electrical components, including communications components, electric motor components, and wireless power components are arranged circumferentially and concentrically around a central axis of the system or even coaxially with the axis of the system. The central axis can also be collinear with the axis of rotation of the upper circuit board assembly, or turret. One or more boards of the rotary actuator also have a central hole that is configured to receive a shaft that can be attached (directly or indirectly) to a lower portion, or base, of a fixed enclosure. In some embodiments, the shaft defines the axis of rotation of the system because one or more bearings attached thereto provide for rotational movement of the upper circuit board assembly relative to the lower circuit board assembly.

[0056] In view of the above architecture, assembly of the rotary actuator is reduced to dropping successive boards in place on the shaft. Because a subset of the electrical components (such as the communications components, electric motor components, and wireless power components) are arranged circumferentially around a central axis of the system these systems can operate effectively without the need for complex alignment procedures once the assembly is complete.

[0057] In some embodiments, the system employs a thermally stable image-space telecentric optics module employed within the light transmission module or the light sensing module, or both. The thermally stable image-space telecentric optics module is engineered to have an image plane that is stable in space relative to transmitter or sensor chip that includes an array of transmitters and/or sensors of the light transmission module or light sensing module, respectively. The coefficients of thermal expansion of a housing and of the optical elements within the housing, along with the change in refractive index with respect to temperature, can be chosen to provide for the thermally stable image plane. In various embodiments, the individual optics in the optical system may be glass and/or plastic to provide for an economical yet thermally stable design.

I. ILLUSTRATIVE AUTOMOTIVE LIDAR SYSTEM

[0058] FIGS. 1A-1B show automotive light ranging devices, also referred to herein as LIDAR systems, according to some embodiments. The automotive application for the LIDAR systems is chosen here merely for the sake of illustration and the sensors described herein may be employed in other types of vehicles, e.g., boats, aircraft, trains, etc., as well as in a variety of other applications where 3D depth images are useful, such as medical imaging, geodesy, geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, atmospheric physics, laser guidance, airborne laser swath mapping (ALSM), and laser altimetry. According to some embodiments, a LIDAR system, e.g., scanning LIDAR system 101 and/or solid state LIDAR system 103, can be mounted on the roof of a vehicle 105 as shown in FIGS. 1A and 1B.

[0059] The scanning LIDAR system 101 shown in FIG. 1A can employ a scanning architecture, where the orientation of the LIDAR light source 107 (e.g., for emitting laser pulses) and/or detector circuitry 109 (e.g., for detecting reflected pulses to determine distance to an object) can be scanned around one or more fields of view 110 within an external field or scene that is external to the vehicle 105. In the case of the scanning architecture, the emitted light 111 can be scanned over the surrounding environment as shown. For example, the output beam(s) of one or more light sources (such as infrared or near-infrared pulsed IR lasers, not shown) located in the scanning LIDAR system 101, can be scanned, e.g., rotated, to illuminate a scene around the vehicle. In some embodiments, the scanning, represented by rotation arrow 115, can be

implemented by mechanical means, e.g., by mounting the light emitters to a rotating column or platform. In some embodiments, the scanning can be implemented through other mechanical means such as through the use of galvanometers. Chip-based steering techniques can also be employed, e.g., by using microchips that employ one or more MEMS based reflectors, e.g., such as a digital micromirror (DMD) device, a digital light processing (DLP) device, and the like. In some embodiments, the scanning can be effectuated through non-mechanical means, e.g., by using electronic signals to steer one or more optical phased arrays.

[0060] For a stationary architecture, like the solid state LIDAR system 103 shown in FIG. 1B, one or more solid state LIDAR subsystems (e.g., 103a and 103b) can be mounted to the vehicle 105. Each solid state LIDAR unit can face a different direction (possibly with partially and/or non-overlapping fields of views between units) so as to capture a composite field of view that is larger than each unit is capable of capturing on its own.

[0061] In either the rotating or stationary architectures, objects within the scene can reflect portions of the light pulses that are emitted from the LIDAR light sources. One or more reflected portions then travel back to the LIDAR system and can be detected by the detector circuitry. For example, reflected portion 117 can be detected by detector circuitry 109. The detector circuitry can be disposed in the same housing as the emitters. Aspects of the scanning system and stationary system are not mutually exclusive and thus can be used in combination. For example, the individual LIDAR subsystems 103a and 103b in FIG. 1B can employ steerable emitters such as a MEMS oscillating mirror or the whole composite unit may rotate through mechanical means thereby scanning the entire scene in front of the LIDAR system, e.g., from field of view 119 to field of view 121.

[0062] FIGS. 2A-2B show high level block diagrams of a rotating LIDAR system 200 and a stationary solid state LIDAR system 202, respectively, according to some embodiments. Both systems employ a light ranging device 201 that includes a light transmission module 203 and a light sensing module 205. The light sensing and transmission modules 203 and 205 can include bulk optics 208, e.g., a multi-element lens assembly positioned at the input/output of the sensing and transmission modules, respectively. Light transmission module 205 can further include a micro-optics array and optional notch filter element (not shown) that is located between the bulk

optics 208 and light emitter circuitry 207. In some embodiments, light emitter circuitry 207 includes a chip-scale array of light sources, such as an array of vertical cavity surface emitting lasers (VCSELs) on an Indium Gallium Arsenide (InGAs) substrate. Light sensing module 205 can also include a micro-optics array and notch filter element (not shown) that is located between
5 the bulk optics 208 and light detector circuitry 209. In some embodiments, light detector circuitry 209 can include a chip-scale array of photon detectors, such as an array of single photon avalanche diodes (SPADS) fabricated in a CMOS technology. Other detector technologies can be employed as well, e.g., avalanche photodiodes, CCD image sensors, CMOS photodiode image sensors, cavity enhanced photodetectors, surface enhanced photodetectors, and
10 the like.

[0063] Turning to FIG. 2A, in rotating LIDAR system 200 light ranging device 201 can be electrically connected to a turret circuit board assembly 211 (also referred to herein as an upper circuit board assembly). Circuit board assembly 211 can be considered ranging to the extent that it is connected to light ranging device 201. As described in more detail in FIG. 3 below, the
15 turret circuit board assembly 211 can include a number of circuit elements including one or more processors and memory. For example, the turret circuit board assembly 211 can include a field programmable gate array (FPGA) and or one or more application specific integrated circuits (ASICs) that are tailored to provide certain LIDAR functionality. In some embodiments, the light ranging device 201 can be hard wired to the turret circuit board assembly 211 via a multi-
20 pin electrical connector or may be wirelessly connected, e.g., through a communication channel employing optical or RF connections, to the turret circuit board assembly 211. The turret circuit board assembly 211 is disposed directly above a base circuit board assembly 213. In some embodiments, the base circuit board assembly 213 can wirelessly transmit power to the turret circuit board assembly 211 to, e.g., power the light ranging device 201 and any other associated
25 circuitry, e.g., ASICS, FPGAs, communications circuits and the like. In addition, optical, inductive, and/or capacitive communications channels can connect the base circuit board assembly 213 to turret circuit board assembly 211 thereby allowing for the light ranging device 201 to be controlled via contactless data transfer from the base circuit board assembly.

[0064] In the embodiment shown in FIG. 2A, the turret circuit board assembly 211 is
30 rotationally coupled to the base circuit board assembly 213 through a rotational coupling 217.

Thus, the light ranging device 201 and the turret circuit board assembly 213 can rotate 360 degrees within housing 215. Rotation of the light ranging device 201 allows the system to acquire data that can be used to construct a full 360 field of view 3D map of the volume around the device. In some embodiments, the base circuit board assembly 213 can be coupled to the housing 215, e.g., by way of a mechanical bracket and screws (not shown), such that the base circuit board assembly 213 is held stationary and does not rotate relative to housing 215.

[0065] Rotational coupling 217 can be implemented in a number of different ways in various embodiments. For example, some embodiments can employ a shaft and bearing structure. In some embodiments, the rotational coupling 217 also includes one or more components for a rotary actuator that not only allows for rotational movement but also drives the rotational movement of the turret circuit board assembly 211. For example, an electric motor rotor assembly, e.g., including an arrangement of rotor elements, e.g., permanent magnets, may be directly integrated into the turret circuit board assembly 211, and an electric motor stator assembly, e.g., including an arrangement of stator elements such as solenoid coils, may be directly integrated into the base circuit board assembly 213. In such embodiments, where one or more rotary actuation components are integrated into the base circuit board assembly 213 and/or the turret circuit board assembly 211, a separate module for rotary actuation is no longer needed. As a result, embodiments of the LIDAR system disclosed herein have a much more compact form factor and much simplified assembly process than existing systems.

[0066] FIG. 2B is a simplified block diagram of stationary solid state LIDAR system 202 according to some embodiments. Like rotating LIDAR system 200 shown in FIG. 2A, stationary solid state LIDAR system 202 includes a light ranging device 201 that is directly connected to the single base circuit board assembly 214. Because there is no need for a rotary actuation of the light ranging device 201, there is no need for a separate rotating turret circuit board assembly. Accordingly, the circuitry that was previously distributed amongst the turret circuit board assembly 211 and the base circuit board assembly 213 can be integrated entirely into the single base circuit board assembly 214 and/or shared amongst the circuitry associated with the light sensing module 205 and/or transmission module 203.

[0067] In some embodiments, for either of the embodiment shown in FIGS. 2A-2B, the hardware and software/firmware for performing one or more LIDAR-specific operations (e.g., photon time series accumulation followed by peak detection and ranging data computation and output) can be incorporated into the circuitry of light ranging device 201 and/or the turret circuit board assembly 211. For example, in some embodiments, the light detector circuitry 209 may also include an ASIC that is integrated onto the same substrate as the array of SPADs. In such a situation, the light ranging device 201 is modular in the sense that a reprogramming/reconfiguring of the software/firmware can allow the light ranging device 201 to operate as part of a rotating LIDAR system (like that shown in FIG. 2A) or as a stand-alone solid state LIDAR system. As already mentioned above, circuitry can be employed (e.g., MEMS, DMD, optical phased arrays, and the like) that will also allow for beam steering without the need for a mechanical rotational actuator. Accordingly, the modular design of the system disclosed herein results in a highly adaptable system that can fit user needs without expensive and time consuming redesign of the overall hardware and mechanical architecture.

A. *Detailed block diagram*

[0068] FIG. 3 illustrates a more detailed block diagram of a rotating LIDAR system 300 according to some embodiments like those described above in reference to FIG. 2A. More specifically, rotating LIDAR system 300 can optionally employ a rotary actuator with wireless data and power transmission and reception capabilities. In some embodiments, the rotary actuator includes an electric motor rotor that is integrated onto a surface of a rotating circuit board and an electric motor stator that is integrated onto a surface of a stationary circuit board and both board assemblies are equipped with wireless power and data transfer capabilities.

[0069] The rotating LIDAR system 300 can interact with one or more instantiations of user interface hardware and software 315. The different instantiations of user interface hardware and software 315 can vary and may include, e.g., a computer system with a monitor, keyboard, mouse, CPU and memory; a touch-screen in an automobile; a handheld device with a touch-screen; or any other appropriate user interface. The user interface hardware and software 315 may be local to the object upon which the rotating LIDAR system 300 is mounted but can also be a remotely operated system. For example, commands and data to/from the rotating LIDAR

system 300 can be routed through a cellular network (LTE, etc.), a personal area network (Bluetooth, Zigbee, etc.), a local area network (WiFi, IR, etc.), or a wide area network such as the Internet.

[0070] The user interface hardware and software 315 can present the LIDAR data from the device to the user but can also allow a user to control the rotating LIDAR system 300 with one or more commands. Example commands can include commands that activate or deactivate the LIDAR system, specify photo-detector exposure level, bias, sampling duration and other operational parameters (e.g., for emitted pulse patterns and signal processing), specify light emitters parameters such as brightness. In addition, commands can allow the user to select the method for displaying results. The user interface can display LIDAR system results which can include, e.g., a single frame snapshot image, a constantly updated video image, and/or a display of other light measurements for some or all pixels such as ambient noise intensity, return signal intensity, calibrated target reflectivity, target classification (hard target, diffuse target, retroreflective target), range, signal to noise ratio, target radial velocity, return signal temporal pulse width, signal polarization, noise polarization, and the like. In some embodiments, user interface hardware and software 315 can track distances (proximity) of objects from the vehicle, and potentially provide alerts to a driver or provide such tracking information for analytics of a driver's performance.

[0071] In some embodiments, the LIDAR system can communicate with a vehicle control unit 317 and one or more parameters associated with control of a vehicle can be modified based on the received LIDAR data. For example, in a fully autonomous vehicle, the LIDAR system can provide a real time 3D image of the environment surrounding the car to aid in navigation. In other cases, the LIDAR system can be employed as part of an advanced driver-assistance system (ADAS) or as part of a safety system that, e.g., can provide 3D image data to any number of different systems, e.g., adaptive cruise control, automatic parking, driver drowsiness monitoring, blind spot monitoring, collision avoidance systems, etc. When a vehicle control unit 317 is communicably coupled to light ranging device 310, alerts can be provided to a driver or the proximity of an object can be tracked and/or displayed.

[0072] The rotating LIDAR system 300 shown in FIG. 3 includes two main modules: the light ranging device 310 and the rotary actuator 302. The light ranging device 310 includes light transmission module 340, light sensing module 330, and light ranging system controller 350. The rotary actuator 302 includes at least two circuit board assemblies, a lower circuit board assembly 305 (also referred to herein as a base subsystem) and an upper circuit board assembly 307. The lower circuit board assembly 305 can be mechanically mounted to a fixed portion of an enclosure while the upper circuit board assembly 307 is free to rotate about an axis of rotation, usually defined by a shaft (not represented in FIG. 3) that is also mounted to the enclosure (directly or indirectly). The light ranging device 310 can be mechanically attached to the rotatable upper circuit board assembly 305 and therefore is free to rotate. While FIG. 3 shows one particular arrangement of components within light ranging device 310 and rotary actuator 302, in some embodiments, certain components may be integrated into one, or the other, module differently than shown. As one example, the ranging system controller 350, which may be, *e.g.*, an FPGA, ASIC, or more general computing device, like an embedded system or system-on-a-chip (SOC) can be mounted directly, *i.e.*, soldered to, a printed circuit board that is part of the upper circuit board assembly 307. In other words, in some embodiments, the parts of the rotary actuator can be integrated within the light ranging device 310 and *vice versa*.

[0073] The rotary actuator 302 includes a number of different systems that are integrated onto, *e.g.*, soldered onto, one or more printed circuit boards of the lower and upper circuit board assemblies 305 and 307. For example, the rotary actuator 302 includes a brushless electric motor assembly, an optical communications subsystem, a wireless power transmission subsystem, and a base controller. These systems are formed by a pair or group of circuit elements on the lower circuit board assembly 305 operating in cooperation with (*e.g.*, having a function that is complementary to) another pair or group of circuit elements on the upper circuit board assembly 307. Complementary functions include, *e.g.*, transmission (Tx) and reception (Rx) of power and or data communication signals as is described in more detail below.

[0074] The brushless electric motor assembly includes a stator assembly 311 (integrated onto a printed circuit board of the lower circuit board assembly 305) and a rotor assembly 313 (integrated onto a printed circuit board of the upper circuit board assembly 307). The rotation of the rotor assembly 313 is driven from a drive signal, *e.g.*, a three phase drive current, that

originates from a motor driver circuit 306. In some embodiments, one or more motor control lines connect the motor driver circuit to the coils of the stator assembly 311 to allow for the drive signal to be provided to the motor stator. Furthermore, the motor driver circuit 306 can be electrically connected to the base controller 309 such that the base controller 309 can control the rotation rate of the rotor assembly and thus the rotation rate (i.e., frame rate) of the light ranging device 310. In some embodiments, the rotor assembly 313 can rotate at 10-30 Hz. In some embodiments, the rotor assembly 313 can be a passive device that includes a series of permanent magnets that are attached to a circuit board of the upper circuit board assembly. These permanent magnets are either attracted to or repelled by an electromagnetic force, e.g., a magnetic force, generated by the coils of the stator assembly to drive a rotation of the upper circuit board assembly 307 relative to the lower circuit board assembly. The rotational orientation of the upper circuit board assembly 307 is tracked by the rotary encoder receiver 325, which can track the angular position of the upper circuit board assembly by detecting the passage of one or more features on the encoder 324. Any rotary encoder technology can be employed. In some embodiments, the encoder 324 is integrated directly onto a surface of a circuit board of the lower circuit board assembly 305.

[0075] The rotary actuator 302 also includes a wireless power system that includes a wireless power transmitter 326 and a wireless power receiver 327 in a configuration referred to herein as a rotary transformer. Once transmitted to the wireless power receiver 327, the power can then be consumed by the light ranging device 310 and/or any circuitry needing power on the turret/upper circuit board assembly. In some embodiments, all system power is provided by the wireless power transmission module and thus there is no need for a rotary electric coupler like a slip ring or mercury based device thereby increasing reliability and decreasing cost of the overall system.

[0076] The rotary actuator 302 also includes an optical communication subsystem that includes a number of optical transmitters (e.g., 321 and 323) and receivers (e.g., 319 and 325) used for bi-directional contactless data transmission between the rotary actuator 302 and the light ranging device 310 (or to/from any other device or system that may be connected to the upper circuit board assembly 307 of the rotary actuator 302). More specifically, the optical communication subsystem can include a set of base optical communication components (that are attached to, e.g., soldered to, the lower circuit board assembly that comprises the base of the

LIDAR system) and a set of turret optical communication components (that are attached to, e.g., soldered to, the rotating upper circuit board assembly that comprises the turret of the LIDAR system). These optical communication components provide an uplink data channel for providing optical signals, e.g., including control signals, to the light ranging device 310 and also provide a downlink data channel for providing optical signals, e.g., including ranging and operational data, from the light ranging device to the base controller, the user interface hardware & software 315, and/or the vehicle control unit 317.

[0077] A downlink optical communication channel from the upper circuit board assembly 307 to the lower circuit board assembly 305 is created between the optical downlink transmitter 323 and the optical downlink receiver 319. The light ranging device 310 can be connected directly to the upper circuit board assembly 307 and therefore can access the downlink optical communication channel to pass ranging and operational data down to the lower circuit board assembly 305 for further use. In some embodiments, the data passed down in the optical signals via the optical downlink could include range data for individual points (pixels) in the field (or possibly multiple ranges for a single pixel and angle, e.g. during fog/rain, when looking through glass windows, etc.), azimuth and zenith angle data, signal to noise ratio (SNR) of the return or signal intensity, target reflectivity, ambient near IR (NIR) levels coming from each pixel field of view, diagnostic operational information from the light ranging device such as temperature, voltage levels, etc. In addition, data from any other system that is connected to the upper circuit board of the rotary actuator can pass data down through the optical downlink, e.g., data from high speed RGB or thermal cameras, e.g., line scan cameras and the like.

[0078] An uplink optical communication channel from the lower circuit board assembly 305 is created between the uplink transmitter 321 and the optical uplink receiver 322. In some embodiments, control signals from the base controller 309 can be passed to the light ranging device 310 via the optical uplink channel. For example, in some embodiments, base controller 309 can monitor various temperatures in the device (as received from the downlink channel) and can, in the case of an overheat condition, send an emergency shutdown signal to the light ranging device via the uplink channel. In some embodiments, the base controller can be a mobile computer, e.g., a programmable system-on-a-chip employing an ARM + FPGA architecture with associated memory and I/O capability (e.g., Ethernet and the like).

[0079] Ranging data can be generated by light ranging device 310 by transmitting one or more light pulses from the light transmission module 340 to objects in a field of view surrounding the light ranging device. Reflected portions of the transmitted light are then detected by the light sensing module 330 after some delay time. Based on the delay time, commonly referred to as the “time of flight”, the distance to the reflecting surface can be determined. Other ranging methods can be employed as well, e.g. continuous wave, Doppler, and the like.

[0080] The Tx module 340 includes an emitter array 342, which can be a one-dimensional or two-dimensional array of transmitters, and a Tx optical system 344, which when taken together form an array of transmitter channels behind a bulk imaging optic. These transmitter channels may optionally include micro-optic structures for beam-shaping, beam-steering, brightness enhancement, or the like. The Tx module 340 further includes optional processor 345 and memory 346, although in some embodiments these computing resources can be incorporated into the ranging system controller 350. In some embodiments, a pulse coding technique can be used, e.g., Barker codes and the like. In such cases, memory 346 can store pulse-codes that indicate when light should be transmitted. In one embodiment the pulse-codes are stored as a sequence of integers stored in memory.

[0081] The Rx module 330 can include sensor array 336, which can be, e.g., a one-dimensional or two-dimensional array of photosensors. Each sensor can include a collection of binary photon detectors, e.g., SPADs or the like, or a sensor can be a linear photodetector (e.g., an APD). Like the Tx module 340, Rx module 330 includes an Rx optical system 337. The Rx optical system 337 and sensor array 336 taken together can form an array of micro-optic receiver channels behind a bulk imaging optic. Each micro-optic receiver channel measures light that corresponds to an image pixel in a distinct field of view of the surrounding volume. Each sensor (e.g., a collection of SPADs) of sensor array 336 can correspond to a particular emitter of emitter array 342, e.g., as a result of a geometrical configuration of light sensing module 330 and light transmission module 340. In an alternative embodiment, each sensor of sensor array 336 can correspond to multiple emitters (e.g., a cluster of VCSELs) of emitter array 342. In yet another embodiment, a single large emitter (e.g., a laser diode bar) could in emitter array 342 could correspond to multiple sensors within sensor array 336.

[0082] In one embodiment, the sensor array 336 of the Rx module 330 is fabricated as part of a monolithic device on a single substrate (using, e.g., CMOS technology) that includes both an array of photon detectors and an ASIC 331 for signal processing the raw signals from the individual photon detectors (or groups of detectors) in the array. As an example of signal processing, for each photon detector or grouping of photon detectors, memory 334 (e.g., SRAM) of the ASIC 331 accumulate counts of detected photons over successive time bins and these time bins taken together can be used to recreate a time series of the reflected light pulse (*i.e.*, a count of photons vs. time). This time-series of aggregated photon counts is referred to herein as an intensity histogram (or just histogram). In addition, the ASIC 331 can accomplish certain signal processing techniques, such as matched filtering, to help recover a photon time series that is less susceptible to pulse shape distortion that can occur due to SPAD saturation and quenching. In some embodiments, one or more components of the ranging system controller 350 can also be integrated into the ASIC 331, thereby eliminating the need for separate a ranging controller module.

[0083] In some embodiments, one or more of the individual components of the Rx optical system 337 can also be part of the same monolithic structure as the ASIC, with separate substrate layers for each receiver channel layer. For example, an aperture layer, collimating lens layer, an optical filter layer and a photodetector layer can be stacked and bonded at the wafer level before dicing. The aperture layer can be formed by laying a non-transparent substrate on top of a transparent substrate or by coating a transparent substrate with an opaque film. In yet other embodiments one or more components of the Rx module 330 may be external to the monolithic structure. For example, the aperture layer may be implemented as a separate metal sheet with pin-holes.

[0084] In some embodiments, the photon time series output from the ASIC are sent to the ranging system controller 350 for further processing, e.g., the data can be encoded by one or more encoders of the ranging system controller 350 and then sent as data packets via the optical downlink. Ranging system controller 350 can be realized in multiple ways including, e.g., by using a programmable logic device such an FPGA, as an ASIC or part of an ASIC, using a processor 338 with memory 334, and some combination of the above. The ranging system controller 350 can cooperate with a base controller 309 or operate independently of the base

controller 309 (via pre-programed instructions) to control the light sensing module 330 by sending commands that include start and stop light detection and adjust photo-detector parameters. Similarly, the ranging system controller 350 can control the light transmission module 340 by sending commands, or relaying commands from the base controller 309, that include start and stop light emission controls and controls that can adjust other light-emitter parameters such as, emitter temperature control (for wavelength tuning), emitter drive power and/or voltage. If the emitter array has multiple independent drive circuits, then there can be multiple on/off signals that can be properly sequenced by the ranging system controller. Likewise, if the emitter array includes multiple temperature control circuits to tune different emitters in the array differently, the transmitter parameters can include multiple temperature control signals. In some embodiments, the ranging system controller 350 has one or more wired interfaces or connectors for exchanging data with the light sensing module 330 and with the light transmission module 340. In other embodiments, the ranging system controller 320 communicates with the light sensing module 330 and light transmission module 340 over a wireless interconnect such as an optical communication link.

B. *Light Transmission and Detection*

[0085] FIG. 4 shows an illustrative example of the light transmission and detection process for a light ranging system according to some embodiments, with a focus on the emitter array and sensor array that form an arrangement of emitter-sensor channels, as introduced above in reference to FIG. 2. FIG. 4 shows a light ranging system (e.g., solid state or and/or scanning) collecting three-dimensional distance data of a volume or scene that surrounds the system.

[0086] Light ranging system 400 includes a light emitter array 402 and a light sensor array 404. The light emitter array 402 includes an array of light emitters, e.g., an array of VCSELs and the like, such as emitter 403 and emitter 409. Light sensor array 404 includes an array of photosensors, e.g., sensors 413 and 415. The photosensors can be pixelated light sensors that employ, for each pixel, a set of discrete photodetectors such as single photon avalanche diodes (SPADs) and the like. However, various embodiments can deploy any type of photon sensors. In some embodiments, the light ranging system 400 includes one or more sets of bulk optical

elements (not shown), referred to herein as bulk optics, placed in front of the light emitter array 402 and/or the Light sensor array 404 for redirecting the beams in the directions shown.

[0087] Each emitter can be slightly offset from its neighbor and can be configured (using a the bulk imaging optical system which is not depicted) to transmit light pulses into a different field of view from its neighboring emitters, thereby illuminating a respective field of view associated with only that emitter. For example, emitter 403 emits an illuminating beam 405 (formed from one or more light pulses) into the circular field of view 407 (the size of which is exaggerated for the sake of clarity). Likewise, emitter 409 emits an illuminating beam 406 (also called an emitter channel) into the circular field of view 410. While not shown in FIG. 4 to avoid complication, each emitter emits a corresponding illuminating beam into its corresponding field of view resulting in a 2D array of fields of view being illuminated (21 distinct fields of view in this example corresponding to the 21 emitters, arranged in a 3 x 7 array, of light emitter array 402).

[0088] Each field of view that is illuminated by an emitter can be thought of as a pixel or spot in the corresponding 3D image that is produced from the ranging data. Each emitter channel can be distinct to each emitter and be non-overlapping with other emitter channels, *i.e.*, there is a one-to-one mapping between the set of emitters and the set of non-overlapping fields or view. Thus, in the example of FIG. 4, the system can sample 21 distinct points in the 3D space. A denser sampling of points can be achieved by having a denser array of emitters or by scanning the angular positions of the emitter beams over time such that one emitter can sample several points in space. As described above, scanning can be accomplished by rotating the entire emitter/sensor assembly. Scanning could also be accomplished using galvanometers, MEMS mirrors, or via some other method.

[0089] Each sensor can be slightly offset from its neighbor and, like the emitters described above, each sensor can see a different field of view of the scene in front of the sensor.

Furthermore, each sensor's field of view substantially coincides with, e.g., overlaps with and is the same size as a respective emitter channel's field of view. Similar to the emitters described above, the fields of view of the sensors can be scanned by rotation of the assembly. Scanning could also be accomplished using galvanometers, MEMS mirrors, or via some other method.

[0090] In FIG. 4, the distance between corresponding emitter-sensor channels is exaggerated relative to the distance to objects in the field of view. In practice, the distance to the objects in the field of view is much greater than the distance between corresponding emitter-sensor channels and thus the path of light from the emitter to the object is approximately parallel to the path of the reflected light back from the object to the sensor (i.e., it is almost “back reflected”). Accordingly, there is a range of distances in front of the system 400 over which the fields of view of individual sensors and emitters are overlapped and it is over this range of distances that the system can most accurately determine depth information.

[0091] Because the fields of view of the emitters are overlapped with the fields of view of their respective sensors, each sensor channel ideally can detect the reflected illumination beam that originates from its respective emitter channel with ideally no cross-talk, i.e., no reflected light from other illuminating beams is detected. For example, emitter 403 emits an illuminating beam 405 into the circular field of view 407 and some of the illuminating beam reflects from the object 408. Ideally, a reflected beam 411 is detected by sensor 413 only. Thus, emitter 403 and sensor 413 share the same field of view, e.g., field of view 407 and form an emitter-sensor pair. Likewise, emitter 409 and sensor 415 form an emitter-sensor pair, sharing field of view 410. While the emitter-sensor pairs are shown in FIG. 4 as being in the same relative locations in their respective array, any emitter can be paired with any sensor depending on the design of the optics used in the system. In some embodiments, having identical bulk imaging optics in front of identically arranged emitter/sensor pairs can be advantageous from a design simplicity/cost perspective.

[0092] During a ranging measurement, the reflected light from the different fields of view distributed around the volume surrounding the LIDAR system is collected by the various sensor and processed, resulting in range information for any objects in each respective field of view. As described above, a time-of-flight technique can be used in which the light emitters emit precisely timed pulses, and the reflections of the pulses are detected by the respective sensors after some elapsed time. The elapsed time between emission and detection and the known speed of light is then used to compute the distance to the reflecting surface. In some embodiments, additional information can be obtained by the sensor to determine other properties of the reflecting surface

in addition to the range. For example, the Doppler shift of a pulse can be measured by the sensor and used to compute the relative velocity between the sensor and the reflecting surface.

[0093] In some embodiments, the LIDAR system can be composed of a relatively large 2D array of emitter and sensor channels and operate as a solid state LIDAR, i.e., it can obtain frames of range data without the need to scan the orientation of the emitters and/or sensors. In other embodiments, the emitters and sensors can be scanned, e.g., rotated about an axis, to ensure that the fields of view of the sets of emitters and sensors sample a full 360 degree region (or some useful fraction of the 360 degree region) of the surrounding volume. The range data collected from the scanning system, e.g., over some predefined time period, can then be post-processed into one or more frames of data that can then be further processed into one or more depth images or 3D point clouds. The depth images and/or 3D point clouds can be further processed into map tiles for use in 3D mapping and navigation applications.

II. LIDAR UNIT WITH INTEGRATED ARCHITECTURE

[0094] FIGS. 5A-5B show a rotating LIDAR system 500 in accordance with one or more embodiments. As described in more detail below, the rotating LIDAR system 500 employs a highly integrated architecture and enables a highly compact configuration for the internal mechanical elements and circuitry. Accordingly, the overall form factor is much smaller than existing systems, e.g., with an overall volume that is smaller than a coffee mug, as can be seen in FIG. 5A.

[0095] FIG. 5B shows an embodiment of the LIDAR system with the outer enclosure removed to highlight the integrated, stacked-board design. The rotating LIDAR system 500 includes a light ranging device 505 that is connected to a printed circuit board that forms the rotating end of stacked board rotary actuator 506. The fixed side of stacked board rotary actuator 506 is attached to base portion 509 of the enclosure. When in place, the enclosure fully encloses the LIDAR system 501 to protect it from the elements, but also may have one or more transparent surfaces or windows to allow for two-way transmission of IR light.

[0096] As described in more detail below, embodiments of the LIDAR system possess a highly integrated design that makes them especially suitable for a highly compact rotating LIDAR system. The various functional elements of the LIDAR system (both mechanical and electronic)

are integrated into a stacked circuit board assembly that includes the one or more stacked circuit boards, as shown in FIG. 5B, *e.g.*, circuit boards 511, 513, 515, and 517. In some embodiments, the power system, electric motor, communication system, and LIDAR control system are all integrated into one or more stacked planar circuit boards of the stacked board rotary actuator

5 506. The light ranging device 505 can be conveniently attached to the top board 517 by way of one or more multi-pin connectors or the like (not shown). As will be detailed below, the boards may have a central aperture through which a central shaft passes. The upper boards are attached to the upper portion of the shaft via one or more bearings. Each of the boards is arranged with its planar surface being perpendicular (*e.g.*, within 5° of a right angle) to the shaft and therefore the
10 axis of rotation. As a result of this configuration, assembly and maintenance are much simpler relative to other systems that employ multiple boards in many different orientations within the LIDAR device.

[0097] FIGS. 6A-6C show cross-sectional views of a LIDAR system 601 in accordance with one or more embodiments. More specifically, the individual components shown in FIGS. 6A-6C
15 correspond to those already described above in reference to FIG. 3, with the views shown FIGS. 6A-6C providing examples of the geometric placement of the various circuit elements according to some embodiments. FIG. 6A-6B show an embodiment that employs all optical communication between the upper and lower circuit board assemblies and FIG. 6C shows an embodiment that employs an inductive communication. FIGS. 6D-6E provide views of surfaces
20 of the individual circuit boards according to some embodiments to further illustrate the concentric circumferential arrangement of a number of individual circuit elements.

[0098] As shown in FIG. 6A, the upper and lower circuit board assemblies 607 and 617, respectively, can include two or more stacked planar circuit boards. Alternatively, as shown in FIG. 6B, the upper and lower assemblies can be single circuit boards 659 and 651, respectively.
25 This highly integrated, stacked board design provides for a system that has a greatly simplified assembly process in comparison to systems that employ numerous stand-alone modules for all of the different functional elements of the LIDAR system.

[0099] As can be seen in FIG. 6A, the rotating turret assembly of the LIDAR includes the upper circuit board assembly 607 and the light ranging system 605. The rotation is enabled by

bearing system 613 located on the hollow shaft 603 (having a longitudinal axis 604 that is also the axis of rotation about which each of the planar circuit boards rotate).

[0100] While not shown explicitly in FIGS. 6A-6B, one or more supporting power circuits, drive/control circuits, and communication circuits are paired with each of the systems discussed below and these supporting systems are also integrated onto one or more circuit boards of the rotary actuator. For example, a motor driver for providing a three phase drive current to the solenoids of the stator can be attached to a surface of a circuit board of the lower circuit board assembly 617. Power drive and conditioning circuits can be paired with the wireless power transmission components and mounted to the upper and/or lower board assemblies. Supporting circuitry for the digital communication system, such as buffers, LED/laser current drivers, encoders/decoders, clock recovery circuits, photodetector drive and conditioning circuits, etc., are also mounted to one or more boards of the circuit board assemblies. Some of these elements will be discussed in further detail below but one of ordinary skill in the art will appreciate that any number of arrangements and configurations of standard circuit components can be employed without departing from the scope of the present disclosure. In some embodiments, because of the nature of the rotationally symmetric optical uplink, wireless power rotary transformer, brushless dc motor, and rotary encoder, any concentric ordering of these subsystems about the shaft can be employed.

A. *Optical Links*

1. **Integrated Central Optical Downlink**

[0101] In some embodiments, the hollow shaft 603 can serve not only as a central structural member that supports each of the board assemblies, but also serves as a housing for a downlink optical communications channel (“the downlink channel”) for providing data, e.g., ranging and/or operational data, from the turret assembly to the control and processing circuitry located in the lower circuit board assembly 617 (also referred to as the base system). The optical downlink channel can include optical downlink transmitter 619 and optical downlink receiver 621. The optical downlink transmitter 619 can be attached, e.g., soldered, directly to a surface of a circuit board of upper circuit board assembly 607 and can be positioned such that it can transmit light through a central hole or opening in the hollow shaft 603. Likewise, the optical

downlink receiver 621 can be attached, e.g., soldered, directly to a surface of a circuit board of the lower circuit board assembly 617. The optical downlink receiver 621 can be positioned on the lower end of the shaft and aligned with the optical downlink transmitter 619 such that it is able to detect the light that is transmitted from the optical downlink transmitter 619.

- 5 **[0102]** The optical transmitters and receivers used for the optical downlink of the rotary actuator can be any type of optical emitter or detector. For example IR LEDs, laser diodes, VCSELs, and the like can be used for the emitters. Likewise any type of light detection technology can be used for the receivers, e.g., photodiodes and the like.

2. **Integrated Optical Uplink**

- 10 **[0103]** An optical uplink channel is formed between a circumferential arrangement of optical uplink transmitters 623 and a complementary circumferential arrangement of optical uplink receivers 625. As with the optical downlink transmitter/receiver pair, the individual optical uplink transmitters and optical uplink receivers can be directly attached, e.g., soldered, to respective circuit boards of the lower and upper circuit board assemblies, respectively. Optical
15 communication components that are disposed on the lower circuit board assembly are also referred to herein as “base optical communication components. Optical communication components that are disposed on the upper circuit board assembly, or turret, are also referred to herein as “turret optical communication components.” Advantageously, the wall of the hollow shaft 603 provides for optical isolation between the uplink and downlink channels and therefore
20 minimizes crosstalk. The individual emitter and receivers of the circumferential arrangements are wired together such that they act together as a single composite receiver and a single composite transmitter. For example, as the system rotates the overall optical intensity up the uplink signal detected by the full arrangement of optical uplink receivers varies only slightly as the individual emitters/detectors pass each other. Furthermore, the number of individual
25 transmitters can be the same as or different from the number of individual receivers.

[0104] The optical transmitters and receivers used for the optical uplink of the rotary actuator can be any type of optical emitter or detector. For example IR LEDs, laser diodes, VCSELs, and the like can be used for the emitters. Likewise any type of light detection technology can be used for the receivers, e.g., photodiodes and the like. In addition, the optical transmitters and

receivers used for the optical uplink can be the same or different type (e.g., power and wavelength) as those used for the downlink.

[0105] An example of a circumferential arrangement of optical uplink transmitters 623 is shown in FIG. 6D, which illustrates a top view of a circuit board, e.g., circuit board 641 of FIG. 6A or circuit board 651 of FIG. 6B. In this example, there are 6 optical uplink transmitters 623 that are circumferentially arranged around the central hole 669. The 6 transmitters are evenly spaced around the circle 665 whose center is located at center of the shaft (not shown) and therefore overlapped with the axis of rotation.

[0106] The opposing surface of the rotating board includes a corresponding circumferential arrangement of optical uplink receivers 625, as shown in FIG. 6E, which illustrates a bottom view of a rotating circuit board, e.g., circuit board 639 of FIG. 6A or circuit board 651 of FIG. 6B according to some embodiments. In this example, there are 7 optical uplink receivers that are circumferentially arranged around the central hole 671. The 7 receivers are evenly spaced around the circle 667 whose center is located at center of the shaft (not shown) and therefore overlapped with the axis of rotation. Accordingly, as the board rotates, the arrangement of optical uplink receivers 625 rotates about the axis of rotation. Because the radius of circle 667 is same as the radius of circle 665, the transmitters are aligned with the receivers and the rotation merely results in a slight rise and fall of the average signal over time with a frequency being a multiple of the rotation frequency of the turret system. The number of transmitters needed for a reliable uplink channel depends on both the nominal power of the transmitters as well as the divergence of the light cone that is emitted from each transmitter. Ideally, the spot size of the transmitter light at the front surface of the rotating board should be large enough that the individual spots overlap to such an extent that as the rotating board rotates, the overall variation in the average intensity seen by the collection of receivers is below a specified value.

B. Inductive Communication Links

[0107] FIG. 6C shows an embodiment that employs an inductive communications system between the upper and lower circuit board assemblies. In this example, data uplink and downlink are provided by pairs of coils 661a-e and 663a-e respectively mounted on the lower circuit board assembly and upper circuit board assembly, as shown. The coils can include both

data lines and clock lines. Each coil can be embedded within a separate channel, e.g., a circular channel, of a housing, such as upper coil housing 661 and lower coil housing 663 that are themselves mounted to the surfaces of their respective circuit boards. In some embodiments, there can be several coils that are used for multiple inductive data lines, e.g., downlink channel 1 transmitter coil 661b and downlink channel 1 receiver coil 663b, downlink channel 2 transmitter coil 661c and downlink channel 2 receiver coil 663c. In some embodiments, the downlink clock signal can be transmitted via a separate coil pair, e.g., downlink clock transmit coil 661a and downlink clock receiver coil 663a. Likewise, data uplink channels can be formed from one or more pairs of coils, e.g., by uplink transmitter coil 663d and uplink receiver coil 661d. Like the downlink, the data uplink clock signal can also have a dedicated channel formed from a pair of coils, e.g., uplink clock transmitter coil 663e and uplink clock receiver coil 661e.

[0108] In some embodiments, the use of an inductive communications links can provide a number of advantages over an optical configuration, including 1) replacement of the hollow shaft 603 with a solid shaft 669 which is simpler and easier to construct; 2) in some situations, an inductive coil arrangement can require less stringent tolerances on mechanical alignment and thus have lower cost of manufacture; 3) an easier arrangement for passing multiple channels of information between the boards; 4) can enable passing a clock along with data, which removes the need for clock and data recovery (CDR) chips; 5) can allow for scaling bandwidth by providing a multichannel (parallel) data transmission lines arrangement; and 6) by distributing a separate clock signal between the boards, deterministic timing behavior can be achieved between lower board assembly (stator) and upper board assembly/light ranging unit (rotor).

[0109] While FIG. 6C shows an embodiment with five coil pairs, any number of coil pairs can be implemented without departing from the scope of the present disclosure. For example, a two coil pair configuration having only one data uplink channel and one downlink channels can be implemented. In this case, the clock signal can be provided via the uplink channel and the downlink clock can be derived from this uplink clock signal. In other embodiments, three coil pairs can be employed, one for uplink data, one for downlink data and one for the uplink clock signal, again, with the downlink clock signal being derived from the uplink clock signal. Four coil pair configurations are also possible that provide for both uplink and downlink clock signal

channels. In addition to all the above, any number of data cannels can be employed without departing from the scope of the present disclosure.

C. *Integrated Electric Motor*

[0110] According to certain embodiments, the electric motor for the rotary actuator is of a “pancake” or “axial” design having a planar rotor assembly on a rotor board that opposes a planar stator assembly on an opposing stator board. The stator and rotor assemblies of the electric motor are also integrated onto the boards of the rotary actuator 606, i.e., the elements of the electric motor are one of many components on the surface of the printed circuit boards and thus a separate motor module is not required for the LIDAR system. For example, the motor stator assembly 627 can include a circular arrangement of stator elements, e.g., vertically oriented solenoids (having their longitudinal axes perpendicular to the surface of the board) that are affixed, e.g., using an adhesive, to a board of the lower circuit board assembly 617 or to a soft magnetic core that is then affixed to the lower circuit board assembly 617. Examples of the solenoid windings are shown in the top view of FIG. 6D. Each solenoid coil can be wound around a core of magnetic material, e.g., ferrite or the like. The coils are oriented such that the magnetic field exiting the solenoid is substantially oriented in a direction that is substantially perpendicular to the plane of the circuit board.

[0111] Positioned above the motor stator assembly 627 and attached to a board of the upper circuit board assembly 607 is the motor rotor assembly 629. In some embodiments, the motor rotor assembly can be a passive element that includes a circular arrangement of permanent magnets, with their poles arranged in an alternating pattern to sequentially oppose and attract the opening of the various solenoid coils of the stator assembly, as shown in more detail in board view shown in FIG. 6E. As can be seen in FIG. 6D and 6E, the motor stator assembly 627 and the motor rotor assembly 629 can have an overall circular ring shape with both stator and rotor circles having the same radius and center positions (e.g., both rings can be centered on the shaft).

[0112] While the embodiments shown here employ rotor elements that are permanent magnets and stator elements that are solenoid coils, the opposite configuration can also be employed without departing from the scope of the present disclosure. For example, solenoids can be employed as the rotor elements and permanent magnets can be employed as the stator elements,

in which case, power to the stator elements can be provided by the wireless power transmission system described below. In addition, rather than employing permanent magnets as rotor/stator elements, electromagnets can be employed in certain embodiments. One of ordinary skill having the benefit of this disclosure will appreciate that any implementation of a PCB mounted
5 brushless DC motor can be employed, e.g., any non-contact configuration of solenoid coils and permanent magnet elements can be employed and any drive scheme that implements rotary motion of the underlying hardware can be employed without departing from the scope of the present disclosure.

D. *Integrated Wireless Power Transmission System*

10 **[0113]** To provide power to the circuit elements connected to the rotating upper circuit board assembly 607, the rotary actuator 606 includes a wireless power system, also referred to herein as a rotary transformer, including a wireless power transmission subsystem including a wireless power transmitter 635 and a wireless power receiving subsystem including a wireless power receiver 637. The wireless power transmitter 635 can be a transmitter coil in the form of a
15 circular loop antenna, i.e. a single turn or multi-turn coil, that is attached to a surface of a circuit board of the lower circuit board assembly 617, e.g., as shown in FIG. 6D. Likewise, the wireless power receiver 637 can be a receiver coil in the form of a circular loop antenna, i.e. a single turn or multi-turn coil, that is attached to a surface of a circuit board of the upper circuit board assembly 617, e.g., as shown in FIG. 6E. The centers of both the wireless power transmitter 635
20 and the wireless power receiver 637 are positioned at the center of the hollow shaft 603 and are therefore concentric with, the optical encoder ring, the electric motor assemblies, and the optical uplink receiver/transmitters. Advantageously the wireless power transmitter and receiver are positioned at the outermost region of the boards to maximize the area (and therefore inductance) of the circular loops which maximizes power transfer efficiency and advantageously blocks light
25 from the environment or the internals of the LIDAR system from reaching the optical encoder, uplink or downlink.

[0114] In some embodiments, the wireless power transmitter 635 and a wireless power receiver 637 can be placed within an annular region of their respective boards with the walls and bottom of the annular regions formed from a magnetic material, e.g., ferrite or the like. For

example, FIG. 6E shows wireless power receiver 637 disposed within an annular region formed from ferrite walls 647 and 649 and occluded ferrite bottom. Such an arrangement of ferrite materials helps channel the magnetic fields between the transmitter and receiver to improve power transfer efficiency and reduce electromagnetic radiation leaking from the system.

5 **E. *Integrated Optical Encoder***

[0115] The rotary actuator 606 further includes an integrated optical encoder assembly that allows for readout of the angular position of the upper circuit board assembly 607 relative to the lower circuit board assembly 617. The optical encoder assembly includes a patterned annular optical encoder 631 and rotary encoder detector 633 for reading off the angular position of the
10 assembly by, e.g., detecting and counting the number of patterns that pass the rotary encoder detector 631 as the system rotates. In certain embodiments, the rotary encoder detector 633 can include an illumination device, such as an LED and a detector, such as a photodiode or imaging detector for illuminating and detecting the patterned surface of the annular optical encoder. In some embodiments, the annular optical encoder can include a start code that occurs at a unique
15 position on the annulus or provides absolute encoding patterns thereby enabling an absolute angular orientation measurement. In some embodiments, the encoder system is magnetic instead of optical in nature and relies on a similarly positioned magnetic encoder strip and magnetic encoder reader.

[0116] In some embodiments, the annular optical encoder 631 can be attached to a surface of a
20 circuit board of the lower circuit board assembly 617 and the rotary encoder detector 633 can be attached to a surface of the upper circuit board assembly 607 as shown here, or vice versa. Regardless of which board it is placed on, the annular optical encoder 631 can be arranged to have its center at the center of the hollow shaft 603 and is therefore concentric with both the electric motor assemblies and the optical uplink receiver/transmitters, e.g., as shown in FIG. 6D.
25 In some embodiments, the rotary encoder detector 633 is positioned on the rotating circuit board, anywhere above the annular optical encoder 631, e.g., as shown in FIG. 6E. Advantageously, the encoder assembly is positioned between the wireless power transmission system and the electric motor assembly to maximize the optical isolation between the encoder detector and the transmitters of the optical uplink system. As shown in the example of FIG. 6A, in some

embodiments the annular optical encoder 631 can be on the stator side of the rotary actuator 606 while the rotary encoder detector 633 on the rotor side. While this is a non-standard configuration for rotary actuators, this configuration is advantageous for a LIDAR application. For example, by removing the rotary connection between the rotary encoder detector 633 and the light ranging system 605 in this manner, the implementation of a low latency connection between the two systems can be implemented. In LIDAR applications a low latency connection can be important for quickly ingesting the angular position measurements of the rotary encoder detector 633 and correlating the current ranging information with the current angular position of the rotor for increased spatial accuracy.

F. Method of assembly

[0117] FIGS. 7-8 show exploded views of a LIDAR system to illustrate the assembly process according to certain embodiments. FIG. 7 illustrates the mechanical assembly of the lower circuit board assembly (also referred to herein as the base assembly). FIG. 8 illustrates the mechanical assembly of the upper circuit board assembly and its attachments to both the lower circuit board assembly and the light ranging device, thereby forming the full LIDAR system.

1. Assembling the Lower Circuit Board Assembly

[0118] FIG. 7 shows an exploded view of the lower circuit board assembly to illustrate the assembly process of the compact LIDAR system according to certain embodiments. The example shown in FIG. 7 includes a lower circuit board assembly that is of a two-board configuration, similar to that described above in reference to FIG. 6A.

[0119] In this example, the lower circuit board assembly is formed from two sub-boards, referred to herein as the base control board 701 and the stator board 703. In some embodiments, base control board 701 and stator board 703 correspond to boards 643 and board 641, respectively, as shown in FIG. 6A.

[0120] The assembly process begins with the base control board 701 being mechanically attached to base 705 by way of four screws. As already described above in reference to FIGS. 3 and 6, the base control board can include a number of circuit elements, including a base controller, similar to base controller 309. Supporting circuitry, e.g., drivers for, the elements of

the optical communications systems, wireless power transmission system, and the rotary encoder system can also be included on the base control board. To enable the optical downlink communications channel, an optical downlink receiver 709 is mounted to, e.g., soldered, to an upper surface of the base control board 701, in the central region of the board, as described above in reference to FIG. 6. In some embodiments, optical downlink receiver 709 and the other supporting circuit elements are integrated directly onto stator board 703 thereby eliminating the need for a separate base control board 701, e.g., as described above in reference to FIG. 6B. In such a case, assembly begins by attaching heat spreading element 707 directly to the base 705 or in cases that do not employ the base heat spreading element 707, the assembly begins by installing stator board 703.

[0121] Returning to the embodiment shown in FIG.7, after base control board 701 is attached to base 705, shaft 711 is attached to base control board 701, using three screws. In some embodiments, shaft 711 can be attached directly to base 705 for improved thermal conduction of heat from the upper circuit board assembly to the base 705 via the bearing system (shows in more detail in FIG. 8, below). As described above in reference to FIGS. 6A-6B, shaft 711 has a central hole 713 through its length that provides an open optical path for an optical downlink channel. As such, shaft 711 is placed directly on top of optical downlink receiver 709 located generally near the center of base 705. In some embodiments, regardless of the shape of the outer circumference of base control board 701 or base 705, shaft 711 defines the axis of rotation 702 of the system. Thus, the position of shaft 711 need not be directly in the center of base control board 701 or in the center of base 705.

[0122] After shaft 711 is attached to base control board 701, a heat spreading element 715 can be attached to base control board 701, again by way of four screws. In some embodiments, the heat spreading element 715 can be made from a material having a high thermal conductivity, e.g., aluminum and the like. In addition, there may be one or more intervening thermal foam pads between heat spreading element 715 and the boards to prevent electrical shorts while providing a conductive heat path. In some embodiments, heat spreading element 715 makes thermal contact with one or more portions of the lower surface of stator board 703 and one or more portions of the upper surface of base control board 701 thereby providing a thermal path for concentrated heat from the circuit elements of these boards to more evenly distribute amongst

the boards. On its periphery, heat spreading element 715 may also make thermal contact with the sides of base 705 and thus provide an improved thermal path for heat to be conducted from the boards to base 705 and eventually out of the system.

[0123] After securing heat spreading element 715, stator board 703 is attached, again by way of four screws, as shown in FIG. 7. In some embodiments, stator board 703 is electrically connected to base control board 701 by way of one or more multi-pin electrical connectors, e.g., lower connectors 717 and 719 shown in FIG. 7. In some embodiments, the physical connection between the boards is made by applying a mechanical connection pressure between stator board 703 and base control board 701, e.g., by pressing the stator board 703 onto the base control board 701 after it has been attached to base 705. The connection pressure is maintained over the life of the systems by the four screws used to secure stator board 703 to base control board 701.

[0124] Once assembled and secured to the base 705 one or more optional color cameras 721 that are positioned around the periphery of the stator board 703 can be positioned to have a clear path out of the base 705 through one or more imaging apertures 725, which in some embodiments can be clear apertures or can contain one or more optical elements to assist with imaging. In other embodiments, the color cameras 721 can be mounted direction to the base 723 rather than be mounted to the stator board 703. Accordingly, the LIDAR data that is accumulated by the LIDAR system can be supplemented by color imaging data such as still frames and/or video.

2. Assembling the Upper Circuit Board Assembly and Attaching to the Lower Circuit Board Assembly

[0125] FIG. 8 shows the assembled lower circuit board assembly, an exploded view of the upper circuit board assembly, the light ranging system, and the enclosure to illustrate the assembly process of the compact LIDAR system according to certain embodiments. The example shown in FIG. 8 includes an upper circuit board assembly that is of a two-board configuration, similar to that described above in reference to FIG. 6A.

[0126] In this example, the upper circuit board assembly is formed from two sub-boards, referred to herein as the ranging device control board 801 and the rotor board 803. In some

embodiments, ranging device control board 801 and rotor board 803 correspond to boards 645 and board 639, respectively described above in reference to FIG. 6A.

[0127] As shown in the exploded view of rotor board 803, bearing assembly 802 includes bearings 807 and 809 which are inserted into either end of a t-shaped bearing housing 805. T-shaped bearing housing 805 is then pressed into rotor board 803 and secured with four screws.

[0128] The rotor board is then placed on top of the assembled lower circuit board assembly by fitting the central portion of the T-shaped bearing housing over the shaft. A circular nut 810 is then fitted into a circular central recess in the top surface of the t-shaped bearing housing 805 and threaded onto the top of shaft 711. This securely attaches the rotor board 803 to the lower circuit board assembly. As already shown in cross-section in FIG. 6A, the rotor board 803 is able to rotate relative to the lower circuit board assembly due to the rotational coupling made between the shaft 711 and bearings 807 and 809.

[0129] Ranging device control board 801 can then be joined to rotor board 803 by applying a downward pressure to the ranging device control board 801. To provide an electrical connection between ranging device control board 801 and rotor board 803, one or more electrical connectors are previously disposed on, e.g., soldered to, the lower surface of ranging device control board 801 (not shown) and the upper surface of rotor board 803, e.g., connector 811. The upper circuit board assembly is then secured together using two screws as shown in FIG. 8.

3. Attaching the Laser Ranging System to the Rotary Actuator

[0130] Once the upper circuit board assembly has been assembled and secured to the lower circuit board assembly, the light ranging device 813 can be electrically connected to the upper surface of ranging device control board 801 and mechanically connected to T-shape bearing housing 805. The Tx module 815 and the Rx module 817 can have dedicated electrical connectors that mate with corresponding connectors 819 and 821 disposed on the upper surface of light ranging device control board 801. As with the other boards in the system, connecting the light ranging device 813 to the rest of the assembled system can be achieved by applying a pressing force to the components. Once the connections are made, the pressing force is maintained by four screws mounted on either side of the light ranging device as shown. In

addition, to apply a connection force more directly to the connectors 819 and 821, a u-shaped bracket 823 can be used to and secured with additional screws as necessary.

[0131] Once all the internal components are assembled, the enclosure 825 dropped over the entire assembly and affixed to base 705, e.g., using one or more screws as well as adhesive, if required to achieve a more robust seal.

[0132] In the assembly process described above, various arrangements of screws and brackets are disclosed merely for the sake of example. Embodiments of the compact LIDAR system are not required to employ screw arrangements that are identical to that shown in FIGS. 7-8 and any number, arrangement, and type of fastener, including adhesive, deformable pins or latches, rivets, or welds, can be used without departing from the scope of the present disclosure.

III. OPTICS AND OPTOELECTRONICS

[0133] FIGS. 9A-9C show a perspective view, a front view, and a zoomed front view, respectively, of a light ranging device 900 according to certain embodiments. The light ranging device 900 corresponds to embodiments described above in reference to FIGS. 1-6, e.g., light ranging device 310 described above in reference to FIG. 3. The light ranging system includes two main modules: a light transmission (Tx) module 903 and a light sensing (Rx) module 905. The light Tx module and light Rx modules each include bulk optics modules (not shown) that are mounted in front of their respective sensors/emitters, e.g., by sliding the bulk optics module into the appropriate lens mount that includes two lens tubes, e.g., transmitter lens tube 907 and detector lens tube 909. The bulk optics modules are described in more detail below. On the transmission side, located behind the Tx-side bulk optics module is, optionally, a Tx-side micro-optics assembly. Details of the micro-optics assembly are set forth below in reference to FIGS. 10-11. Behind the optional transmit-side micro-optics assembly is an emitter array 911, e.g., a monolithic single-chip NIR VSCSEL array fabricated on InGaAs, or the like. On the detector side, located behind the Rx-side bulk optics module is a Rx-side micro-optics assembly, also described in more detail below in reference to FIGS. 10-11. Behind the Rx-side micro-optics assembly is a single chip detector array and ASIC combination 913, e.g., a monolithic single-chip NIR SPAD array fabricated on a CMOS process, or the like.

[0134] Both Rx module 905 and Tx module 903 are backed by circuit boards 917 and 915, respectively, that include additional supporting circuitry for the light ranging device, e.g., voltage regulators, VCSEL current drivers, and the like. For example, circuit board 917 can include circuitry for counting signals from SPADs to include in a histogram of time bins, which may be specified by a time-to-digital converter. Circuit board 917 can also include match filtering for analyzing the histogram to determine a received time. In some embodiments, a programmable computation element such as an FPGA (e.g., to perform advanced filtering, such as interpolation) may be operatively connected to the Rx module 905.

[0135] While not shown in FIG. 9A-9B, the FPGA can be located on one or more boards of the upper board assembly of the rotary actuator described above, that include, e.g., the rotor half of a brushless motor, the receive side of a rotary transformer power link, the receive side of a rotary optical uplink, and the transmit side of a rotary optical downlink. These elements taken together are referred to herein as the turret assembly of the LIDAR system. In certain embodiments, the turret assembly can spin at a frequency of 1Hz to 30Hz, taking range measurements at fixed angular intervals. In one embodiment, for any given full rotation (“frame”), a 64x2048 resolution depth image can be produced, although the user may select other resolutions by changing device operating parameters. In some embodiments, the LIDAR system can acquire 2,621,440 points (range measurements) per second.

A. Optical Systems for the Tx and Rx Modules

[0136] FIG. 10 shows an optical block diagram of a light ranging device 1000 showing both the optical systems for a Rx module 1001 and a Tx module 1003 according to certain embodiments. Embodiments of the light ranging device 1000 can be employed within the compact LIDAR system disclosed herein as already described above in reference to, e.g., FIG. 4. The Tx module 1003 provides active illumination of objects in the area around the LIDAR system by, e.g., transmitting narrow band light, e.g., NIR light having a spectral width of, e.g., 2nm, 1nm, 0.5nm, 0.25 nm or less, into one or more fields of view, as shown in FIGS. 1A-1B and 4 above. The Rx module 1001 detects reflected portions of the transmitted narrowband light that is reflected by the objects in the scene.

[0137] As shown here, Tx module 1003 includes an optional TX-side micro-optics package 1009 and a bulk optical element 1021. The TX-side micro-optics package 1009 includes a one or two-dimensional array of transmitter channels, e.g., channel 1011 shown in the boxed region. Each one of the transmitter channels has one or more light emitters 1013, e.g., NIR VCSELs and the like, capable of emitting narrowband light. The light emitted from each one of the transmitters diverges as it approaches one of the micro-optics of the Tx-side micro-optic array 1015. Micro-optic array 1015 includes a one or two-dimensional array of microlenses 1016 that serve to capture the diverging light and refocus it to a focal plane that is coincident with an aperture array 1017 that includes an array of apertures that correspond in position to the array of micro-optics and the array of emitters. Aperture array 1017 is optional and may reduce crosstalk in the system. After exiting the micro-lenses, the focused light again diverges in the form of cones that then encounter the Tx-side bulk imaging optics module 1021. Details of the Tx-side bulk imaging optics module 1021 are discussed in more detail below.

[0138] In some embodiments, the separation between the micro-optic array 1015 Tx-side bulk imaging optics module 1021 is equal to the sum of their focal lengths, such that light focused at the aperture array 1017 appears as collimated light at the output of the Tx-side bulk imaging optics module 1021 with each collimated bundle of rays exiting the Tx-side bulk imaging optics module 1021 at a different angle. Accordingly, the light from each emitter is directed to a different field of view ahead of the device. In some embodiments, the Tx-side bulk imaging optic 1021 is telecentric on the VCSEL side of the lens, i.e., in a ray diagram of the system, all the chief rays entering anywhere within the aperture of the bulk imaging optic 1021 leave the lens travelling parallel to each other and intersect the VCSEL (image) plane at an angle of incidence that is substantially perpendicular to the VCSEL (image) plane. This is advantageous because in this configuration the VCSEL array operates as a telecentric source, i.e., the optics capture substantially all light produced by the emitter array, even light that is emitted from the emitters on the outer edges of the array. On the contrary, without the telecentric design, light captured by the outer emitters may be reduced because of their highly oblique angle of incidence.

[0139] The Rx module 1001 includes an Rx-side bulk imaging optics module 1005 and an RX-side micro-optics package 1002. The RX-side micro-optics package 1002 has either a one or two-dimensional array arrangement that matches the TX-side micro-optics package 1009, with a

micro-optic receiver channel 1029 for every corresponding micro-optic transmitter channel 1011. The RX-side micro-optics package 1002 includes an Rx-side aperture array layer 1023, an Rx-side micro-optics array layer 1019, a narrow band optical filter layer 1025 and a sensor array layer 1026. The portions of the emitted light that reflect off of objects in the field, shown as light rays 1027, enter the Rx-side bulk imaging optics module 1005 from multiple directions. The Rx-side bulk imaging optics module 1005 focuses light rays at a plane that is coincident with the Rx-side aperture array layer 1023. The focused light then is captured by the micro-lenses 1020 of the Rx-side micro-optics array layer 1019 and directed to a sensor array layer 1026 in a collimated fashion (i.e. having a divergence half angle of less than ten degrees).

[0140] In some embodiments, the sensor array layer 1026 includes a 1-D or 2-D array of light sensors or a one or two dimensional array of groups of light sensors, e.g., SPADS and the like. In some embodiments, each sensor or group of sensors in the array corresponds to an emitter in the emitter module and thus a “pixel” in the ranging data.

[0141] In some embodiments, to remove spurious background light, a narrow band optical filter layer 1025 can be disposed within the layered structure, e.g. between the micro-optics array and the sensor array layer 1026. The pass band of the narrow band optical filter layer 1025 can be chosen to correspond with the center wavelength of the emitters and the width of the pass band can be wide enough to accommodate any variation in the output wavelength across the emitter array. In some embodiments, where a very narrow pass band is desired, a control system can stabilize the wavelength of the emitters individually or as a whole. In some embodiments, where a very narrow pass band is desired, the collimation angle of the light passing through filter layer 1025 must be tightly controlled so that no angle-of-incidence shifts occur (as is common in thin-film interference filters); the collimation angle is primarily controlled by the size of apertures in RX-side aperture array layer 1023, the focal lengths of the lenses in RX-side micro-optic array layer 1019, the relative positioning between RX-side aperture array layer 1023 and RX-side micro-optic array layer 1019, and surface quality and form precision of RX-side micro-optic array layer 1019. In some embodiments the narrow band optical filter layer 1025 is continuous planar layer across the entire array of sensors. In other embodiments, the narrow band optical filter layer 1025 can be fabricated as an array of micro-optical elements that correspond with the pixel geometry of the sensor array layer 1026.

[0142] As with the Tx side, the individual elements of the Rx module 1001 form micro-optic receiver channels, e.g., receiver channel 1029. According to certain embodiments, the array of micro-optics and receivers can have a layered monolithic structure. Each micro-optic receiver channel 1029 measures light for a different pixel in the sensor array layer 1026, i.e., the optics of the Rx module 1001 serve to map bundles of parallel rays entering the module from different angles to different corresponding spatial positions on the sensor array layer 1026. In some embodiments, the bulk imaging optics module 1005 is telecentric on the detector side of the system to avoid the non-idealities in the image plane in a manner similar to the TX side, as described above.

[0143] In some embodiments, the micro-optic receiver channels as formed by the cooperation between the micro-optic array layer 1019, narrow band optical filter layer 1025, and Rx-side aperture array layer 1023 provide for increased isolation between different pixels on the sensor array layer. This is advantageous because in some situations, such as when the emitter light is reflected from a strong reflector in the field, such as a stop sign, the photon flux at the Rx side for each channel can be sizable, making the system susceptible to cross talk and blooming (i.e. the incoming light from one channel may be so bright that it is detectable by an adjacent channel). One solution to the booming problem is to employ a complex time multiplexing scheme such that only one emitter-detector pair (or a carefully chosen group of emitter-detector pairs) are triggered at any given time, therefore eliminating the risk of cross talk. Such an arrangement requires additional timing electronics and multiplexing software and hardware which adds additional cost and complexity to the system. In addition, time-multiplexing is an inefficient data collection method because each receiver emitter pair must be sequentially activated in series thereby increasing the overall acquisition time of the array as a whole. Advantageously, the design of the Rx side micro-optics assembly reduces cross-talk to such an extent that time multiplexing and sequential activation is not necessary, i.e., all channels can be employed at the same time to collect data points in parallel, in a manner similar to a flash LIDAR system.

[0144] The above design is advantageous for a number of reasons. First the design of the micro-optical systems for the Rx module 1001 and the Tx module 1003 enable the conceptual LIDAR arrangement described above in reference to FIG. 4 where each transmitter element is

paired with a sensor element such that the sensor element views light only from the field of view that the transmitter illuminates. This 1:1 pairing of fields of view helps eliminate cross-talk in the detector from adjacent or neighboring pixels. The additional micro-optical aperture layer also helps to eliminate cross-talk. The narrow band filter layer helps to remove background light which may contribute to spurious signal detection, eventually leading to ranging errors.

B. *Micro-Optics*

[0145] FIG. 11A shows a top view of a micro-optics package according to certain embodiments. This micro optics package could be applied on either the transmitter or detector side of the light ranging device. For example if implemented on the receiver side, each black dot would correspond to a single micro optical receiver channel. In this example, the micro-optical receiver channels are laid out as an $m \times n$ staggered array, e.g., laid out in 16×4 array. As an example, for a receiver channel size of 0.500mm (diameter) the layout illustrated can be implemented in a chip of size 8.000mm by 2.000mm.

[0146] Other array patterns are possible without departing from the scope of the present disclosure. For example, rather than a staggered array, any of the following shaped arrays can be employed: a square array, a 1-D straight line array ($m \times 1$), a warped linear ($m \times 1$) array, a warped rectangular $m \times n$ array, or arrays having any arbitrary pattern. As used herein the term “warped” refers to embodiments where the spacing between receiver channels is uneven. For example, receiver channels near the center, are spaced closer together, while the exterior channels are spaced further apart. The warped layout has an advantage of being able to allow for correction of the distortion curve of a lens (i.e. the angles between the receiver channel fields of view are evenly spaced in the object space).

[0147] FIG. 11B shows a cross-section of a single micro-optic receiver channel according to some embodiments. The receiver channel 1132 serves to accept an input cone of light containing a wide range of wavelengths, filters out all but a narrow band of those wavelengths centered at the operating wavelength, and allow pixel 1171 to detect only or substantially only photons within the aforementioned narrow band of wavelengths.

[0148] In some embodiments, the receiver channel 1132 includes an input aperture layer 1140 including an optically-transparent aperture 1144 and optically-non-transparent stop region 1146

configured to define a narrow field of view when placed at the focal plane of any imaging optic. As used herein, the term “optically-transparent” refers to a material that allows most or all incident light to pass through. As used herein, the term “optically non-transparent” refers to a material that allows little to no light to pass through, e.g., a reflecting or absorbing surface. The aperture layer 1140 is configured to receive the input marginal ray lines 1133. The aperture layer 1140 may include an array of optically-transparent apertures and optically-non-transparent stop regions built upon a single monolithic piece such as an optically-transparent substrate. The aperture layer 1140 may optionally include of multiple apertures 1144.

[0149] In some embodiments, the receiver channel 1132 includes an optical lens layer 1150 including a collimating lens 1151 characterized by a focal length. The collimating lens is offset from the plane of the aperture 1144 and stop region 1146 by the focal length and aligned axially with aperture 1144, i.e., the optical axis of the collimating lens is aligned with the center of the aperture. Accordingly, the collimating lens is configured to collimate light rays passed by the aperture such that the light rays are travelling approximately parallel to the optical axis of collimating lens 1151. The optical lens layer 1150 may optionally include apertures, optically-non-transparent regions and tube structures to reduce cross talk.

[0150] In some embodiments, the receiver channel 1132 includes an optical filter layer 1160 including an optical filter 1161, e.g., a Bragg reflector type filter or the like. In some embodiments, the optical filter layer is disposed on a detector-side of the an optical lens layer 1150 (as opposed to the aperture side). The optical filter layer is configured to pass normally incident photons at a specific operating wavelength and passband. The optical filter layer 1160 may contain any number of optical filters 1161. The optical filter layer 1160 may optionally include apertures, optically-non-transparent regions and tube structures to reduce cross talk.

[0151] In some embodiments, receiver channel 1132 includes a pixel layer 1170 including a pixel 1171 disposed behind the filter layer. The pixel can be a photon sensor capable of detecting photons with a detector active area made of, e.g., a standard photodiode, an avalanche photodiode, a SPAD (Single Photon Avalanche Detector), RCP (Resonant Cavity Photo-diodes), or any other photodetector. Pixel 1171 may be composed of several photon detector areas (e.g., each a different SPAD) cooperating together to act as a single pixel, often with higher dynamic

range, faster response time, or other beneficial properties as compared to a single large photon detection area. Pixel layer 1170 refers to a layer made of pixels and contains optional structures to improve detection efficiency and reduce cross talk with neighboring receiver structures. Pixel layer 1170 may optionally include diffusers, converging lenses, apertures, optically-non-transparent tube spacer structures, optically-non-transparent conical spacer structures, etc.

[0152] Stray light may be caused by roughness of optical surfaces, imperfections in transparent media, back reflections, and so on, and may be generated at many features within the receiver channel 1132 or external to receiver channel 1132. The stray light may be directed: through the filter region 1161 along a path non-parallel to the optical axis of collimating lens 1151; reflecting between the aperture 1144 and the collimating lens 1151; and generally taking any other path or trajectory possibly containing many reflections and refractions. If multiple receiver channels are arrayed adjacent to one another, this stray light in one receiver channel may be absorbed by a pixel in another channel, thereby contaminating the timing, phase, or other information inherent to photons. Accordingly, the receiver channel 1132 may also feature several structures to reduce crosstalk and increase signal between receiver channels, as described in U.S. Patent Application 62/515,291 that is hereby incorporated by reference in its entirety for all purposes.

C. *Detector Array (e.g., SPADs)*

[0153] FIGS. 12A and 12B show a top view of a SPAD-based photodetector array layer according to certain embodiments. The embodiment shown in FIG. 12A is a two-dimensional array of groups of SPADs with each group of SPAD corresponding to detector channel or pixel as described above. The array is 18 x 4 for a total of 72 sensor channels. The array also includes 8 calibration pixels at the top of the array. For example, these pixels can be covered by an opaque surface such that they are not exposed to any light and therefore can be used to measure dark counts.

[0154] FIG. 12B shows a magnified view of a subset of the pixels illustrating that each pixel is actually formed from a group of SPADS cooperating together to act as a single pixel. Such an arrangement is advantageous when SPADS are used as the photodetectors because after a photon detection event, a SPAD suffers some deadtime during which external circuitry must quench the SPAD so that it is ready to detect again. Thus, a single SPAD has an upper limit to the light

intensity (measured in photons/sec) that it can detect, i.e. a single SPAD cannot detect a light intensity that is greater than one photon per quench time. Collecting multiple SPADS together like that shown in FIG. 12B increases the overall intensity that can be detected because not all SPADS will be saturated at the same time. Thus a collection of N SPADs may be able to detect
5 with N-times the dynamic range of a single SPAD.

D. Emitter Array (e.g., VCSELs)

[0155] FIG. 13 shows an emitter array in the form of a two-dimensional VCSEL array according to certain embodiments. The VCSEL array can include a two-dimensional array of VCSEL emitters that are fabricated on a single monolithic chip and whose pattern matches the
10 detector pixels on the corresponding sensor layer. In this example, the VCSEL array is 16 x 4 for a total of 64 emitter channels to match the middle 64 detector channels shown in FIG. 12 above.

[0156] As was described in reference to FIG. 12, the monolithic VCSEL array of optical emitters arranged can be arranged behind the TX-side micro-optics package and behind the TX-
15 side bulk optics module. Each VCSEL emitter can output an illuminating beam of an initial diameter that is substantially identical to (or slightly greater than) the diameter of a corresponding aperture defined either by the aperture layer or the numerical aperture of the micro-lenses of the micro-optics layer to ensure that all or substantially all of the light emitted by the VCSEL will be transmitted to objects in the field.

E. Bulk optics

[0157] In some embodiments, the present application discloses a telecentric LIDAR system comprising a fast lens system (e.g., f-number = 1.0, 1.2, or 1.4) and/or is passively athermal over a temperature range, e.g., from -40 to 85 degrees Celsius or more (e.g., for use with automobile sensing). In addition, the bulk optical system possesses a low focal plane distortion and one or
25 more of the optical elements may be AR coated to maximize optical throughput and reduce stray reflections, ghosting, and cross-talk amongst different sensor channels. Advantageously, the optical system is image-space telecentric and thus provides a “straight on” view (when viewed from the object side) of each of the detector channels of the sensor array (each chief ray arrives perpendicular to the focal plane), even those on the outer edges of the array. On the contrary,

without the telecentric design, sensors on the edge of the array are optically accessible at only a highly oblique angle of incidence, thereby leading to loss of detection efficiency at the edge of the array.

5 **[0158]** In this application, passively athermal describes an optics system, wherein the spot quality of light from an extended source with non-zero angular size focused by a lens system on an array does not change significantly as temperature changes. If the back focal length of the lens system changes, and the array remains in the same place relative to the rear lens element, then the spot quality of light on the array would change. In this application, spot quality can be defined by a fraction of light from an extended source with angular size of 0.13 degrees that is
10 focused onto the image plane and contained by a circle 25 μm in diameter. An opto-mechanical system is considered to be passively athermal over a temperature range if the spot quality remains above 50% for all temperatures in the temperature range. The diameters and angular sizes listed are exemplary and depend on the size of the apertures in the micro-optic array, the focal length of the system, etc.

15 **[0159]** FIG. 14 depicts a simplified schematic of an embodiment of a LIDAR system. The LIDAR system comprises a sensor array (also just called an “array”), a lens system, a housing, and a mount to mechanically couple the housing with the array. The array can be a detector array and/or an emitter array. The array can be planar (e.g., having irregularity from a perfect plane less than 1 mm peak-to-valley over a 10 mm diameter disc). The array can be planar for ease in
20 manufacturing (e.g., forming arrays in bulk on a semiconductor substrate, wherein there are a plurality of emitters or detectors in one array). In this example, the lens system comprises a first lens, a second lens, a third lens, and a fourth lens. In some embodiments. The first lens, the second lens, the third lens, and the fourth lens are mounted in the housing. The housing, the lens system, and the mount are configured to passively focus light from the lens system to the
25 detector array over a temperature range (e.g., from -40 Celsius to 85 Celsius, -50 Celsius to 95 Celsius, -35 Celsius to 60 Celsius, -40 Celsius to 105 Celsius, -45 Celsius to 110 Celsius, or -35 Celsius to 100 Celsius)).

[0160] The array can be kept at the image plane of the lens system for varying temperatures. Materials may be chosen to reduce cost, reduce weight, and/or maintain the image plane at the

array. To reduce costs, the first lens, the second lens, and the forth lens can be made of plastic (e.g., OKP-1). The third lens can be made of glass (e.g., to reduce temperature variations in the lens system). A nominal distance between an apex of the fourth lens and the image plane is 8 mm. In the lens assembly shown, the image plane moves toward the fourth lens as temperature
5 increases. This is perhaps counter intuitive given that the index of refraction for plastic decreases as temperature increases, which would usually push the image plane away from a plastic lens since a lens with a lower refractive index would refract light less sharply (i.e., longer focal length) than a convex plastic lens of similar shape with a higher refractive index (e.g., according to the Lensmaker's Equation where focal length is inversely proportional to a difference between
10 the refractive index of the lens and air, where refractive index of air equals 1; see also Snell's Law). The combination of a glass lens with two or more plastic lenses may allow the effective focal length of the lens system to decrease with increase of temperature even though one or more plastic lenses in the lens system has a focal length that increases with temperature.

[0161] The lens housing (e.g., made of polycarbonate) can elongate as temperature increases.

15 In some embodiments, the mount attaches to the housing near the third lens, so that the fourth lens moves to the right as temperature of the housing increases. Material of the mount, which separates the housing from the array, expands with increasing temperature, moving the housing away (e.g., left) from the array. Simultaneously, the housing expands with increasing temperature moving lens 4 toward (e.g., right) the array. Also simultaneously, the back focal
20 shift moves the image plane leftward, as described above. By choosing the housing material CTE, mount material CTE, and the housing-to-mount interface location appropriately, the back focal shift can be compensated by the aforementioned housing expansion and mount expansion such that the image plane remains approximately coincident with the array over the temperature range.

25 **[0162]** In some embodiments, the mount can be coupled with the housing near the glass lens (i.e., the third lens in some embodiments). In some embodiments, the mount can be coupled with the housing near the glass lens so that a lens of the lens system nearest the array (e.g., the fourth lens) can move in relation to the array (e.g., toward the array) as the focal length of the lens system moves in relation to the array (e.g., away from the array). In some embodiments,

near can be a point or line on the outside of the housing, nearest the glass lens, and/or or within +/- 5 mm or +/- 10 mm from the point or line.

[0163] The spot quality of the lens system in FIG. 14 was experimentally verified for a temperature range from 20 degrees C to 70 degrees C. A shift in the focal plane of the lens

5 system can be predicted to remain linear for temperatures below 20 degrees. Thus the system can be expected to perform well from at least temperatures ranging from -30 degrees C to 70 degrees C (a temperature range of 100 degrees). In various embodiments, the system can be stable from 0 degrees C to 32 degrees C; from 0 degrees C to 55 degrees C; from -10 degrees C to 32 degrees C; from -10 degrees C to 55 degrees C; from -20 degrees C to 60 degrees C; and
10 combinations thereof. In some embodiments, the temperature range can be from -40 degrees C to 105 degrees C (a temperature range of 145 degrees).

[0164] It can be often desirable to make the housing out of material with a comparable coefficient of thermal expansion (CTE) to the lenses to avoid stressing the lenses. Changing the housing material can also change how the lens elements are spread apart as temperature
15 increases. In some embodiments, the material CTE of the housing is not changed/tuned substantially to prevent reduction in optical performance. Thus the housing material has a CTE close to that of the lenses; and not all possible materials for the housing are considered because some housing materials have CTEs that are so different from CTEs of lenses that stress in the lenses will occur, which will result in degradation of optical performance of the lenses.

20 **[0165]** The CTE of the housing can be matched, over a temperature range, with the lens system so that a focal plane of the lens system is stable relative to the housing over the temperature range. In some embodiments, a thermal coefficient of the mount is matched with the lens system and/or with thermal expansion of the housing so that the focal plane is stable relative to a position of the detector (e.g., detector array) over the temperature range. The CTE of the
25 material of the mount may be chosen with a caveat that material of the mount is strong and/or mechanically rigid (lower CTE materials tend to be stronger). In this example, the fact that the back focal shift is negative (leftward) rather than positive (rightward) allows a very rigid glass filled polymer, or even a metal like magnesium or aluminum, to be used for the separating material of the mount.

[0166] FIGS. 15A, 15B, and 15C depict an embodiment of a lens assembly. The lens assembly comprises the lens system and the housing. Since image sensors are generally not circular, shapes of lenses generally do not need to be circular. For example, the array can be narrow and tall, so lenses can be clipped in a rectangular fashion. It is typically easier and less expensive to make rectangular molded polymer optics, while it can be more expensive to grind glass lenses into rectangular shapes. The diameter of the third lens can define a minimum width of the lens system, thereby defining part of the rectangular shape. By using a circular glass element and rectangular molded polymer optics the system is easy and cheap to manufacture.

[0167] In some embodiments, two housings are put as close together as possible (e.g., touching), which is another reason to keep the glass lens (e.g., lens 3) small. For example, the LIDAR system can comprise a first lens system mounted in a first housing, a second lens system mounted in a second housing, a sensor array, and an emitter array. The first lens system, the first housing, and the sensor array can form a first unit. The second lens system, the second housing, and the emitter array can form a second unit. The first unit and the second unit can be placed side by side as close as possible (e.g., no more than 2.5 cm spaced apart) so that light emitted from the second unit and reflected/scattered is gathered by the first unit in similar field of views as the second lens system projected light from the emitter array.

[0168] The lens system can be designed to be a fast lens system. In some embodiments, the f-number of the lens system is between 1.0 and 2.4 (e.g., 1.2). The spot sizes on the sensor array can have 80% of light in a 20 μm circle. Further, the lens system can have a track length equal to or less than 100 mm, 50 mm, 35 mm, and/or 20 mm, and/or equal to or greater than 5, 10, 15, 20, and/or 25 mm.

[0169] In various embodiments, the LIDAR system can comprise: two or more plastic lenses and at least one glass lens; two or more plastic lenses; and/or one or more glass lenses. In some embodiments, micro-optics are between the array and the lens system. The micro-optics can modify light differently for different emitters and/or detectors on the array, whereas the lens system modifies light for the entire array. In some embodiments there is a micro-optic for each array element.

[0170] FIG. 16A depicts a top view of an embodiment of a lens assembly. Cross section A-A is identified in FIG. 16A.

[0171] FIG. 16B depicts an embodiment of cross section A-A. Element 1 (e.g., lens 1), Element 2 (e.g., lens 2), Element 3 (e.g., lens 3), Element 4 (e.g., lens 4), and the housing are shown.

[0172] FIG. 16C shows a magnified portion of the cross section A-A. The magnified portion shows how lens 2 and lens 3 can be mounted in the housing. The aperture stop of the lens system is between lens 2 and lens 3. The aperture stop can be used to secure lens 2 within the housing.

[0173] FIG. 16D depicts a side view of an embodiment of a lens assembly. Cross section B-B is identified in FIG. 16D.

[0174] FIG. 16E depicts an embodiment of cross section B-B. Lens 1, lens 2, lens 3, lens 4, and the housing are shown.

[0175] FIG. 17A, depicts a cross section of an embodiment of the first lens (lens 1). The first lens has a first surface S1 and a second surface S2. The first surface S1 of lens 1 and the second surface S2 of lens 1 are spherical. The first surface S1 of the first lens can be a convex surface. The second surface S2 of the first lens can be a concave surface. Light traveling from left to right can be focused by the first lens. The first surface of the first lens can be larger than the second surface of the first lens to gather light (e.g., reduce the f-number of lens system) for the lens system.

[0176] FIG. 17B, depicts a cross section of an embodiment of the second lens (lens 2). The second lens has a first surface S1 and a second surface S2. The first surface S1 of lens 2 and the second surface S2 of lens 2 are aspherical. The first surface S1 of the second lens can be a convex surface. The second surface S2 of the second lens can be planar, slightly convex, or slightly concave. Light traveling from left to right can be defocused by the second lens.

[0177] FIG. 17C, depicts a cross section of an embodiment of the third lens (lens 3). The third lens has a first surface S1 and a second surface S2. The first surface S1 of lens 3 and the second surface S2 of lens 3 are spherical. As examples, the third lens can have a width (e.g., diameter) equal to or greater than 10 mm and equal to or less than 20 mm (e.g., 11, 11.5, 12, 12.5, 13, 13.5,

14, and/or 14.5 mm). In some embodiments, the third lens is a high-index glass. In some embodiments, an index of the glass does not change (e.g., change equal to or less than 0.05%) for the temperature range of 100 degrees. The first surface S1 of the third lens can be planar, slightly convex, or slightly concave. The second surface S2 of the third lens can be convex. Light traveling from left to right can be collimated or slightly focused by the third lens.

[0178] FIG. 17D, depicts a cross section of an embodiment of the fourth lens (lens 4). The fourth lens has a first surface S1 and a second surface S2. The first surface S1 of lens 4 and the second surface S2 of lens 4 are aspherical. The first surface S1 of the fourth lens can be convex. The second surface S2 of the third lens can be convex. Light traveling from left to right can be focused to the array.

[0179] By mixing plastic and glass lenses, as well as mixing aspherical and spherical lenses, an economical, light, compact, and/or athermal LIDAR system can be made for autonomous vehicles.

[0180] In some embodiments, the lens system has a fixed focal length (e.g., fixed focal length while at constant temperature; not a zoom lens). In some embodiments, the lens system has a fixed focal length to reduce size, weight, number of parts, and/or complexity of the lens system.

[0181] FIG. 18 depicts an embodiment of a lens assembly with three lenses: a first lens, lens A; a second lens, lens B; and a third lens, lens C. The first lens, the second lens, and the third lens are mounted in a housing. A connector couples the housing with a sensor (e.g., a sensor in an array). The first lens, the second lens, and the third lens can be made of plastic (e.g., OKP-1). The first lens, the second lens, and the third lens are part of a lens system. The lens system is estimated to have a focal shift of around 105 μm over a 50 degree C temperature range (e.g., from 0 to 50 degrees C). The housing material can be made of a high CTE material, and/or the mount attaches near lens A, to hold the focal plane of the lens system at the array. In the embodiment in FIG. 18, polycarbonate (CTE = 70 ppm/C) is used and the mount is attached to the housing 25-35 mm away from the array. A combination of the mount attached to the housing 30 mm away from the array, a movement of lenses of the lens system due to thermal expansion of the housing, a movement of the housing due to thermal expansion of the mount, and/or a focal

shift of the lens system due to temperature change are matched to align the focal plane of the lens system with the array.

[0182] While some embodiments disclosed herein have focused on the application of light ranging within the context of 3D sensing for automotive use cases, systems disclosed herein can be used in any application without departing from the scope of the present disclosure. For example, systems can have a small, or even miniature, form factors that enable a number of additional use cases, e.g., for solid-state light ranging systems. For example, systems can be used in 3D cameras and/or depth sensors within devices, such as mobile phones, tablet PCs, laptops, desktop PCs, or within other peripherals and/or user-interface devices. For example, one or more embodiments could be employed within a mobile device to support facial recognition and facial tracking capabilities, eye tracking capabilities, and/or for 3D scanning of objects. Other use cases include forward-facing depth cameras for augmented and virtual reality applications in mobile devices.

[0183] Other applications include deployment of one or more systems on airborne vehicles, such as airplanes, helicopters, drones, and the like. Such examples could provide 3D sensing and depth imaging to assist with navigation (autonomous or otherwise) and/or to generate 3D maps for later analysis, e.g., to support geophysical, architectural, and/or archeological analyses.

[0184] Systems can also be mounted to stationary objects and structures, such as buildings, walls, poles, bridges, scaffolding, and the like. In such cases, the systems can be used to monitor outdoor areas, such as manufacturing facilities, assembly lines, industrial facilities, construction sites, excavation sites, roadways, railways, bridges, etc. Furthermore, systems can be mounted indoors and used to monitor movement of persons and or objects within a building, such as the movement of inventory within a warehouse or the movement of people, luggage, or goods within an office building, airport, train station, etc. As would be appreciated by one of ordinary skill in the art with the benefit of this disclosure, many different applications of light ranging systems are possible and, as such, the examples provided herein are provided for illustrative purposes only and shall not be construed to limit the uses of such systems to only the examples explicitly disclosed.

[0185] The specific details of particular embodiments may be combined in any suitable manner without departing from the spirit and scope of embodiments of the invention. However, other embodiments of the invention may be directed to specific embodiments relating to each individual aspect, or specific combinations of these individual aspects. For example, to reduce a spot size on the array, more than four lenses could be used, using more aspheric surfaces, and/or using multiple types of plastics could be used. In some embodiments, a curved detector and/or emitter are used. In some embodiments, three lenses are used instead of four (e.g., two lenses plastic and one lens glass).

[0186] The above description of exemplary embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form described, and many modifications and variations are possible in light of the teaching above. The embodiments were chosen and described in order to explain the principles of the invention and its practical applications to thereby enable others skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated.

[0187] The specific details of particular embodiments may be combined in any suitable manner without departing from the spirit and scope of embodiments of the invention. However, other embodiments of the invention may be directed to specific embodiments relating to each individual aspect, or specific combinations of these individual aspects. For example, to reduce a spot size on the array, more than four lenses could be used, using more aspheric surfaces, and/or using multiple types of plastics could be used.

[0188] The above description of exemplary embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form described, and many modifications and variations are possible in light of the teaching above. The embodiments were chosen and described in order to explain the principles of the invention and its practical applications to thereby enable others skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated.

WHAT IS CLAIMED IS:

1 1. A light ranging system comprising:
2 a shaft having a longitudinal axis;
3 a light ranging device configured to rotate about the longitudinal axis of the shaft,
4 the light ranging device including a light source configured to transmit light pulses to objects in a
5 surrounding environment, and detector circuitry configured to detect reflected portions of the
6 light pulses that are reflected from the objects in the surrounding environment and to compute
7 ranging data based on the reflected portion of the light pulses;
8 a base subsystem that does not rotate about the shaft; and
9 an optical communications subsystem configured to provide an optical
10 communications channel between the base subsystem and the light ranging device, the optical
11 communications subsystem including one or more turret optical communication components
12 connected to the detector circuitry and one or more base optical communication components
13 connected to the base subsystem.

1 2. The light ranging system of claim 1, wherein the optical communications
2 subsystem is configured to optically transmit an uplink signal from at least one optical uplink
3 transmitter of the one or more base optical communication components to at least one optical
4 uplink receiver of the one or more turret optical communication components.

1 3. The light ranging system of claim 1, wherein the optical communications
2 subsystem is configured to optically transmit the ranging data from at least one optical downlink
3 transmitter of the one or more turret optical communication components to at least one optical
4 downlink receiver of the one or more base optical communication components.

1 4. The light ranging system of claim 1 wherein:
2 the one or more turret optical communication components comprise an optical
3 downlink transmitter disposed on a turret circuit board assembly of the light ranging device that
4 rotates around the shaft, and
5 the one or more base optical communication components comprise an optical
6 downlink receiver disposed on a base circuit board assembly of the base subsystem,

7 the shaft is a hollow shaft having a central opening, and
8 the optical downlink transmitter and the optical downlink receiver are positioned
9 to transmit and receive, respectively, an optical signal through the central opening of the shaft.

1 5. The light ranging system of claim 1, wherein the one or more base optical
2 communication components comprise at least one optical uplink transmitter disposed on a base
3 circuit board assembly of the base subsystem, the at least one optical uplink transmitter
4 configured to communicate uplink signals to the light ranging system; and

5 wherein the one or more turret optical communication components comprise at
6 least one optical uplink receiver disposed on a turret circuit board assembly of the light ranging
7 device, the at least one optical uplink receiver configured to receive the uplink signals.

1 6. The light ranging system of claim 5, wherein the at least one optical uplink
2 transmitter includes a plurality of transmitters arranged in a first ring; and the at least one optical
3 uplink receiver includes a plurality of receivers arranged in a second ring that is concentric with
4 the first ring.

1 7. The light ranging system of claim 6 wherein:
2 the second ring is oriented in a first plane defined by the turret circuit board
3 assembly, the first plane being perpendicular the shaft;
4 the second ring is centered on the shaft; and
5 the turret circuit board assembly and the base circuit board assembly are spatially
6 separated from each other along a length of the shaft.

1 8. The light ranging system of claim 7 wherein:
2 the first ring is oriented in a second plane defined by the base circuit board
3 assembly of the base subsystem, the second plane being perpendicular to the shaft; and
4 the first ring is centered on the shaft.

1 9. The light ranging system of claim 6, wherein the turret circuit board
2 assembly comprises a single circuit board including an optical downlink transmitter and the
3 plurality of receivers.

1 10. The light ranging system of claim 6, wherein the base circuit board
2 assembly of the base subsystem comprises a single circuit board including an optical downlink
3 receiver and the plurality of transmitters.

1 11. A light ranging system comprising:
2 a shaft;
3 a lower circuit board assembly that includes a motor stator assembly, the motor
4 stator assembly comprising a plurality of stator elements disposed on a surface of the lower
5 circuit board assembly, wherein the plurality of stator elements is arranged about the shaft;
6 an upper circuit board assembly that is rotationally coupled to the shaft, wherein
7 the upper circuit board assembly includes a motor rotor assembly, the motor rotor assembly
8 comprising a plurality of rotor elements disposed on a surface of the upper circuit board
9 assembly, wherein the plurality of rotor elements is arranged about the shaft; and
10 a motor driver circuit disposed on either the upper or the lower circuit board
11 assemblies and configured to provide a drive signal to the plurality of stator elements, thereby
12 imparting an electromagnetic force on the plurality of rotor elements to drive a rotation of the
13 upper circuit board assembly about the shaft.

1 12. The light ranging system of claim 11, wherein the plurality of rotor
2 elements and the plurality of stator elements are arranged symmetrically about the shaft.

1 13. The light ranging system of claim 11, wherein the upper circuit board
2 assembly further includes a plurality of optical uplink receivers disposed on a circuit board of the
3 upper circuit board assembly and symmetrically arranged about the shaft.

1 14. The light ranging system of claim 13, wherein the plurality of rotor
2 elements are farther from the shaft than plurality of optical uplink receivers.

1 15. The light ranging system of claim 11, wherein the lower circuit board
2 assembly further includes a plurality of optical uplink transmitters disposed on a circuit board of
3 the lower circuit board assembly and symmetrically arranged about the shaft.

1 16. The light ranging system of claim 15, wherein a distance between the shaft
2 and each of the plurality of stator elements is greater than a distance between the shaft and each
3 of a plurality of optical uplink transmitters.

1 17. The light ranging system of claim 11, wherein the plurality of stator
2 elements includes a plurality of solenoid coils, each of the plurality of solenoid coils being
3 arranged in a ring around the shaft.

1 18. The light ranging system of claim 11, wherein the plurality of stator
2 elements includes a plurality of permanent magnets, each of the plurality of permanent magnets
3 being arranged in a ring around the shaft.

1 19. The light ranging system of claim 17, wherein the plurality of stator
2 elements includes at least 12 stator elements.

1 20. The light ranging system of claim 19, wherein the drive signal is a 3-phase
2 alternating signal and a number of stator elements is a multiple of three.

1 21. The light ranging system of claim 11, wherein the plurality of rotor
2 elements includes a plurality of permanent magnets.

1 22. The light ranging system of claim 11, wherein the plurality of rotor
2 elements includes a plurality of solenoid coils.

1 23. The light ranging system of claim 11, further comprising a light ranging
2 device electrically connected to the upper circuit board assembly.

1 24. The light ranging system of claim 23, wherein the upper circuit board
2 assembly further includes an optical downlink transmitter configured to transmit ranging data
3 from the light ranging device through a central hole within the shaft, and wherein the lower
4 circuit board assembly further includes an optical downlink receiver configured to receive
5 ranging data from the optical downlink transmitter via the central hole within the shaft.

1 25. The light ranging system of claim 23, wherein the lower circuit board
2 assembly comprises a wireless power transmission subsystem configured to transmit power to
3 the light ranging device that is electrically connected to the upper circuit board assembly, the
4 wireless power transmission subsystem comprising a transmitter coil disposed on the lower
5 circuit board assembly and disposed around the shaft,

6 wherein the upper circuit board assembly comprises a wireless power receiver
7 subsystem configured to receive power from the wireless power transmission subsystem, the
8 wireless power receiver subsystem comprising a receiver coil that is disposed on the upper
9 circuit board assembly and disposed around the shaft.

1 26. The light ranging system of claim 11, wherein a first plane defined by the
2 upper circuit board assembly is parallel to a second plane that is defined by the lower circuit
3 board assembly, and wherein the first plane is perpendicular to the shaft.

1 27. A light ranging system comprising:
2 a housing;
3 a shaft defining an axis of rotation;
4 a lower circuit board assembly coupled to the housing;
5 an upper circuit board assembly rotationally coupled to the shaft, such that the
6 upper circuit board assembly rotates about the axis of rotation and a first plane of the upper
7 circuit board assembly is perpendicular to the shaft;
8 a light ranging device electrically connected to the upper circuit board assembly,
9 the light ranging device configured to transmit light pulses to objects in a surrounding
10 environment, to detect reflected portions of the light pulses that are reflected from the objects in
11 the surrounding environment, and to compute ranging data based on the reflected portion of the
12 light pulses; and
13 a plurality of upper circuit elements disposed on a first circuit board of the upper
14 circuit board assembly;
15 a plurality of lower circuit elements disposed on a second circuit board of the
16 lower circuit board assembly, wherein at least one of the plurality of lower circuit elements is

17 configured to function in wireless cooperation with at least one of the plurality of upper circuit
18 elements.

1 28. The light ranging system of claim 27, wherein the at least one of the
2 plurality of lower circuit elements is aligned with the at least one the plurality of upper circuit
3 elements.

1 29. The light ranging system of claim 27, wherein a second plane defined by
2 the lower circuit board assembly is parallel to the first plane of the upper circuit board.

1 30. The light ranging system of claim 27, wherein the plurality of lower
2 circuit elements comprise a wireless power transmitter coil and the plurality of upper circuit
3 elements include a wireless power receiver coil, wherein the wireless power transmitter coil and
4 the wireless power receiver coil cooperate to provide power to the upper circuit board assembly.

1 31. The light ranging system of claim 30, wherein wireless power transmitter
2 coil is concentric to the wireless power receiver coil.

1 32. The light ranging system of claim 27, wherein the plurality of lower
2 circuit elements comprises a plurality of uplink transmitters and wherein the plurality of upper
3 circuit elements comprises a plurality of optical uplink receivers, wherein the plurality of uplink
4 transmitters and the plurality of optical uplink receivers cooperate to create an optical uplink
5 communications channel.

1 33. The light ranging system of claim 32, wherein plurality of uplink
2 transmitters is arranged concentric to the plurality of optical uplink receivers.

1 34. The light ranging system of claim 27, wherein the plurality of lower
2 circuit elements includes an annular optical encoder and the plurality of upper circuit elements
3 includes a rotary encoder detector.

1 35. The light ranging system of claim 27, wherein the plurality of lower
2 circuit elements comprises an optical downlink receiver and the plurality of upper circuit
3 elements comprises an optical downlink transmitter for transmitting the ranging data, wherein

4 the optical downlink receiver and the optical downlink transmitter cooperate to create an optical
5 downlink communications channel.

1 36. The light ranging system of claim 35, wherein the optical downlink
2 transmitter is positioned above a central hole within the shaft, and the optical downlink receiver
3 is positioned below the central hole in the shaft, such that the optical downlink receiver can
4 receive an optical signal from the optical downlink transmitter via the central hole within the
5 shaft.

1 37. A system for LIDAR, the system comprising:
2 a lens system, wherein:
3 the lens system comprises a first lens, a second lens, and a third lens;
4 the first lens, the second lens, or the first lens and the second lens are
5 plastic;
6 the third lens is glass; and
7 the lens system focuses light to a focal plane;
8 an array of optical sensors; and
9 a housing, wherein:
10 the first lens, the second lens, and the third lens are mounted in the
11 housing; and
12 a thermal coefficient of the housing is matched, over a temperature range,
13 with the lens system so that the focal plane is stable relative to the array over the
14 temperature range.

1 38. The system of claim 37 further comprising a sensor positioned at the focal
2 plane.

1 39. The system of claim 38, further comprising a mount mechanically
2 coupling the housing with the sensor.

1 40. The system of claim 38, wherein the sensor is one sensor of a sensor array
2 positioned at the focal plane.

1 41. The system of claim 40, wherein the sensor array is planar.

1 42. The system of claim 37, wherein the third lens is spherical.

1 43. The system of claim 37, wherein the lens system has an f-number equal to
2 or less than 2.4 and/or equal to or greater than 0.7.

1 44. The system of claim 37, wherein the third lens has a width equal to or less
2 than 18 mm and equal to or greater than 5 mm.

1 45. The system of claim 37, wherein the temperature range is from 20 degrees
2 C to 70 degrees C.

1 46. The system of claim 45, wherein the temperature range is from -40
2 degrees C to 85 degrees C.

1 47. The system of claim 37, wherein the lens system further comprises a
2 fourth lens.

1 48. The system of claim 47, wherein the second lens and the fourth lens are
2 the only lenses in the lens system with aspherical curvatures.

1 49. The system of claim 37, wherein housing has a length between 10 mm and
2 60 mm.

1 50. The system of claim 37, wherein the lens system is a telecentric lens
2 system.

1 51. The system of claim 37, wherein the lens system has a fixed focal length
2 while temperature remains constant.

1 52. The system of claim 37, wherein:

2 the housing is a first housing;
3 the lens system is a first lens system;
4 the system further comprises a second housing and a second lens system;
5 the second housing has a same shape as the first housing;
6 the second lens system has similar lenses as the first lens system;
7 lenses of the second lens system are mounted in the second housing;
8 the second lens system is configured to disperse light from an emitter array; and
9 a detector array senses light emitted from the emitter array, after light is focused
10 to the detector array by the first lens system.

1 53. The system of claim 52, wherein the first housing and the second housing
2 are separated by no more than 2.5 cm.

1 54. The system of claim 52, wherein the emitter array comprises a plurality of
2 lasers and/or light emitting diodes.

1 55. The system of claim 52 further comprising an optical element for each
2 element of the emitter array and/or the detector array.

1 56. A system for LIDAR, the system comprising:
2 a sensor;
3 a lens system, wherein:
4 the lens system comprises a first lens, a second lens, and a third lens;
5 the first lens, the second lens, or the first lens and the second lens are
6 plastic; and
7 the third lens is glass;
8 a housing, wherein the first lens, the second lens, and the third lens are mounted
9 in the housing; and
10 a mount that mechanically couples the housing with the sensor, wherein the
11 housing, the lens system, and the mount are configured to passively focus light from the lens
12 system onto the detector over a temperature range.

1 57. The system of claim 56, wherein the housing, the lens system, and the
2 mount are configured to match, as a function of temperature, a focal length of the lens system
3 with an expansion coefficient of the housing and with an expansion coefficient of the mount so
4 that light is passively focused onto the detector over the temperature range.