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(54) **ROTATING LIGHT RANGING SYSTEM WITH OPTICAL COMMUNICATION UPLINK AND DOWNLINK CHANNELS**

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(73) Assignee: **Ouster, Inc.**, San Francisco, CA (US)

(21) Appl. No.: **16/209,875**

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Publication Classification

(51) **Int. Cl.**

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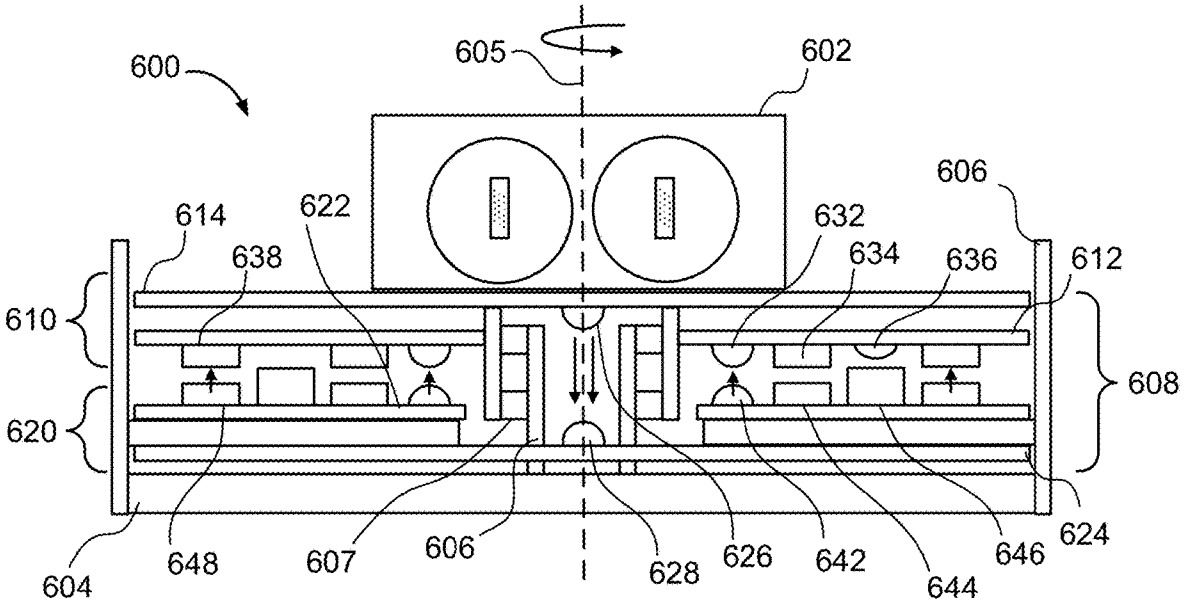
G01S 17/10	(2006.01)
H04B 10/114	(2006.01)

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

CPC ***G01S 7/4813*** (2013.01); ***H04B 10/1143*** (2013.01); ***G01S 17/10*** (2013.01)

(57) **ABSTRACT**

A light ranging system including a shaft having a longitudinal axis; a light ranging device configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; a base subsystem that does not rotate about the shaft; and an optical communications subsystem configured to provide an optical communications channel between the base subsystem and the light ranging device, the optical communications subsystem including one or more turret optical communication components connected to the detector circuitry and one or more base optical communication components connected to the base subsystem.



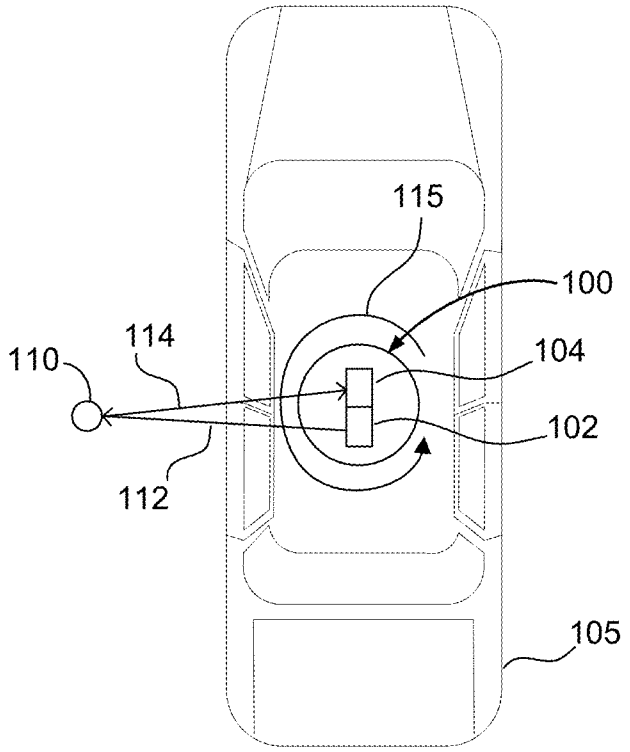


FIG. 1A

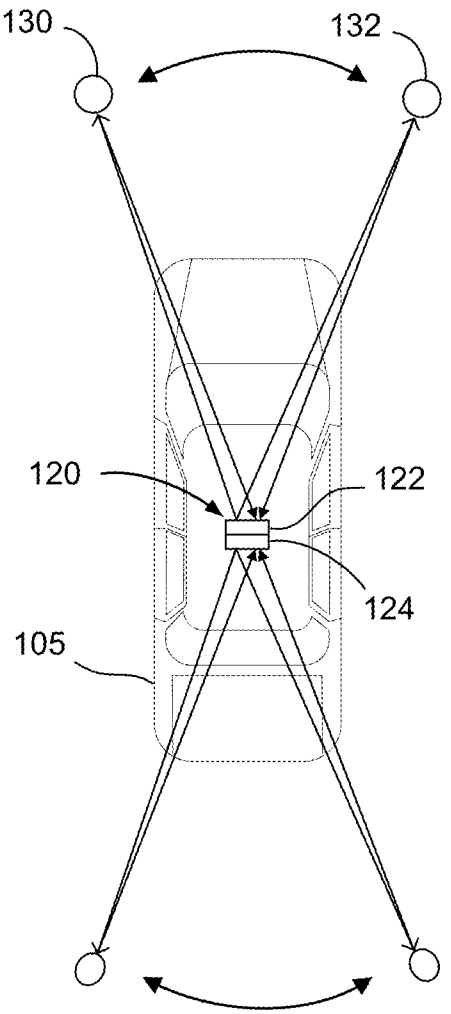
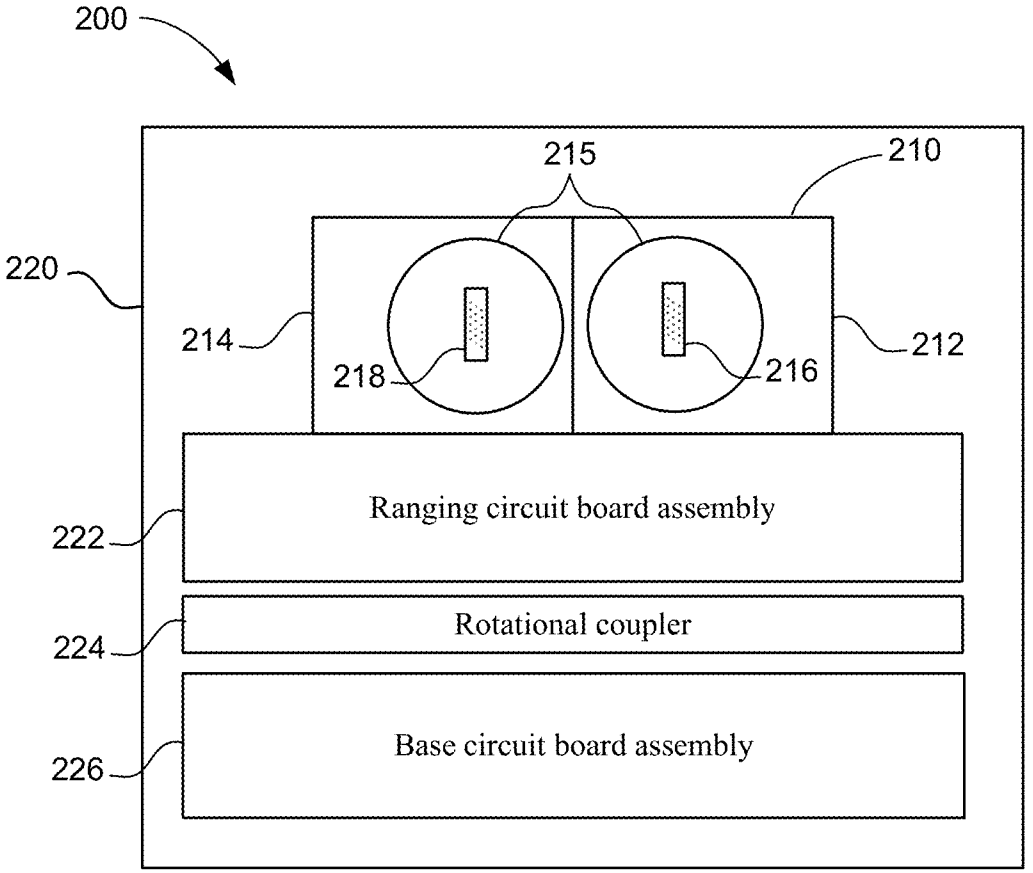


FIG. 1B


200
215
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216
Ranging circuit board assembly
222
Rotational coupler
224
Base circuit board assembly
226

FIG. 2A

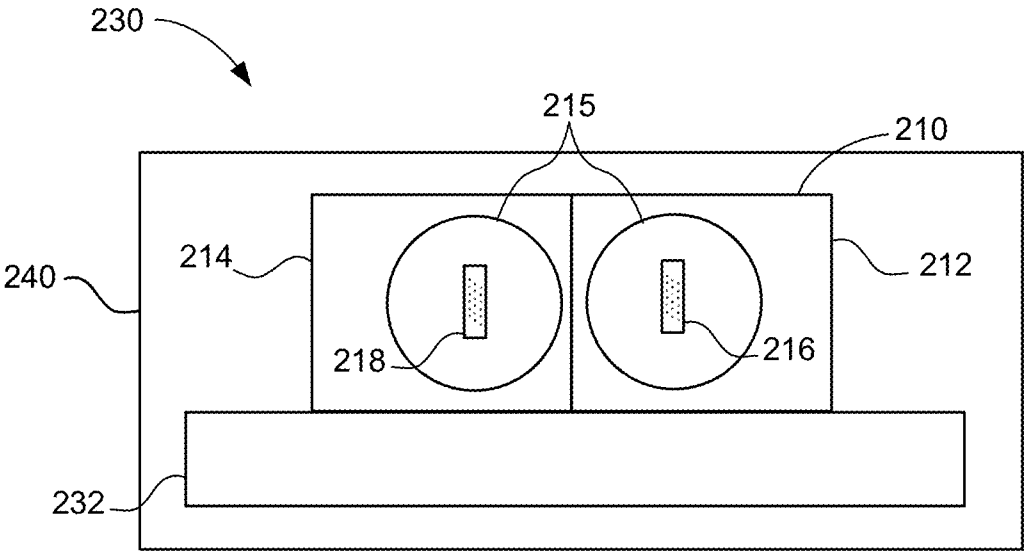
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FIG. 2B

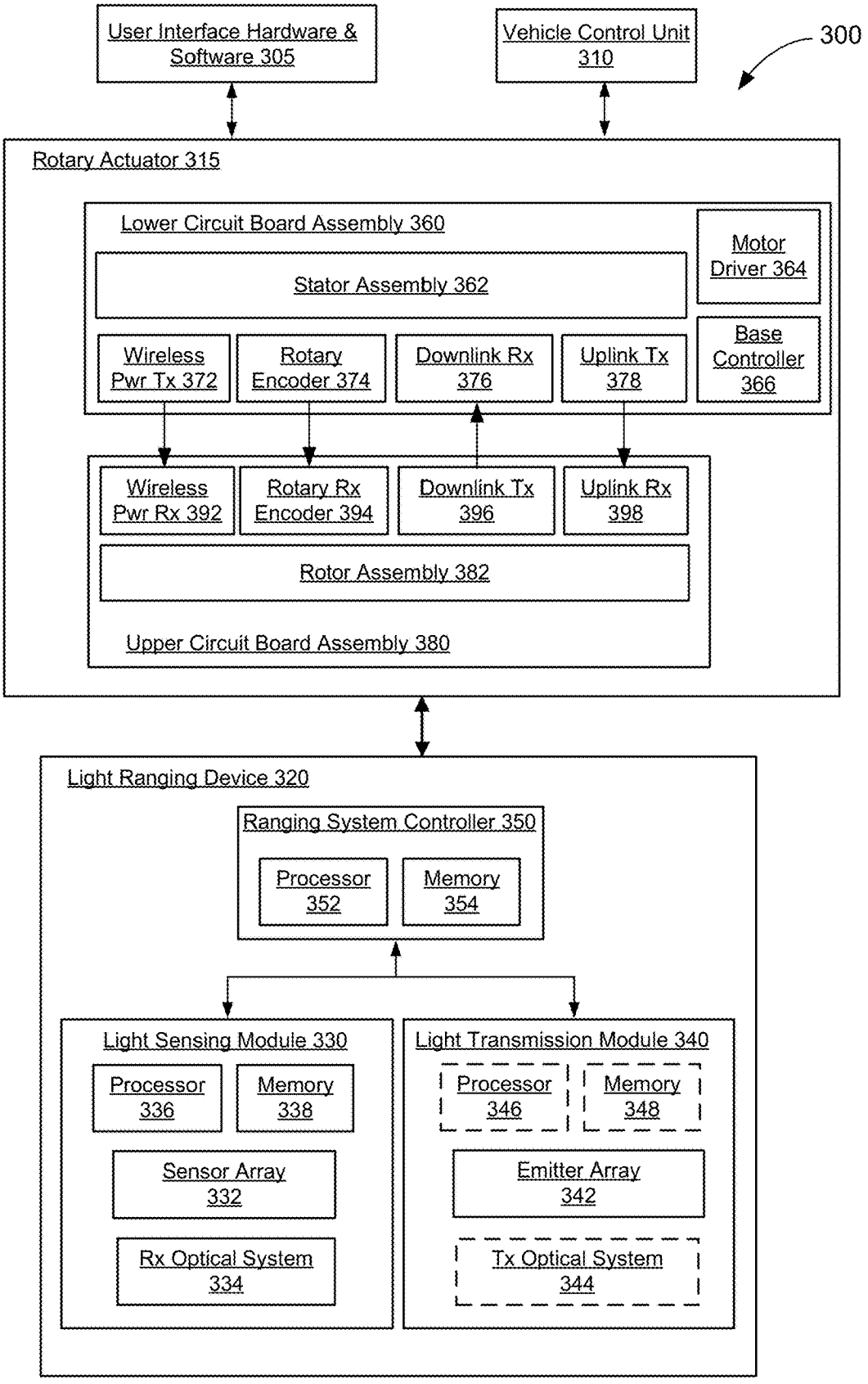
User Interface Hardware & Software 305
Vehicle Control Unit 310
300
Rotary Actuator 315
Lower Circuit Board Assembly 360
Motor Driver 364
Stator Assembly 362
Wireless Pwr Tx 372
Rotary Encoder 374
Downlink Rx 376
Uplink Tx 378
Base Controller 366
Wireless Pwr Rx 392
Rotary Rx Encoder 394
Downlink Tx 396
Uplink Rx 398
Rotor Assembly 382
Upper Circuit Board Assembly 380
Light Ranging Device 320
Ranging System Controller 350
Processor 352
Memory 354
Light Sensing Module 330
Processor 336
Memory 338
Sensor Array 332
Rx Optical System 334
Light Transmission Module 340
Processor 346
Memory 348
Emitter Array 342
Tx Optical System 344

FIG. 3

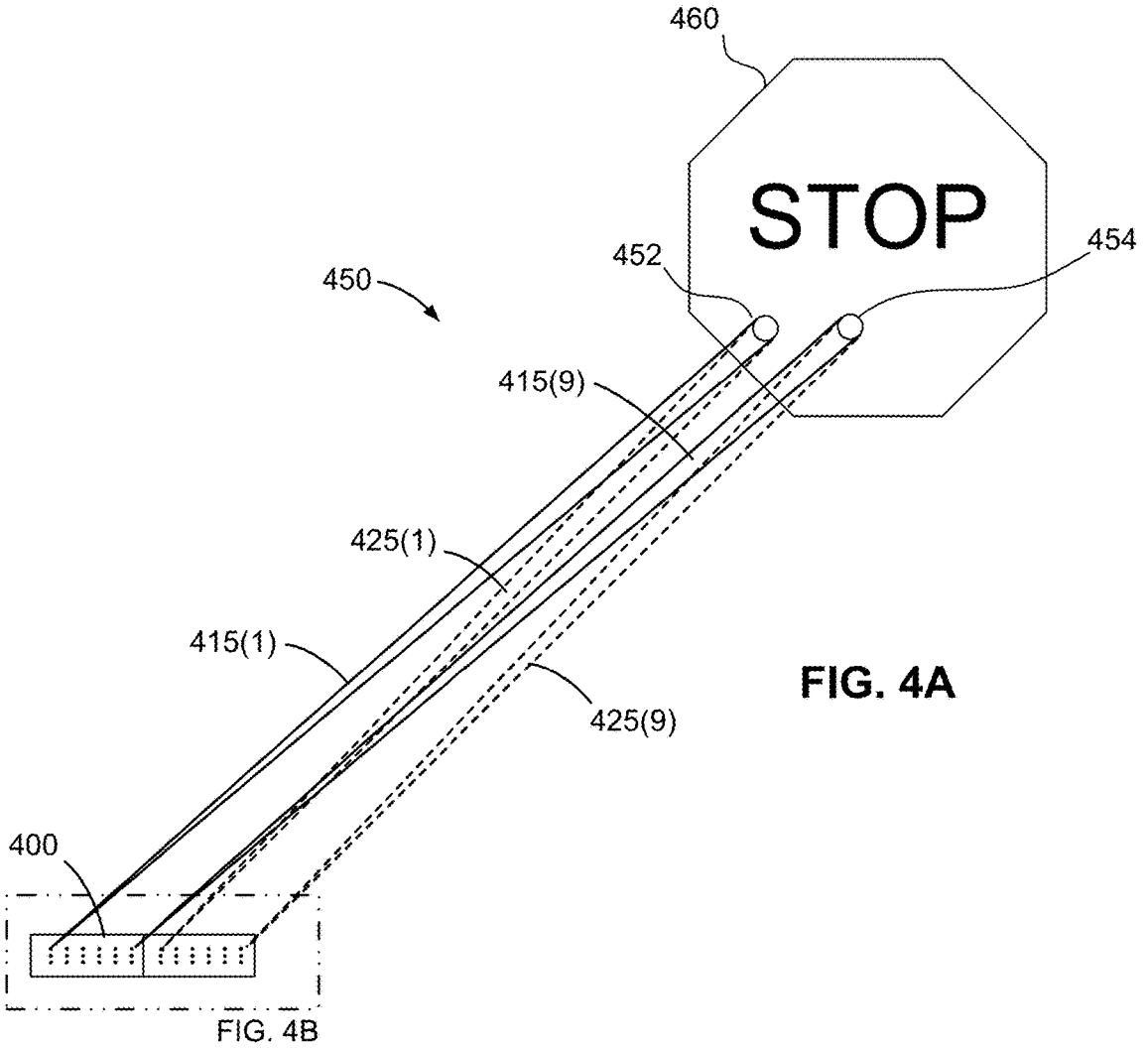

FIG. 4A

FIG. 4B

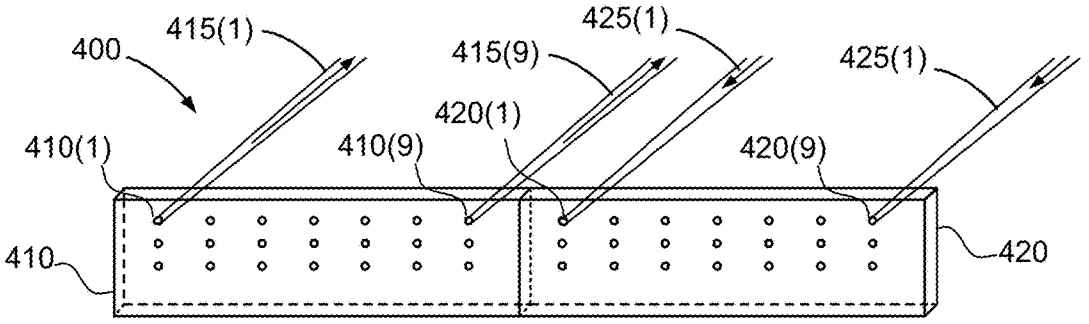

FIG. 4B

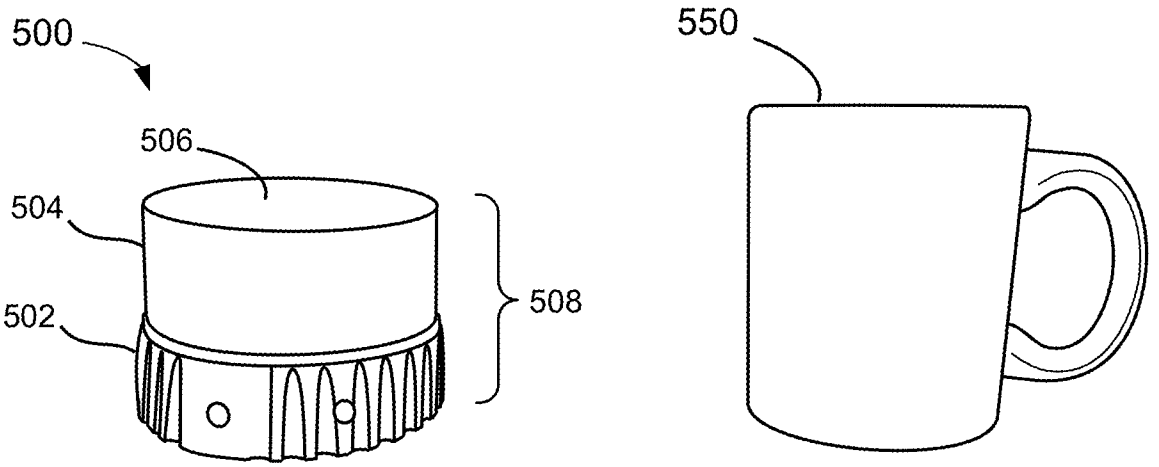
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FIG. 5A

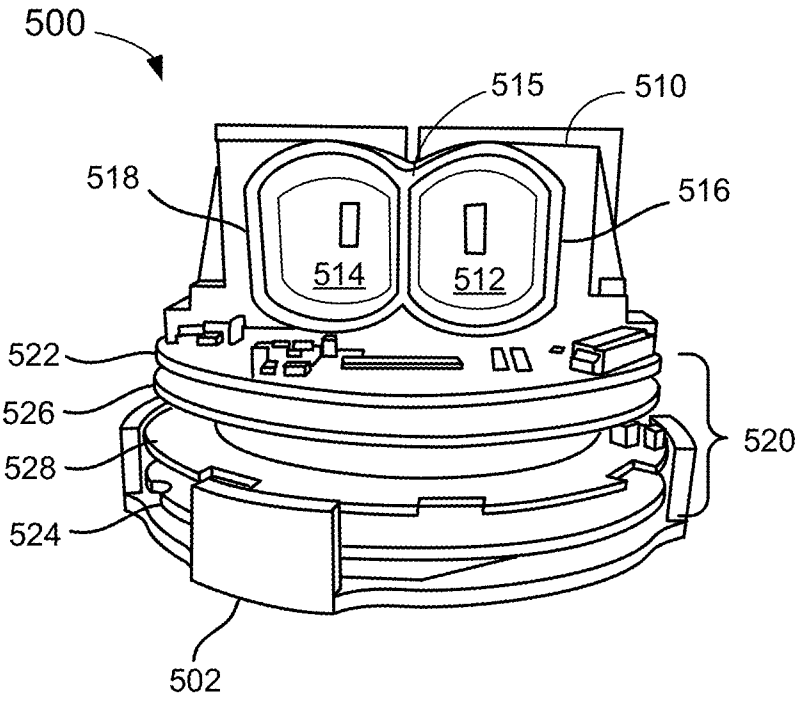
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FIG. 5B

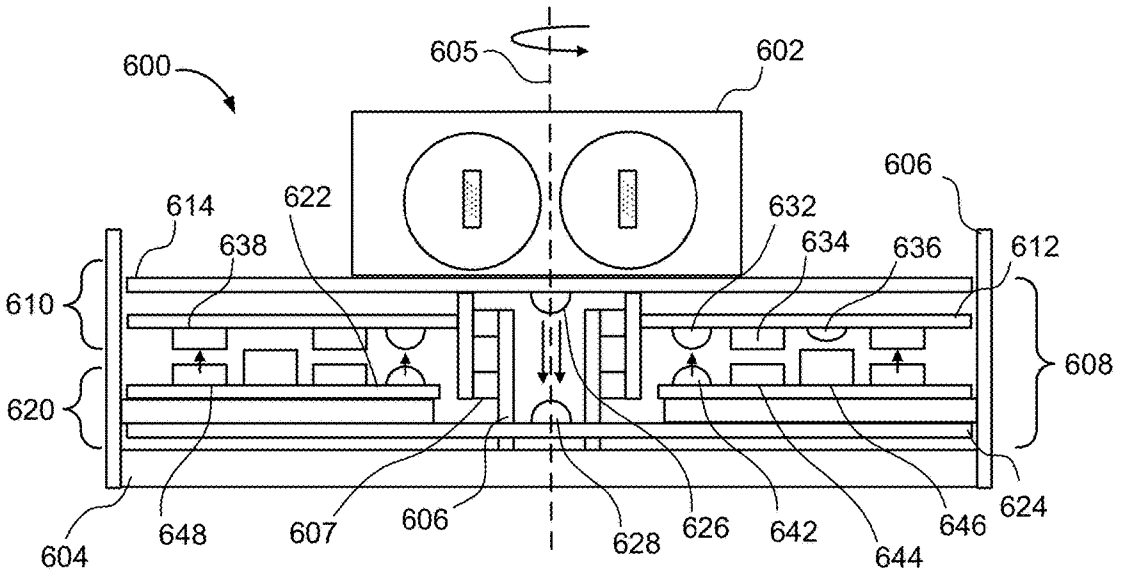


FIG. 6A

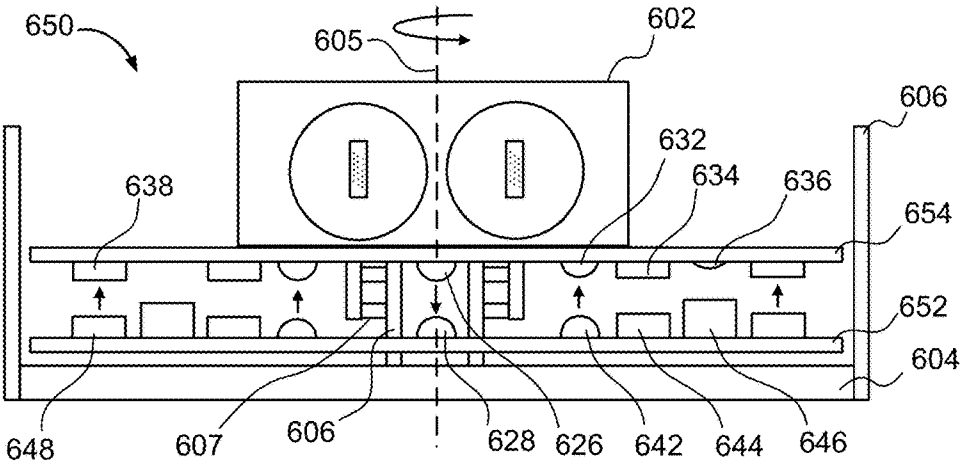


FIG. 6B

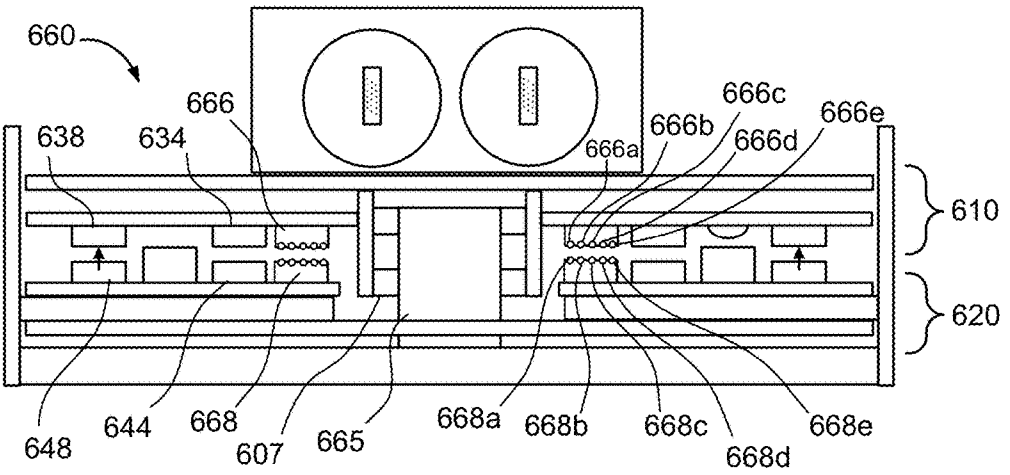
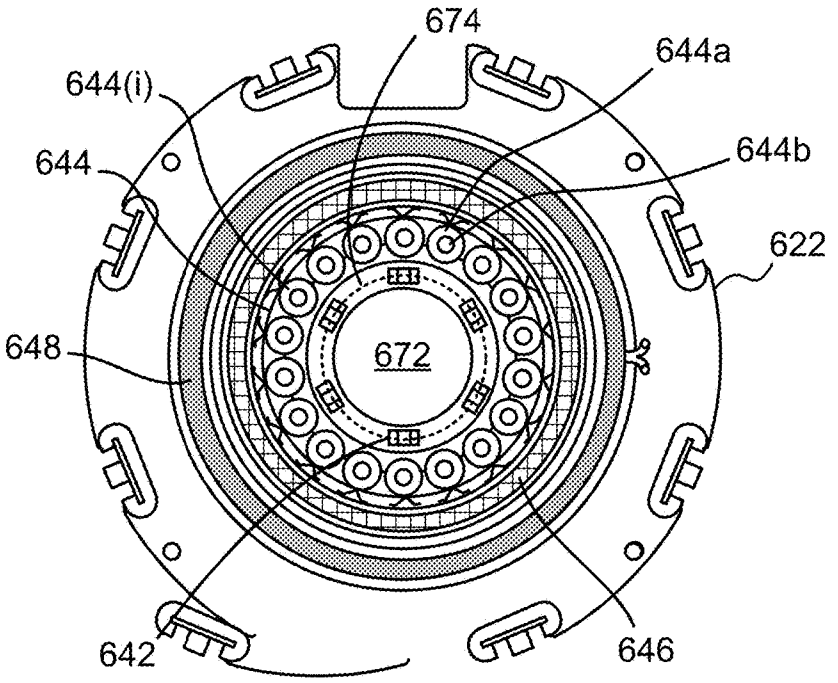


FIG. 6C

FIG. 6D



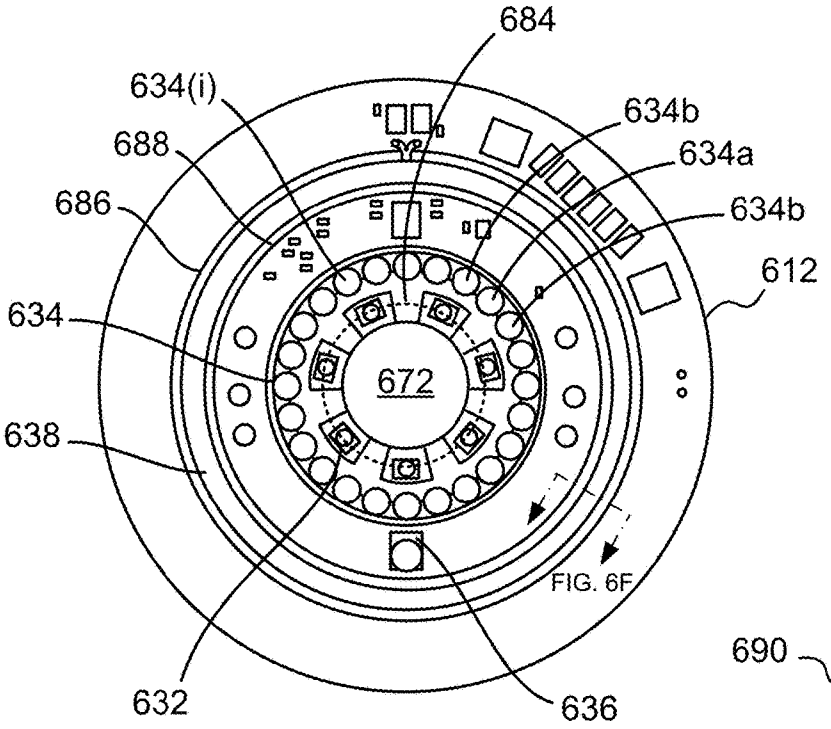


FIG. 6E

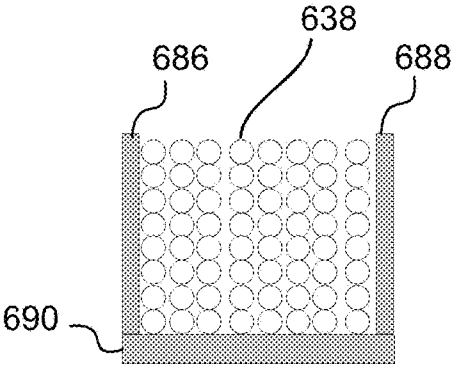


FIG. 6F

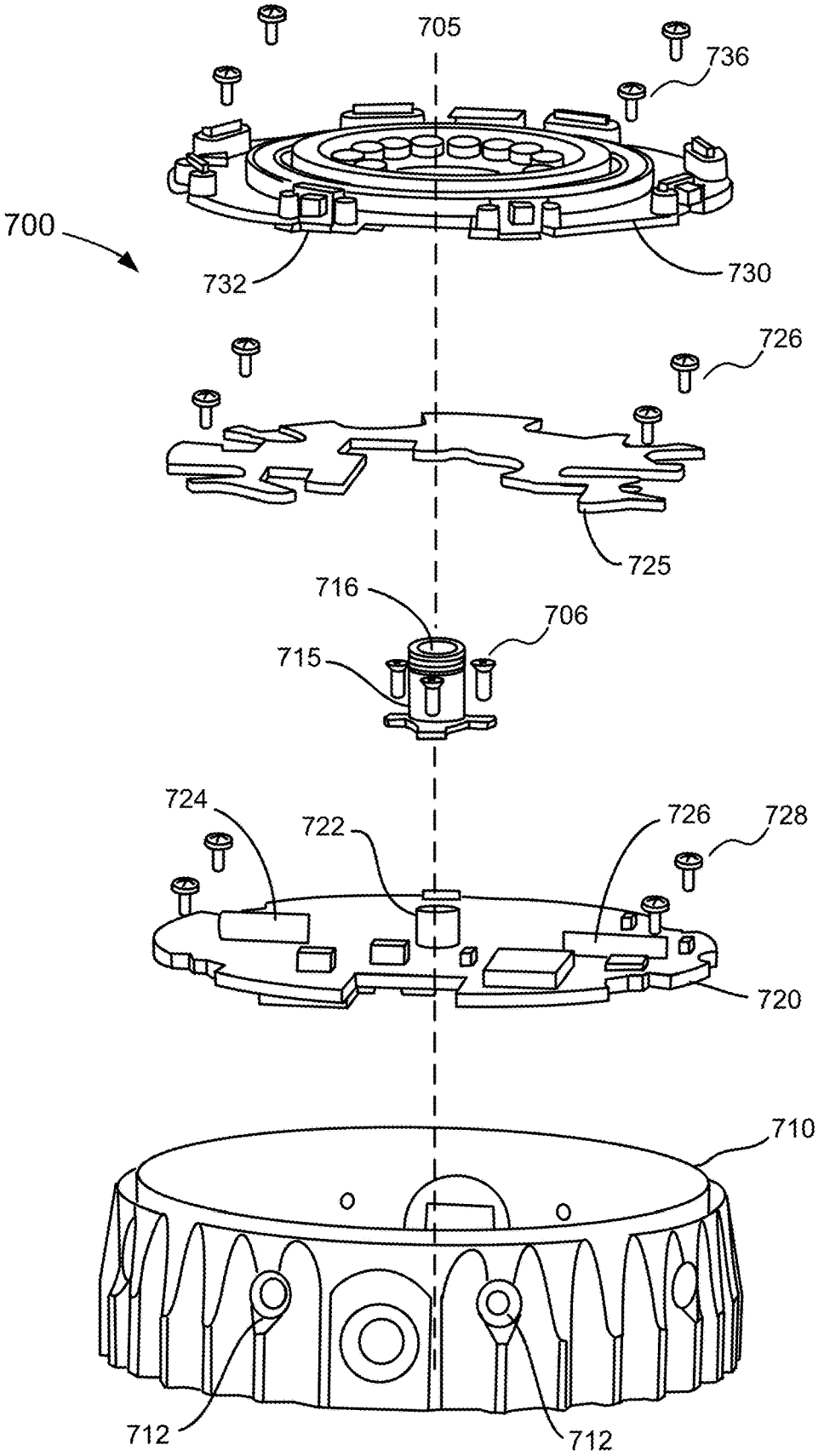

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FIG. 7

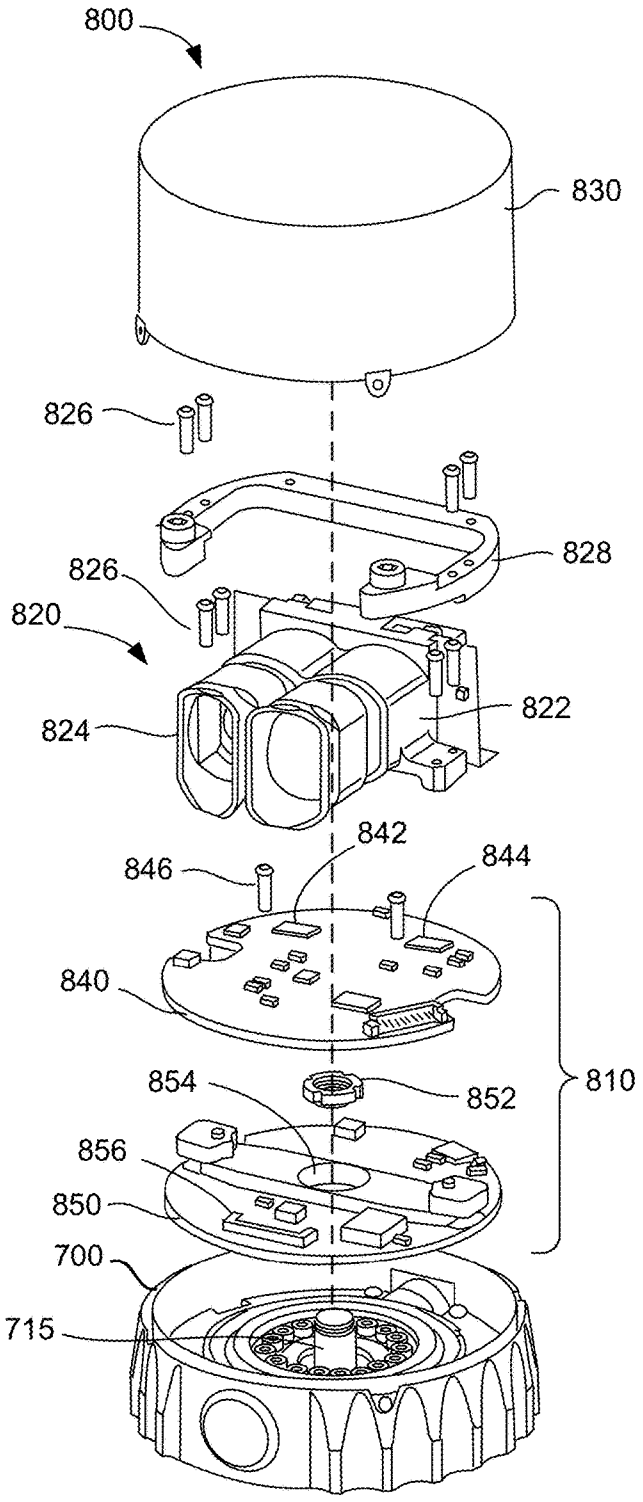
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FIG. 8A

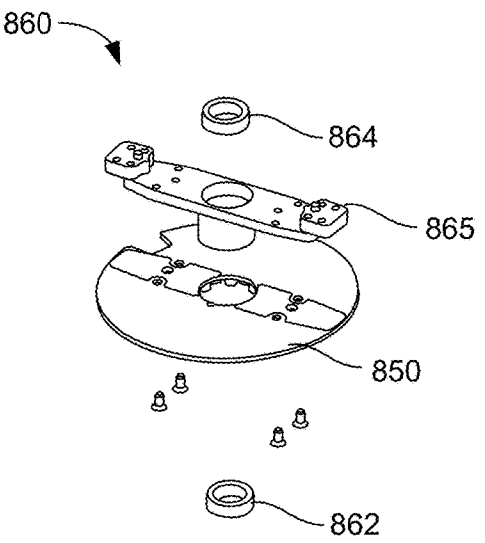
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FIG. 8B

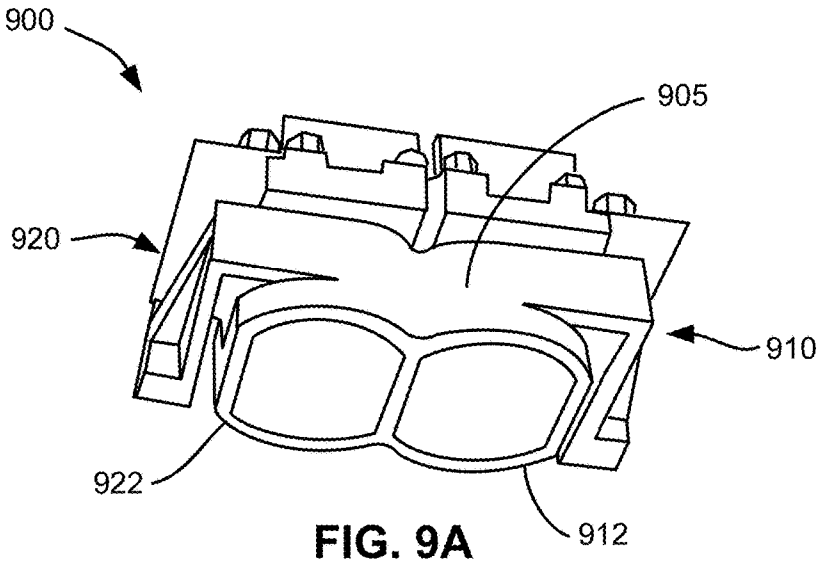

FIG. 9A

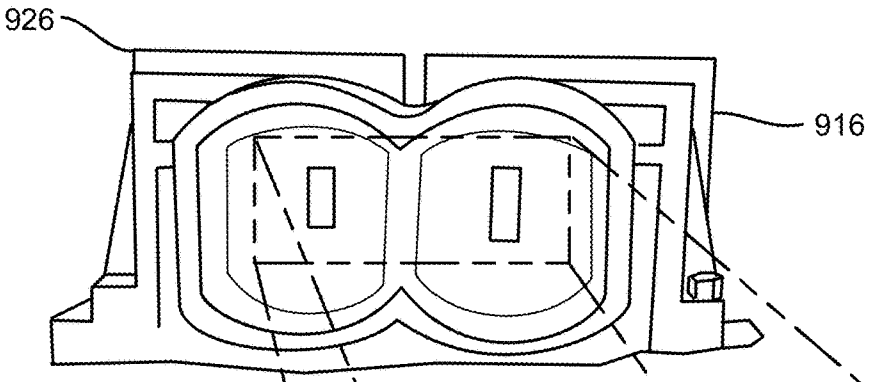

FIG. 9B

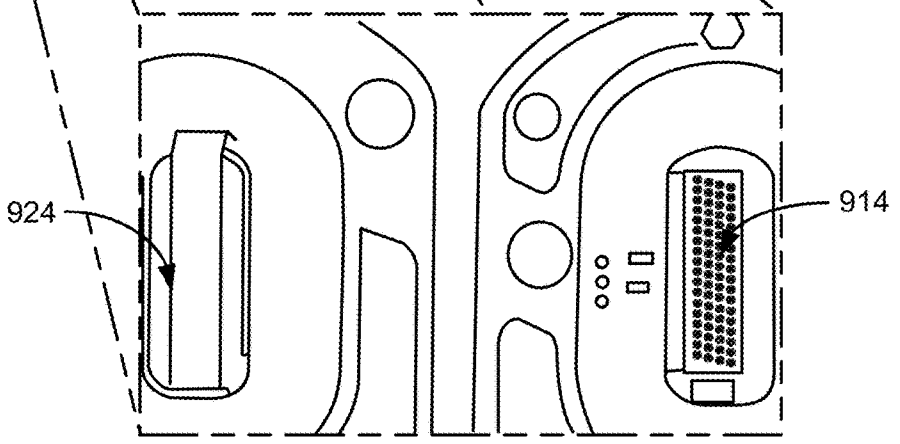

FIG. 9C

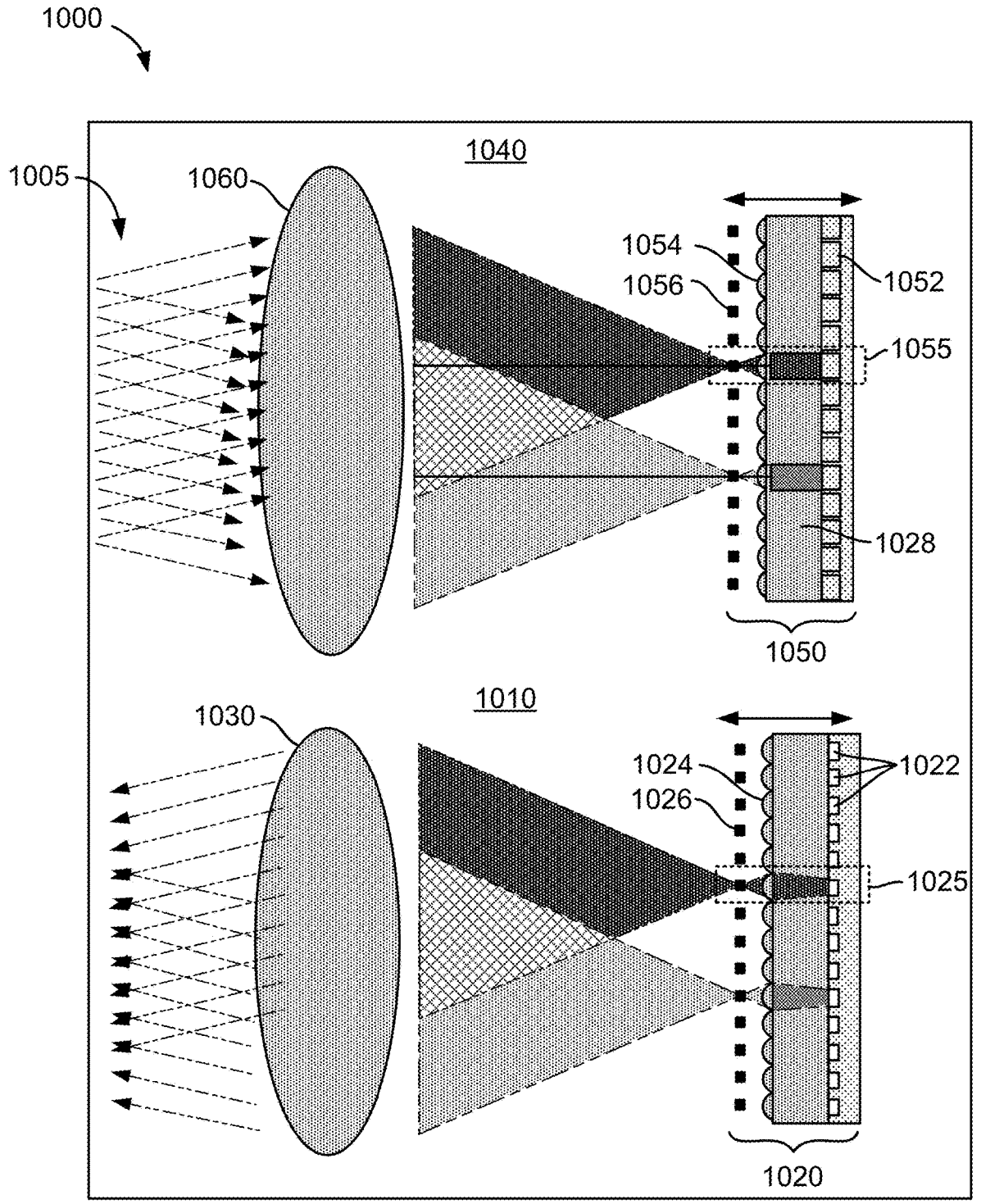
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FIG. 10

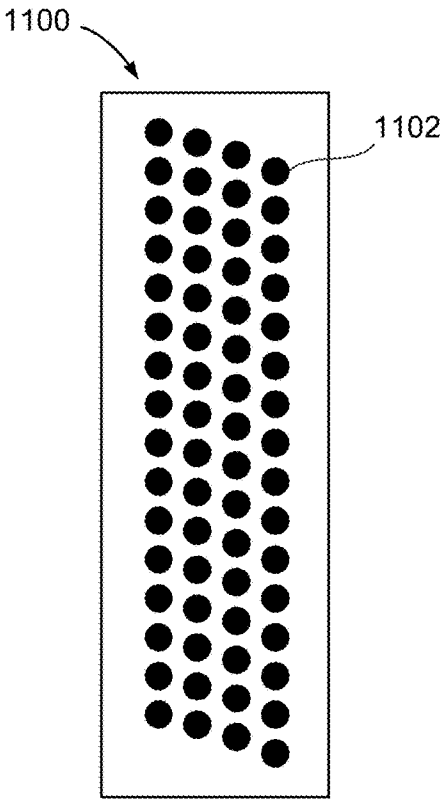


FIG. 11A

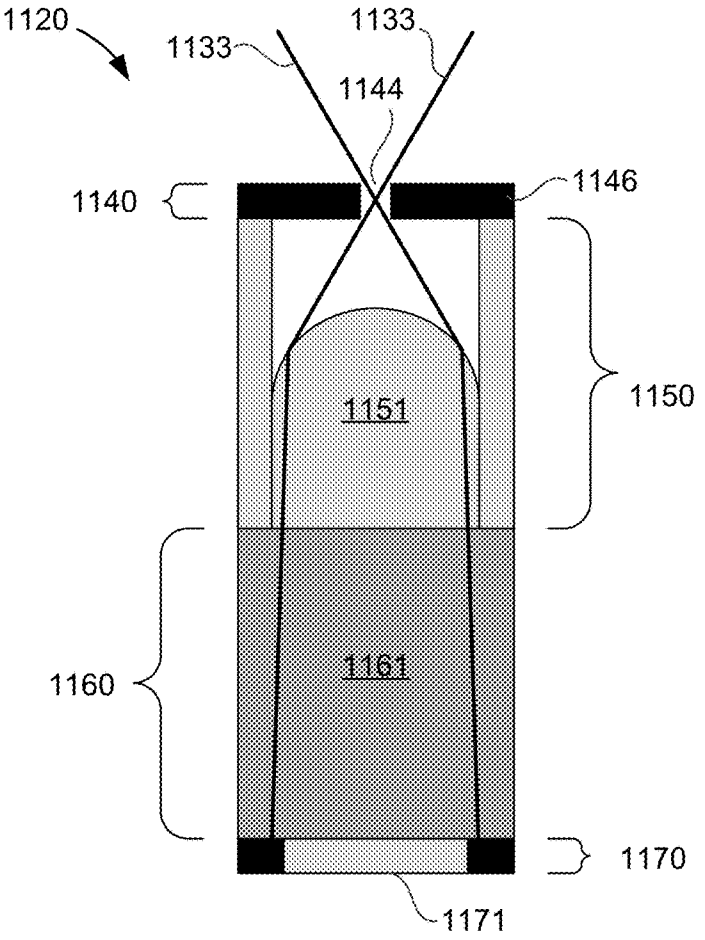


FIG. 11B

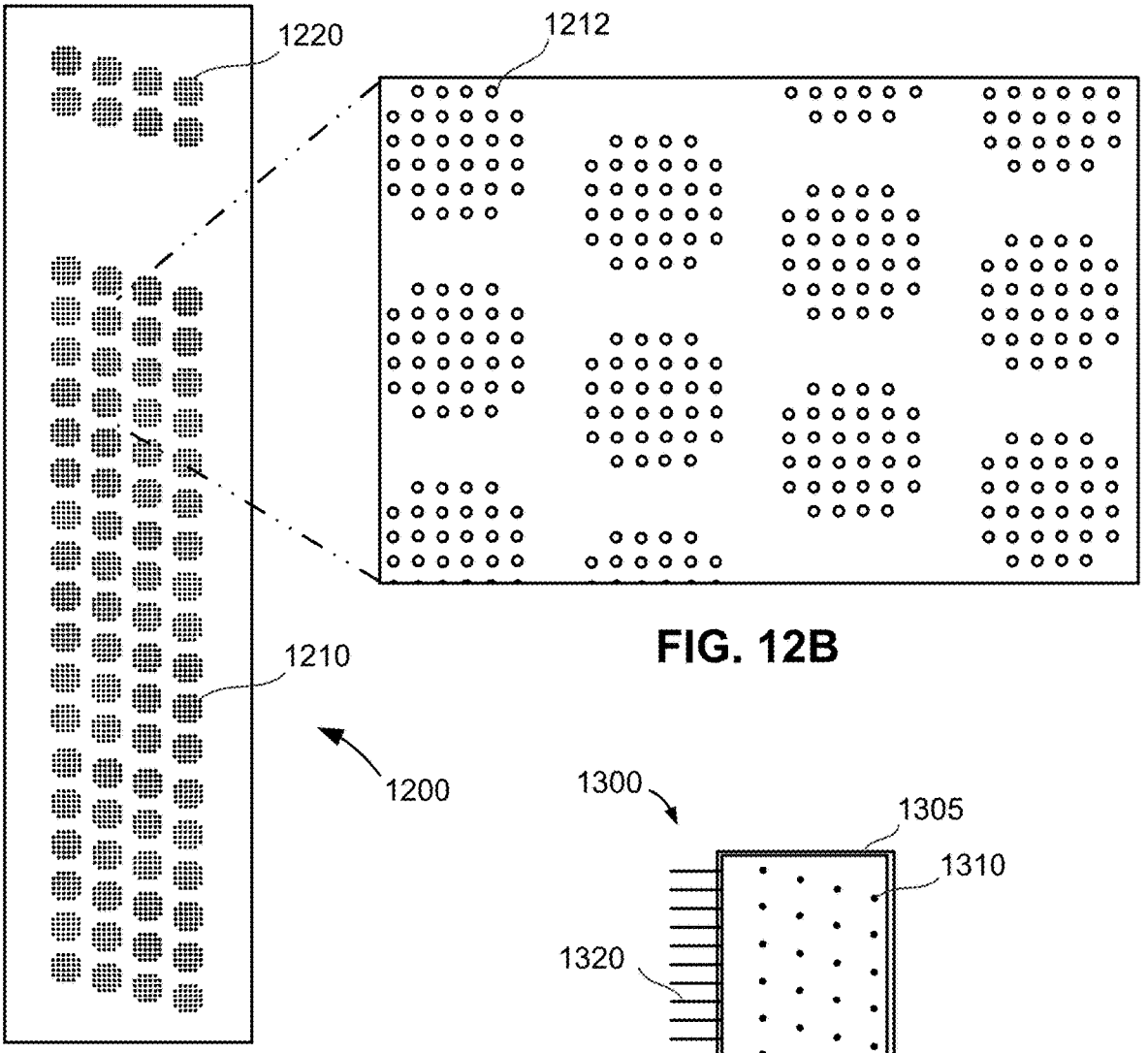


FIG. 12A

FIG. 12B

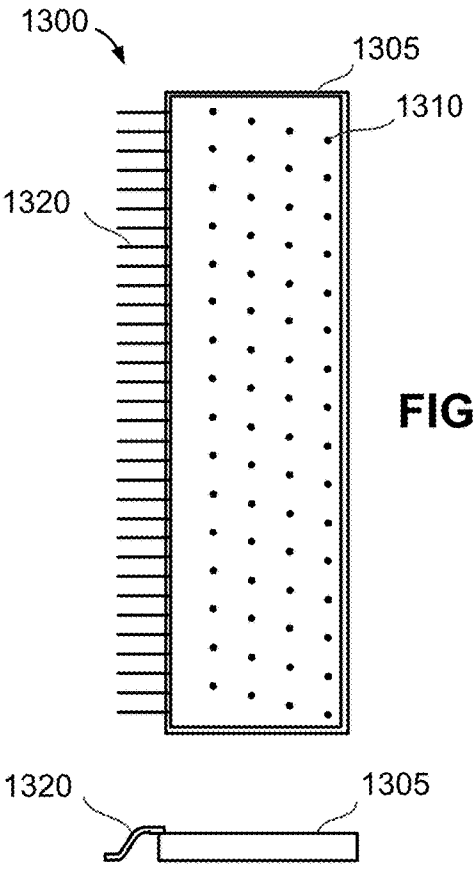


FIG. 13A

FIG. 13B

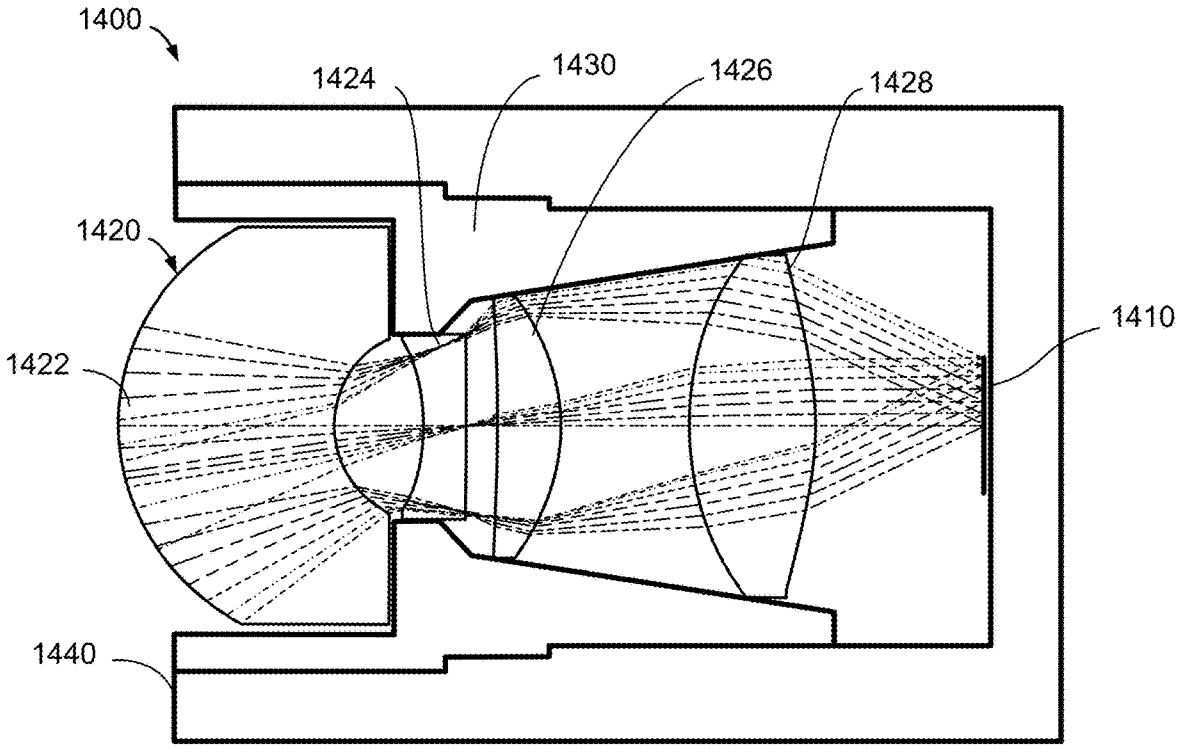


FIG. 14

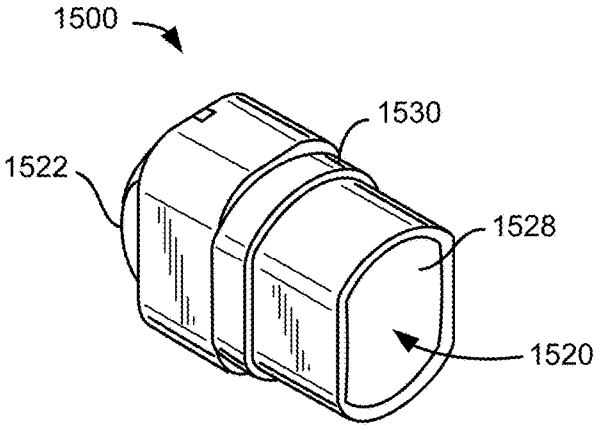


FIG. 15A

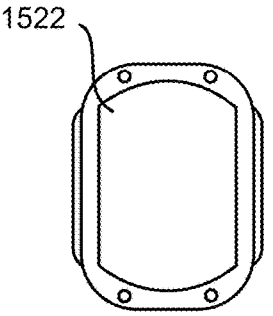


FIG. 15B

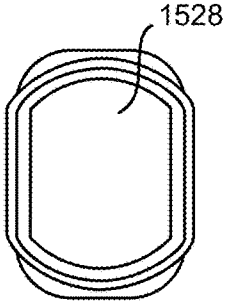


FIG. 15C

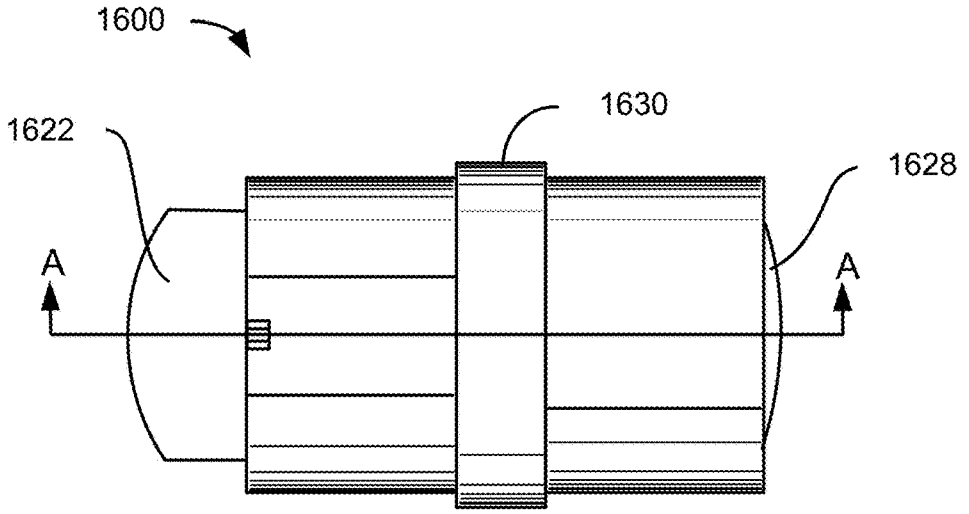


FIG. 16A

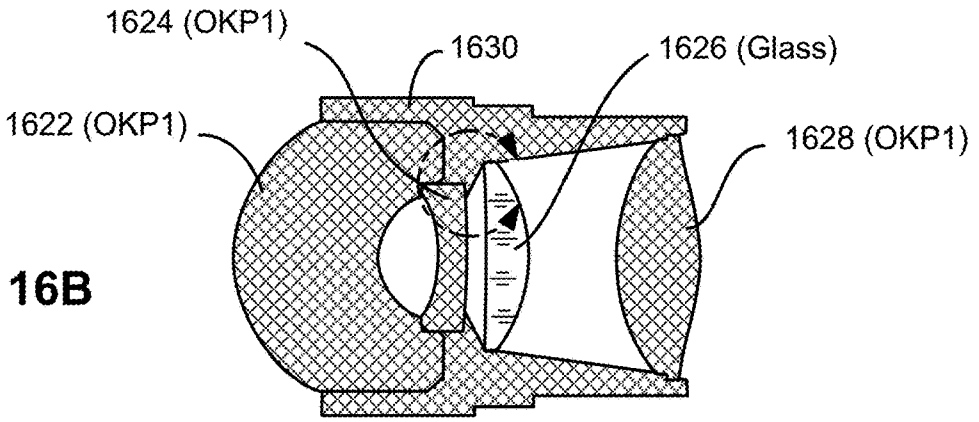


FIG. 16B

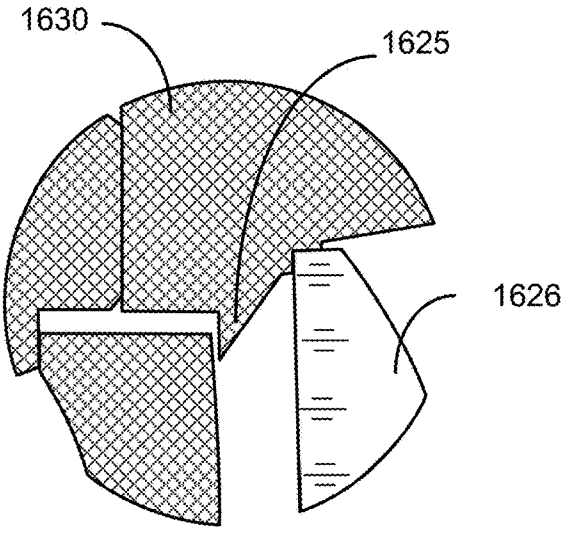


FIG. 16C

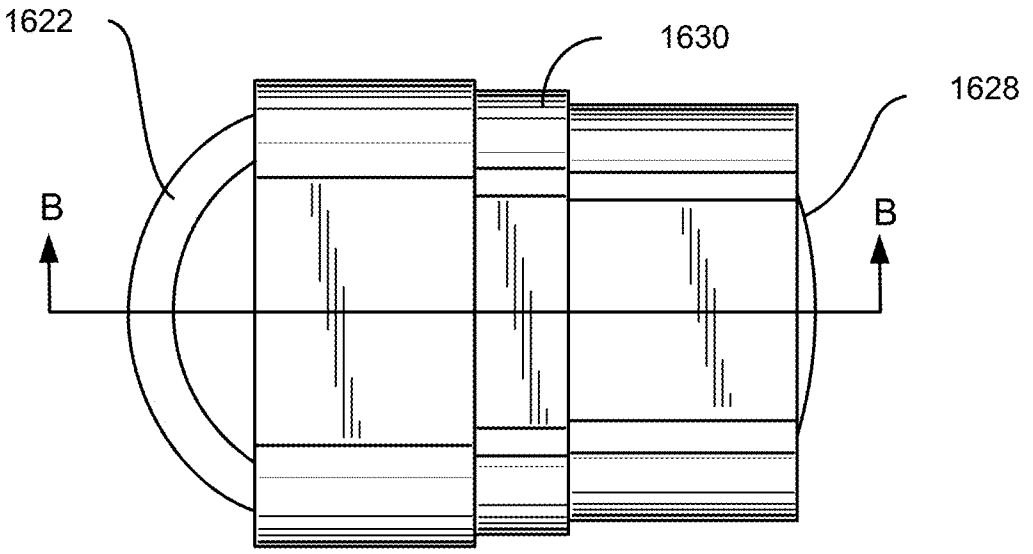
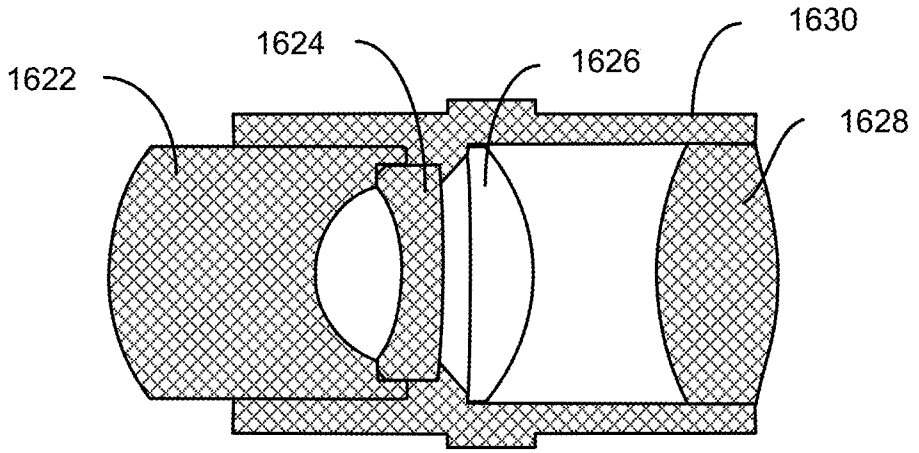


FIG. 16D



SECTION B-B

FIG. 16E

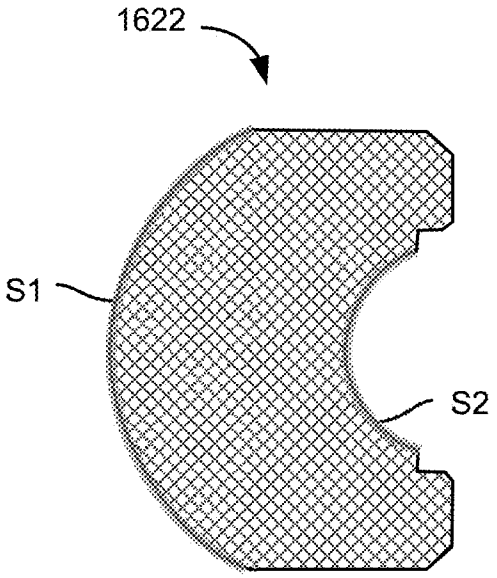


FIG. 17A

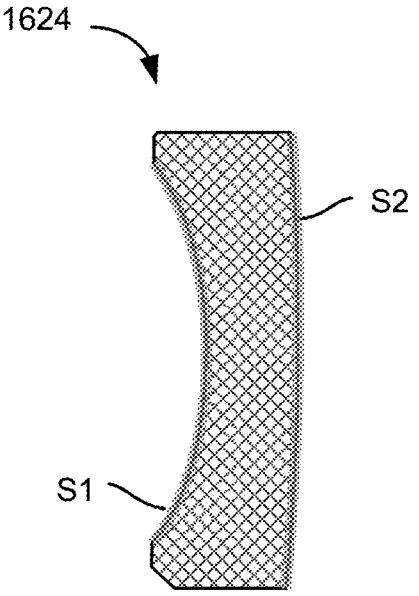


FIG. 17B

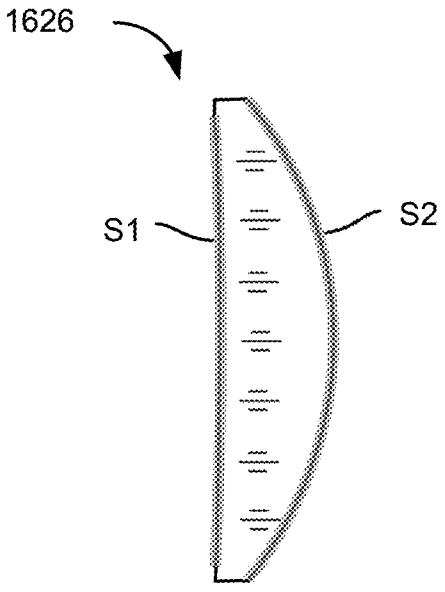


FIG. 17C

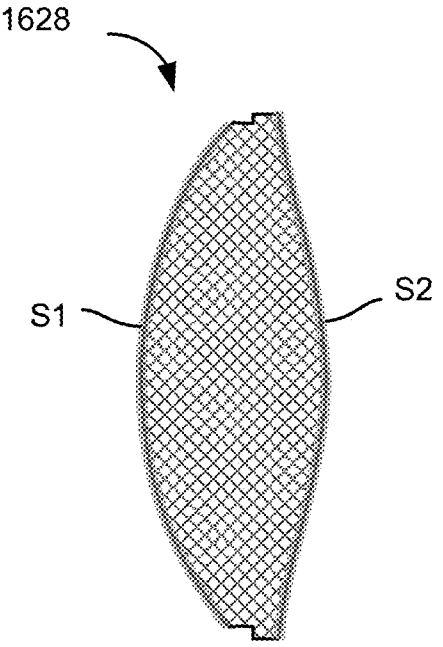


FIG. 17D

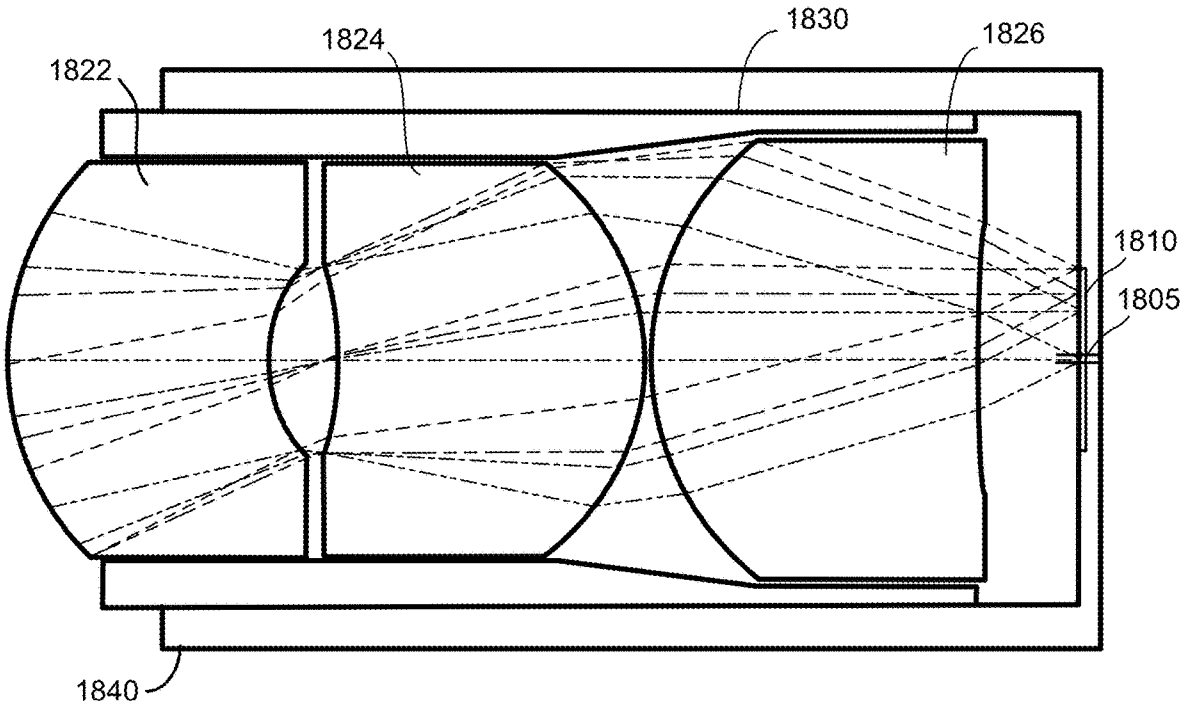


FIG. 18

ROTATING LIGHT RANGING SYSTEM WITH OPTICAL COMMUNICATION UPLINK AND DOWNLINK CHANNELS

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/596,018, entitled "Compact LIDAR System," filed Dec. 7, 2017, the disclosure of which is incorporated herein by reference in its entirety for all purposes.

[0002] This application is related to the following commonly assigned and concurrently filed patent applications, the disclosures of each of which are incorporated herein by reference in their entirety for all purposes: "Rotating Compact Light Ranging System", U.S. patent application Ser. No. 16/209,867 (Attorney Docket Number 103033-P010US1); "Light Ranging System with Opposing Circuit Boards", U.S. patent application Ser. No. 16/209,869 (Attorney Docket Number 103033-P010US2); and "Light Ranging Device with a Multi-element Bulk Lens System", U.S. patent application Ser. No. 16/209,879 (Attorney Docket Number 103033-P010US4).

BACKGROUND

[0003] Light imaging, detection and ranging (LIDAR) systems measure distance to a target by illuminating the target with a pulsed laser light and measuring the reflected pulses with a sensor. Time-of-flight measurements can then be used to make a digital 3D-representation of the target. LIDAR systems can be used for a variety of applications where 3D depth images are useful including archaeology, geography, geology, forestry, mapping, construction, medical imaging and military applications, among others. Autonomous vehicles can also use LIDAR for obstacle detection and avoidance as well as vehicle navigation.

[0004] Many currently available LIDAR sensors that provide coverage and resolution sufficient for obstacle detection and avoidance in autonomous vehicles are both technologically complex and costly to manufacture. Such sensors can thus be too expensive to allow for wide deployment in mass-market automobiles, trucks and other vehicles. Overall component cost and manufacturing complexity of a particular type of LIDAR sensor is typically driven by the underlying complexities in the architecture of the LIDAR sensor itself. This can be further exacerbated in some modern LIDAR sensors which are a conglomeration of different internal sub-systems, each of which can be in itself quite complex, e.g., optoelectronic systems, electromechanical systems, computer control systems, high-speed communication systems, data processing systems, and the like.

[0005] To achieve the high positional accuracy, long distance range, and low power consumption that can be important to some modern sensing applications, stringent technical requirements for each one of these sub-systems have led to architectures and designs that are complex and difficult to build and often require expensive calibration and alignment procedures before individual LIDAR units can be used by a customer. 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 some of these systems, separate laser emitter/detector pairs are mounted to individual, separate circuit boards. Thus, 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 each 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.

[0006] The above-described architecture becomes increasingly problematic when one desires to scale the resolution of the device. 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.

[0007] In addition to the complexities of alignment and assembly of the optical systems, most currently available LIDAR units have a relatively low overall degree of system integration. For example, control and drive circuits in many currently available LIDAR units are separate modules mounted to custom boards. These custom boards may, in turn, need to be mounted to a motherboard within the LIDAR unit or may be mounted somewhere else on a structural element of the LIDAR unit 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.

[0008] For rotating LIDAR systems even more additional specialized mounts and interconnects may be required for the electric motor rotor and/or stator. In addition to power connections, data uplink and downlink lines are needed and typically 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 potentially 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 disfavored or even banned in some jurisdictions.

[0009] With respect to the optoelectronic systems, the industry has experienced challenges in incorporating cost-effective single photon photodetectors such as CMOS-based single photon avalanche diodes (SPADs) due to their low quantum efficiency in the near infrared wavelengths and their low dynamic range. To improve quantum efficiency, some SPAD-based detectors employ InGaAs technology but such systems are more challenging to integrate in a cost-effective manner than CMOS devices. Therefore, the external/supporting circuitry (e.g., 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) associated with the SPAD detectors manufactured using InGaAs technology is typically fabricated separately from the SPAD array, for example, in a package that is external to the SPAD array. In addition, InGaAs substrates are relatively expensive and the associated manufacturing processes typically have a lower yield than silicon substrate manufacturing processes further compounding the costs increase. To complicate matters further, InGaAs substrates typically 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.

[0010] Rather than employing SPAD-based detectors, many 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, for example, analog circuits such as transimpedance amplifiers and/or 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.

[0011] 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.

SUMMARY

[0012] Embodiments of the disclosure pertain to a LIDAR unit that can, among other uses, be used for obstacle detection and avoidance in autonomous vehicles. Various embodiments of the disclosure can address one or more of the problems discussed above that are associated with some currently available LIDAR systems. Some specific embodiments pertain to LIDAR systems that include design features that enable the systems to be manufactured cheaply enough and with sufficient reliability and to have a small enough footprint to be adopted for use in mass-market automobiles, trucks and other vehicles.

[0013] In some embodiments, a spinning light ranging system according to the present disclosure can include 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, and/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 and/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.

[0014] 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 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 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.

[0015] According to some embodiments, a rotation of an upper circuit board assembly can be driven by stator and rotor elements integrated on upper and lower circuit boards, 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 driver circuit can drive the stator elements. Having such rotor 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).

[0016] According to some embodiments, a light ranging system includes a shaft having a longitudinal axis; a first circuit board assembly that includes a stator assembly comprising a plurality of stator elements arranged about the shaft on a surface of the first circuit board assembly; a second circuit board assembly rotationally coupled to the shaft and spaced apart from and in an opposing relationship with the first circuit board assembly, wherein the second circuit board assembly includes a rotor assembly comprising a plurality of rotor elements arranged about the shaft on a surface of the second circuit board assembly such that the plurality of rotor elements are aligned with and spaced apart from the plurality of stator elements; a stator driver circuit disposed on either the second or the first circuit board assemblies and configured to provide a drive signal to the plurality of stator elements, thereby imparting an electromagnetic force on the plurality of rotor elements to drive a rotation of the second circuit board assembly about the longitudinal axis of the shaft; and a light ranging device mechanically coupled to the second circuit board assembly such that the light ranging device rotates with the second circuit board assembly.

[0017] In some embodiments a light ranging system includes a shaft; a first circuit board assembly that includes a stator assembly comprising a plurality of stator elements arranged about the shaft on a surface of the first circuit board assembly; a second circuit board assembly rotationally coupled to the shaft, wherein the second circuit board assembly includes a rotor assembly comprising a plurality of rotor elements arranged about the shaft on a surface of the

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second circuit board assembly such that the plurality of rotor elements are aligned with and spaced apart from the plurality of stator elements; a light ranging device coupled to rotate with the second circuit board assembly, the light ranging device including a light source configured to transmit light pulses to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; and a stator driver circuit disposed on either the second or the first circuit board assemblies and configured to provide a drive signal to the plurality of stator elements, thereby imparting an electromagnetic force on the plurality of rotor elements to drive a rotation of the second circuit board assembly about the shaft.

[0018] In some embodiments a light ranging system includes a stationary enclosure having an optically transparent window and a base; a hollow shaft disposed within the enclosure; a bearing system coupled to the hollow shaft; a first circuit board assembly disposed within the enclosure and parallel with a first plane perpendicular to the hollow shaft, the first circuit board assembly including a stator assembly comprising a plurality of evenly spaced stator elements arranged annularly about the shaft on a surface of the first circuit board assembly; a second circuit board assembly disposed within the enclosure parallel to the first plane and rotationally coupled to the shaft by the bearing system, wherein the second circuit board assembly includes a rotor assembly comprising a plurality of evenly spaced rotor elements arranged annularly about the shaft on a surface of the second circuit board assembly such that the plurality of rotor elements are aligned with and spaced apart from the plurality of stator elements; a light ranging device coupled to rotate with the second circuit board assembly within the stationary enclosure, the light ranging device including a light source configured to transmit light pulses through the window to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses received through the window that are reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; and a stator driver circuit disposed on either the second or the first circuit board assemblies and configured to provide a drive signal to the plurality of stator elements, thereby imparting an electromagnetic force on the plurality of rotor elements to drive a rotation of the second circuit board assembly and the light ranging device about the shaft.

[0019] According to some embodiments a light ranging system includes a housing; a shaft defining an axis of rotation; a first circuit board assembly disposed within and coupled to the housing in a fixed relationship such that the first circuit board assembly is aligned along a first plane perpendicular to the axis of rotation, the first circuit board assembly including a plurality of first circuit elements disposed on a first circuit board; a second circuit board assembly spaced apart from the first circuit board assembly within the housing in a second plane parallel to the first plane and rotationally coupled to the shaft such that the second circuit board assembly rotates about the axis of rotation, the second circuit board assembly including a plurality of second circuit elements disposed on a second circuit board and aligned with and configured to function in wireless cooperation with at least one of the first plurality of circuit elements; and a light ranging device electrically connected to and coupled to rotate with the second circuit board assembly, the light ranging device configured to transmit light pulses to objects in a surrounding environment, to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment, and to compute ranging data based on the reflected portion of the light pulses.

[0020] In some embodiments, a light ranging system includes an enclosure having an optically transparent window; a shaft defining an axis of rotation through the enclosure; a first circuit board assembly disposed within and fixedly coupled to the enclosure and aligned perpendicular to the axis of rotation; a second circuit board assembly disposed within the enclosure and spaced apart from and in an opposing relationship with the first circuit assembly, the second circuit board assembly rotatably coupled to the shaft; a light ranging device coupled to the second circuit board assembly in a fixed relationship such that the light ranging device rotates with the second circuit board assembly around the shaft; an annular encoder comprising an annular encoder strip mounted on one of the first or second circuit boards and an encoder reader mounted on the other of the first or second circuit boards at a location facing and opposite the annular encoder strip; a wireless communication system comprising a first annular wireless communication component mounted to the first circuit board and a second annular wireless communication component mounted to the second circuit board at a location facing and opposite the first annular wireless communication component; and an annular wireless power transfer system comprising an annular wireless power transmitter mounted to the first circuit board and an annular wireless power receiver mounted to the second circuit board at a location facing and opposite the annular wireless power transmitter.

[0021] In some embodiments, a light ranging system includes an enclosure having an optically transparent window; a shaft defining an axis of rotation through the enclosure; a first circuit board assembly disposed within and fixedly coupled to the enclosure and aligned perpendicular to the axis of rotation; a second circuit board assembly disposed within the enclosure and spaced apart from and in an opposing relationship with the first circuit assembly, the second circuit board assembly rotatably coupled to the shaft; a light ranging device mounted to the second circuit board assembly such that the light ranging device rotates with the second circuit board assembly around the shaft, the light ranging device configured to transmit light pulses to objects in a surrounding environment, to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment, and to compute ranging data based on the reflected portion of the light pulses; an annular encoder comprising an annular encoder strip mounted on one of the first or second circuit boards and an encoder reader mounted on the other of the first or second circuit boards at a location facing and opposite the annular encoder strip; a wireless communication system comprising a first annular wireless communication component mounted to the first circuit board and a second annular wireless communication component mounted to the second circuit board at a location facing and opposite the first annular wireless communication component; an electric motor including a stator assembly comprising a plurality of stator elements arranged about the shaft on a surface of the first circuit board

assembly and a rotor assembly comprising a plurality of rotor elements arranged about the shaft on a surface of the second circuit board assembly such that the plurality of rotor elements disposed at a location facing and opposite the plurality of stator elements; a stator driver circuit disposed on either the second or the first circuit board assemblies and configured to provide a drive signal to the plurality of stator elements, thereby imparting an electromagnetic force on the plurality of rotor elements to drive a rotation of the second circuit board assembly about the shaft; and an annular wireless power transfer system comprising an annular wireless power transmitter mounted to the first circuit board and an annular wireless power receiver mounted to the second circuit board at a location facing and opposite the annular wireless power transmitter.

[0022] According to some embodiments a light ranging system includes a shaft having a longitudinal axis; a light ranging device configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; a base subsystem that does not rotate about the shaft; and an optical communications subsystem configured to provide an optical communications channel between the base subsystem and the light ranging device, the optical communications subsystem including one or more turret optical communication components connected to the detector circuitry and one or more base optical communication components connected to the base subsystem.

[0023] In some embodiments a light ranging system includes a housing having an optically transparent window; a hollow shaft having a longitudinal axis disposed within the housing; a light ranging device disposed within the housing and configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses through the optically transparent window to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses through the optically transparent window reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; a base subsystem disposed within the housing that does not rotate about the shaft; and an optical communications subsystem disposed within the housing and configured to provide an optical communications channel between the base subsystem and the light ranging device, the optical communications subsystem including a first optical channel disposed within the hollow shaft and a second optical channel arranged annularly outside the hollow shaft.

[0024] In some embodiments, a light ranging system includes a housing having an optically transparent window; a hollow shaft having a longitudinal axis disposed within the housing; a light ranging device disposed within the housing and configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses through the optically transparent window to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses through the optically transparent window reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses; a base subsystem disposed within the housing that does not rotate about the shaft; a first optical communication channel configured to optically transmit data between the light ranging device and the base subsystem through the hollow shaft, the first optical communication channel including a first optical component coupled to circuitry coupled to rotate with the light ranging device and a second optical component coupled to circuitry disposed on the base subsystem; and a second, annular optical communication channel surrounding the hollow shaft and configured to optically transmit data between the light ranging device and the base subsystem, the annular optical communication channel including a first annular optical component coupled to circuitry coupled to rotate with the light ranging device and a second annular optical component coupled to circuitry disposed on the base subsystem.

[0025] According to some embodiments, a light ranging device can include a light emitting module and a light sensing module. The light emitting module can include a light source configured to transmit light pulses to objects in a surrounding environment. The light sensing module can include a lens housing; a bulk lens system coupled to the lens housing and configured to receive light from the surrounding environment and focus the received light to a focal plane, the bulk lens system comprising a first lens, a second lens, and a third lens mounted in the lens housing; wherein the first lens, the second lens, or the first lens and the second lens are plastic; and wherein the third lens is glass; an array of photosensors configured to receive light from the bulk lens system and detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment; and a mount that mechanically couples the lens housing with the array of photosensors, wherein the lens housing, the bulk lens system, and the mount are configured to passively focus light from the bulk lens system onto the array of photosensors over a temperature range. In some instances the lens housing, the bulk lens system, and the mount are configured to match, as a function of temperature, a focal length of the lens system with an expansion coefficient of the lens housing and with an expansion coefficient of the mount so that light is passively focused onto the array of photosensors over the temperature range, such as −5 degrees C. to 70 degrees C.

[0026] In some embodiments, a light ranging system includes an enclosure having an optically transparent window, a light ranging device disposed within the enclosure and circuitry configured to compute ranging data. The light ranging device can include an optical transmitter comprising a bulk transmitter lens system and a plurality of transmitter channels, each channel including a light emitter configured to generate and transmit pulses of narrowband light through the bulk transmitter optic and through the optically transparent window into a field external to the light ranging system; and an optical receiver comprising a bulk receiver lens system, a lens housing and a plurality of micro-optic receiver channels, each micro-optic channel including an aperture coincident with a focal plane of the bulk receiver optic, a collimating lens behind the aperture, an optical filter behind the collimating lens and a photosensor responsive to incident photons passed through the aperture into the collimating lens and through the filter. The bulk receiver lens system can include a first lens, a second lens, and a third lens mounted in the lens housing; wherein the first lens, the

second lens, or the first lens and the second lens are plastic; the third lens is glass; and a coefficient of thermal expansion (CTE) of the lens housing is matched, over a temperature range, with the bulk receiver lens system so that the focal plane is stable relative to each photosensor in the plurality of micro-optic receiver channels over the temperature range. In some instances the temperature range is from 20 degrees C. to 70 degrees C. and in some instances the temperature range is from −5 degrees C. to 70 degrees C.

[0027] In some embodiments an image sensing device is provided. The image sensing device can include a lens housing; a bulk lens system mechanically coupled to the lens housing and configured to receive light from the surrounding environment and focus the received light to a focal plane. The bulk lens system can include a first lens, a second lens, and a third lens mounted in the lens housing, wherein the first lens, the second lens, or the first lens and the second lens are plastic and wherein the third lens is glass. The image sensing device can further include an array of photosensors configured to receive light from the bulk lens system, and a mount that mechanically couples the lens housing with the array of photosensors. The coefficient of thermal expansion (CTE) of the lens housing can be matched, over a temperature range, with the bulk lens system so that the focal plane is stable relative to the array of photosensors over the temperature range. In some instances the temperature range is from 20 degrees C. to 70 degrees C. and in some instances the temperature range is from −5 degrees C. to 70 degrees C. And, in some embodiments, a CTE of the mount is matched with the CTE of the lens housing.

[0028] These and other embodiments of the invention are described in detail below. Additionally, other aspects and advantages of various embodiments of the disclosure will become apparent from the following detailed description taken in conjunction with the accompanying drawings which illustrate, by way of example, the principles of the described embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIGS. **1**A-**1**B show a rotating light ranging system and a non-rotating, solid-state light ranging system, respectively, that can be used in automotive applications according to some embodiments;

[0030] FIGS. **2**A-**2**B show high level block diagrams of rotating and solid-state LIDAR systems, respectively, according to some embodiments;

[0031] 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. **2**A;

[0032] FIGS. **4**A and **4**B show 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**;

[0033] FIGS. **5**A-**5**B show a rotating LIDAR system **500** in accordance with one or more embodiments;

[0034] FIGS. **6**A-**6**C show cross-sectional views of a LIDAR system in accordance with one or more embodiments;

[0035] FIG. **6**D shows a top view of a stator board in accordance with one or more embodiments;

[0036] FIG. **6**E shows a bottom view of a rotor board in accordance with one or more embodiments;

[0037] FIG. **6**F is a simplified cross-sectional view of a portion of a multi-coil wireless power receiver positioned within an annular ferrite channel according to some embodiments;

[0038] 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;

[0039] FIGS. **8**A and **8**B show an exploded view of a LIDAR system according to some embodiments;

[0040] FIGS. **9**A-**9**C show a perspective view, a front view, and a zoomed front view, respectively, of a light ranging device **900** according to certain embodiments;

[0041] 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;

[0042] FIG. **11**A shows a top view of a micro-optics package according to certain embodiments;

[0043] FIG. **11**B shows a cross-section of a single micro-optic receiver channel according to some embodiments;

[0044] FIG. **12**A-**12**B shows top views of a SPAD-based detector according to some embodiments;

[0045] FIGS. **13**A and B show simplified top and side views of a VCSEL chip transmitter according to some embodiments;

[0046] FIG. **14** depicts a simplified schematic of an embodiment of a LIDAR bulk optical system;

[0047] FIGS. **15**A, **15**B, and **15**C depict an embodiment of a bulk optics lens assembly;

[0048] FIGS. **16**A-**16**E depicts various views of an embodiment of a lens assembly;

[0049] FIG. **17**A-**17**D, depict a cross sections of embodiment of the lenses of a lens assembly; and

[0050] FIG. **18** depicts an embodiment of a lens assembly with three lenses.

TERMS

[0051] 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. The following definitions, however, 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.

[0052] 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 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.

[0053] The term turret can 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

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components located in a light ranging device and/or one or more components located on a rotating circuit board of a rotary actuator.

[0054] In the context of a rotating LIDAR system (sometimes referred to herein as a "spinning LIDAR system"), the term base can refer to the non-rotating part or non-rotating 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.

[0055] 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.

[0056] 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.

[0057] One or more shapes that are referred to as symmetric can 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.

[0058] 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.

[0059] 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.

[0060] The term photosensor (or just sensor) refers to a sensor that can convert light into an electrical signal (e.g., an analog electrical signal or binary electrical signal). An avalanche photodiode (APD) is one example of a photosensor. A single photosensor can include a plurality of smaller "photodetectors". Thus, a plurality of single-photon avalanche diodes (SPADs) can be another example of a photosensor where each individual SPAD in the plurality of SPADs (e.g., each SPAD in an array of SPADs) can be referred to as a photodetector. The term sensor array can sometimes refer to a sensor chip that includes an array of multiple sensors. Additionally, the term pixel is sometimes used interchangeably with photosensor or sensor.

[0061] The term transmitter can refer to a structure that includes one or more light transmitting elements, e.g., LED, laser, VCSEL, and the like. The term transmitter can also include a transmitter chip that includes an array of transmitters, sometimes referred to as an emitter array.

[0062] 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 micro-optics 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. In general, micro-optics can modify light differently for different emitters and/or different detectors of an array of emitters or an array of detectors, whereas the bulk optics modify light for the entire array.

[0063] 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

[0064] 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 (sometimes referred to as a "light emitting 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 (e.g., a CMOS chip) that includes an array of photosensors, each of which can be, for example, an array of SPADs.

[0065] 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 can be 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.

[0066] In some embodiments, these same boards include electric motor components 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.

[0067] 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.

[0068] 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.

[0069] 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 can include 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 and one or more bearings attached thereto provide for rotational movement of the upper circuit board assembly relative to the lower circuit board assembly.

[0070] In view of the above architecture, assembly of the rotary actuator in some embodiments can be 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.

[0071] 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 can be 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 lens housing and of the optical elements within the lens 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.

[0072] A modular light ranging device according to some embodiments of the disclosure includes a set of vertical-cavity surface-emitting lasers (VCSELs) as illumination sources that emit pulses of radiation into a field and includes arrays of single-photon avalanche diode (SPAD) detectors as a set of pixels (photosensors) that detect radiation reflected or scattered from a surface in the field. As stated above, SPADs have a relatively low dynamic range as compared to APDs that are used in some currently available LIDAR sensors. 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 electrical signal (photon detected or not detected) in the form of an avalanche current pulse. Using VCSELs as the emitters and SPADs as the detectors enables multiple measurements to be taken at the same time (i.e., the VCSEL emitters can be fired simultaneously) and also enables the set of emitters and the set of photosensors to each be fabricated using standard CMOS processes on a single chip, greatly simplifying the manufacturing and assembly process. Using VCSELs and SPADs in certain embodiments presents challenges, however, that various embodiments of the invention overcome. For example, VCSELs are much less powerful than the lasers used in some currently available LIDAR sensors and SPADs are much less efficient than the detectors used in some LIDAR sensors. To address these challenges, as well as challenges presented by firing multiple emitters simultaneously, certain embodiments of the disclosure can include optical components to enhance the brightness of the VCSEL emitter as well as various optical components (e.g., lenses, filters, and an aperture layer), which may work in concert with multiple arrays of SPADs, each array corresponding to a different photosensor, as described herein.

I. Illustrative Automotive LIDAR System

[0073] FIGS. **1**A-**1**B 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 **100** and/or solid state LIDAR system **120**, can be mounted on the roof of a vehicle **105** as shown in FIGS. **1**A and **1**B. In other embodiments one or more LIDAR sensors can be mounted on other locations of a vehicle including, but not limited to, the front or back of the vehicle, the sides of the vehicle and/or corners of the vehicle.

[0074] The scanning LIDAR system **100** shown in FIG. **1**A can employ a scanning architecture, where the orienta-

tion of the LIDAR light transmission module **102** (e.g., light source for emitting laser pulses) and/or light sensing module **104** (e.g., detector circuitry 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 **112** 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 **100**, 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.

[0075] For a stationary architecture, like the solid state LIDAR system **120** shown in FIG. **1**B, one or more solid state LIDAR subsystems (e.g., light transmission module **122** and light sensing module **124**) 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.

[0076] 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 **114** can be detected by detector circuitry **104**. The light transmission module can be disposed in the same housing as the light sensing module. 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 **122** and **124** in FIG. **1**B 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 **130** to field of view **132**.

[0077] FIGS. **2**A-**2**B show high level block diagrams of a rotating LIDAR system **200** and a stationary solid state LIDAR system **230**, respectively, according to some embodiments. Both systems employ a light ranging device **210** that includes a light transmission module **212** and a light sensing module **214**. The light transmission and sensing modules **212** and **214** can each include bulk optics **215**, e.g., a multi-element lens assembly positioned at the input/output of the sensing and transmission modules, respectively. Light transmission module **212** can further include a micro-optics array and optional notch filter element (not shown) that is located between the bulk optics **215** and light emitter circuitry **216**. In some embodiments, light emitter circuitry **216** 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 **214** can also include a micro-optics array and notch filter element (not shown) that is located between the bulk optics **215** and light detector circuitry **218**. In some embodiments, light detector circuitry **218** can includes 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 the like.

[0078] Turning to FIG. **2**A, in rotating LIDAR system **200**, light ranging device **210** can be electrically connected to a turret circuit board assembly **222** (also referred to herein as an upper circuit board assembly or ranging circuit board assembly). Circuit board assembly **222** can be considered ranging to the extent that it is connected to light ranging device **210**. As described in more detail in FIG. **3** below, the turret circuit board assembly **222** can include a number of circuit elements including one or more processors and memory. For example, the turret circuit board assembly **222** 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 **210** can be hard wired to the turret circuit board assembly **222** via a multi-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 **222**.

[0079] Turret circuit board assembly **222** can be disposed directly above a base circuit board assembly **226**. In some embodiments, the base circuit board assembly **226** can wirelessly transmit power to the turret circuit board assembly **222** to, for example, power light ranging device **210** and any other associated 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 **226** to turret circuit board assembly **222** thereby allowing for the light ranging device **210** to be controlled via contactless data transfer from the base circuit board assembly.

[0080] In the embodiment shown in FIG. **2**A, turret circuit board assembly **222** is rotationally coupled to base circuit board assembly **226** through a rotational coupler **224**. Rotational coupler **224** enables light ranging device **210** and turret circuit board assembly **222** to rotate a full 360 degrees within a housing **220** of LIDAR system **200**. Rotation of the light ranging device **210** allows the system to acquire data that can be used to construct a full 360 field-of-view 3D map of a volume around the device. In some embodiments, the base circuit board assembly **226** can be coupled to the housing **220**, for example, by way of a mechanical bracket and screws (not shown), such that base circuit board assembly **226** is held stationary and does not rotate relative to housing **220**. Housing **220** can be a waterproof housing that protects light ranging device **210** and other internal components of LIDAR system **200** from moisture and various elements of the environment that LIDAR system **200** operates within.

[0081] Rotational coupler **224** 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, rotational coupler **224** 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 **222**. For example, an electric motor rotor assembly including an arrangement of rotor elements (e.g., permanent magnets), can be directly integrated into the turret circuit board assembly **222**, and an electric motor stator assembly including an arrangement of stator elements, such as solenoid coils, can be directly integrated into the base circuit board assembly **226**. In such embodiments, where one or more rotary actuation components are integrated into the base circuit board assembly **226** and/or the turret circuit board assembly **222**, a separate module for rotary actuation is no longer needed. As a result, embodiments of the LIDAR system disclosed herein can have a more compact form factor and much simplified assembly process than spinning LIDAR systems that employ a separate electric motor module.

[0082] FIG. **2**B is a simplified block diagram of a stationary solid state LIDAR system **230** according to some embodiments. Like rotating LIDAR system **200** shown in FIG. **2**A, stationary solid state LIDAR system **230** includes a light ranging device **210** housed within a waterproof housing **240**. Light ranging device **210** can be directly connected to a base circuit board assembly **232** within housing **240**. Since system **230** does not rotate light ranging device **210**, there is no need for a separate rotating turret circuit board assembly or a rotational coupler. Accordingly, the circuitry that was previously distributed amongst the turret circuit board assembly **222** and the base circuit board assembly **226** can be integrated entirely into the single base circuit board assembly **232** and/or shared amongst the circuitry associated with the light sensing module **214** and/or transmission module **212**.

[0083] In some embodiments, for either of the embodiment shown in FIGS. **2**A-**2**B, 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 **210** and/or one or more of the circuit board assemblies (e.g., turret circuit board assembly **222** and/or base circuit board assembly **226** for LIDAR system **200**, or base circuit board assembly **232** for LIDAR system **230**). For example, in some embodiments, the light detector circuitry **218** 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 **210** is modular in the sense that a reprogramming/reconfiguring of the software/firmware can allow the light ranging device **210** to operate as part of a rotating LIDAR system (like LIDAR system **200** shown in FIG. **2**A) or as a stand-alone solid state LIDAR system (like LIDAR system **230** shown in FIG. **2**B). 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.

II. Detailed Block Diagram

[0084] 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. **2**A. 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 a rotor that is integrated onto a surface of a rotating circuit board and a 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.

[0085] Rotating LIDAR system **300** shown in FIG. **3** includes two main modules: a light ranging device **320** and a rotary actuator **315** described in detail below. Additionally, rotating LIDAR system **300** can interact with one or more instantiations of user interface hardware and software **305**. The different instantiations of user interface hardware and software **305** 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 **305** may be local to the object upon which rotating LIDAR system **300** is mounted but can also be a remotely operated system. For example, commands and data to/from 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.

[0086] The user interface hardware and software **305** 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 **305** 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.

[0087] In some embodiments, the LIDAR system can communicate with a vehicle control unit **310** 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, for example, 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 **310** is communicably coupled to light ranging

device **320**, alerts can be provided to a driver or the proximity of an object can be tracked and/or displayed.

[0088] Light ranging device **320** includes light sensing module **330**, light transmission module **340** and light ranging system controller **350**. The rotary actuator **315** includes at least two circuit board assemblies, a lower circuit board assembly **360** (also referred to herein as a base subsystem) and an upper circuit board assembly **380** (also referred to herein as a turret subsystem). The lower circuit board assembly **360** can be mechanically mounted to a fixed portion of an enclosure or housing (not shown) while the upper circuit board assembly **380** 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 **320** can be mechanically attached to the rotatable upper circuit board assembly **380** and therefore is free to rotate within the housing.

[0089] While FIG. **3** shows one particular arrangement of components within light ranging device **320** and rotary actuator **315**, in some embodiments, certain components may be integrated into one, or the other, module differently than shown. As one example, ranging system controller **350**, which can be, for example, an FPGA, ASIC, or a more general computing device, like an embedded system or system-on-a-chip (SOC), can be mounted directly (e.g., soldered) to, a printed circuit board that is part of the upper circuit board assembly **380**. In other words, in some embodiments, the parts of the rotary actuator can be integrated within the light ranging device **320** and vice versa.

[0090] The rotary actuator **315** includes a number of different systems that are integrated onto one or more printed circuit boards of the lower and upper circuit board assemblies **360** and **380**. For example, rotary actuator **315** can include a brushless electric motor assembly, an optical communications subsystem, a wireless power transmission subsystem, and a base controller. These systems are formed by pairs of cooperating circuit elements with each pair including one or more circuit elements on the lower circuit board assembly **360** operating in cooperation with (e.g., having a function that is complementary to) one or more circuit elements on the upper circuit board assembly **380**. Complementary functions include, for example, transmission (Tx) and reception (Rx) of power and/or data communication signals as is described in more detail below.

[0091] The brushless electric motor assembly includes a stator assembly **362** integrated onto a printed circuit board of the lower circuit board assembly **360** and a rotor assembly **382** integrated onto a printed circuit board of the upper circuit board assembly **380**. The rotation of rotor assembly **382** is driven from a drive signal, for example, a three-phase drive current, that originates from a motor driver circuit **364**. In some embodiments, one or more motor control lines connect the motor driver circuit to the coils of the stator assembly **362** to allow for the drive signal to be provided to the motor stator. Furthermore, the motor driver circuit **364** can be electrically connected to a base controller **366** such that the base controller **366** can control the rotation rate of the rotor assembly and thus the rotation rate (i.e., frame rate) of the light ranging device **320**.

[0092] In some embodiments, rotor assembly **382** can rotate at a rate between 10-30 Hz. In some embodiments, the rotor assembly **382** 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, for example, a magnetic force, generated by the coils of the stator assembly to drive a rotation of the upper circuit board assembly **380** relative to the lower circuit board assembly **360**. The rotational orientation of the upper circuit board assembly **380** can be tracked by a rotary encoder receiver **394**, which can track the angular position of the upper circuit board assembly by detecting the passage of one or more features on the rotary encoder **374**. A variety of different rotary encoder technologies can be employed. In some embodiments, rotary encoder **374** is integrated directly onto a surface of a circuit board of the lower circuit board assembly **360**.

[0093] Rotary actuator **310** can also include a wireless power system that includes a wireless power transmitter **372** and a wireless power receiver **392** in a configuration referred to herein as a rotary transformer. Power transmitted from transmitter **372** to wireless power receiver **392** can be consumed by light ranging device **320** and/or any circuitry needing power on the turret/upper circuit board assembly. In some embodiments, all power required by light ranging device **320** is provided through wireless power receiver **392** 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.

[0094] Rotary actuator **310** can also include an optical communication subsystem that includes a number of optical transmitters (e.g., optical transmitters **378** and **396**) and a number of optical receivers (e.g., optical receivers **376** and **398**) used for bi-directional contactless data transmission between rotary actuator **315** and light ranging device **320** (or to/from any other device or system that is mechanically connected to upper circuit board assembly **380** of the rotary actuator **315**). More specifically, the optical communication subsystem can include a set of base optical communication components that are attached to (e.g., soldered to) lower circuit board assembly **360** that is part of the stationary base of LIDAR system **300**, and can include a set of turret optical communication components that are attached to (e.g., soldered to) rotating upper circuit board assembly **380** that is part of the rotating turret of LIDAR system **300**. These optical communication components provide an uplink data channel for providing optical signals, including control signals, to light ranging device **320** and also provide a downlink data channel for providing optical signals, including ranging and operational data, from light ranging device **320** to base controller **366**, user interface hardware and software **305**, and/or the vehicle control unit **310**.

[0095] A downlink optical communication channel from the upper circuit board assembly **360** to the lower circuit board assembly **380** can be created between the optical downlink transmitter **396** and the optical downlink receiver **376**. Light ranging device **320** can be connected directly to upper circuit board assembly **380** and therefore can access the downlink optical communication channel to pass ranging and operational data down to lower circuit board assembly **360** for further use. In some embodiments, the data passed down in the optical signals via the optical downlink can 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 connected to upper circuit board **380** of the rotary actuator can be passed down through the optical downlink. For example, data from high speed RGB or thermal cameras, line scan cameras and the like.

[0096] An uplink optical communication channel from lower circuit board assembly **360** can be created between optical uplink transmitter **378** and optical uplink receiver **398**. In some embodiments, control signals from the base controller **366** can be passed to light ranging device **320** via the optical uplink communication channel. For example, in some embodiments, base controller **366** 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 light ranging device **320** 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).

[0097] Ranging data can be generated by light ranging device **320** by transmitting one or more light pulses from 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 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, for example, continuous wave, Doppler, and the like.

[0098] Light transmission module **340** can include an emitter array **342** and a Transmit (Tx) optical system **344**. Emitter array **342** can be a one-dimensional or two-dimensional array of transmitters, which when combined with transmit optical system **344** form an array of transmitter channels behind a bulk imaging optic. These transmitter channels can optionally include micro-optic structures for beam-shaping, beam-steering, brightness enhancement, or the like. Light transmission module **340** can further include an optional processor **346** and memory **348**, although in some embodiments these computing resources can be incorporated into 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 **348** 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.

[0099] Light sensing module **330** can include a sensor array **332** and a receiver (Rx) optical system **334**. Sensor array **332** can be a one-dimensional or two-dimensional array of photosensors. In some embodiments, each photosensor can include a collection of binary photon detectors (e.g., SPADs or the like), while in other embodiments each photosensor can be a linear photodetector (e.g., an APD). Receiver optical system **334** and sensor array **332** taken together can form an array of micro-optic receiver channels behind a bulk imaging optic as described in more detail below. Each micro-optic receiver channel measures light that corresponds to an image pixel in a distinct field of view of the surrounding volume. Each photosensor (e.g., a collection of SPADs) of sensor array **332** can correspond to a particular emitter of emitter array **342** 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 **332** 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**.

[0100] In some embodiments, sensor array **332** of light sensing module **330** can be fabricated as part of a monolithic device on a single substrate using, for example, CMOS technology, that includes both an array of photosensors, a processor **336** and a memory **338** for signal processing the raw signals from the individual photosensors (or groups of photosensors) in the array. The monolithic structure including sensor array **332**, processor **336**, and memory **338** can be fabricated as a dedicated ASIC. In some embodiments, micro-optical components that are part of receiver optical system **334** can also be a part of the monolithic structure in which sensor array **332**, processor **334**, and memory **338** are a part. In such instances, the micro-optical components can be formed on the ASIC so that they become part of the monolithic structure with separate substrate layers for each layer of the receiver channel. For example, an aperture layer, a collimating lens layer, an optical filter layer and a photodetector layer can be stacked and bonded to multiple ASICs 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 such an embodiment, the dicing step forms multiple ASICs, each with its own micro-optic structure bonded directly thereto. As another example, the micro-optical components can be formed as a separate monolithic structure that can be bonded directly to an ASIC after the ASIC is separated from a larger wafer via a dicing process. In this manner, the ASIC and micro-optic structure can be bonded together to form a single monolithic structure. 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.

[0101] As mentioned above, processor **336** and memory **338** (e.g., SRAM) can perform the signal processing. As an example of signal processing, for each photosensor or grouping of photosensors, memory **338** of light sensing module **330** can 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, processor **336** 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 ranging system controller **350** can also be integrated into the same ASIC as sensor array **332**, processor **336** and memory **338**, thereby eliminating the need for separate a ranging controller module.

[0102] In some embodiments, the output from processor **336** is sent to ranging system controller **350** for further processing. For example, the data can be encoded by one or more encoders of ranging system controller **350** and then sent as data packets via the optical downlink to lower circuit board assembly **360**. Ranging system controller **350** can be realized in multiple ways including, e.g., by using a pro-

grammable logic device such an FPGA, as an ASIC or part of an ASIC, using a processor **352** with a memory **354**, and some combination of the above. Ranging system controller **350** can cooperate with base controller **366** or operate independently of the base controller (via pre-programed instructions) to control light sensing module **330** by sending commands that include start and stop light detection and adjust photo-detector parameters. Similarly, ranging system controller **350** can control the light transmission module **340** by sending commands, or relaying commands from the base controller **366**, 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.

[0103] If emitter array **342** has multiple independent drive circuits, then there can be multiple on/off signals that can be properly sequenced by ranging system controller **350**. 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, ranging system controller **350** has one or more wired interfaces or connectors (e.g., traces on a circuit board) for exchanging data with light sensing module **330** and with light transmission module **340**. In other embodiments, 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.

III. Light Transmission and Detection

[0104] FIGS. **4**A and **4**B depict 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**A depicts a light ranging system **400** (e.g., solid state or and/or scanning) collecting three-dimensional distance data of a volume or scene **450** external to light ranging system **400**. FIG. **4**B is an enlarged view of light ranging system **400** from FIG. **4**A. Light ranging system **400** can be representative of any of light ranging systems **200**, **220** or **300** discussed above, as well as the various light ranging devices discussed below. FIGS. **4**A and **4**B are highly simplified drawings to highlight relationships between emitters and sensors, and thus other components are not shown.

[0105] As shown in FIGS. **4**A and **4**B, light ranging system **400** includes a light emitter array **410** and a light sensor array **420**. Light emitter array **410** includes an array of light emitters (e.g., an array of VCELs or the like) that includes individual emitters, such as emitter **410**(**1**) and emitter **410**(**9**). Light sensor array **420** includes an array of photosensors that includes individual photo sensors, such as sensors **420**(**1**) and **420**(**9**). The photosensors can be pixelated light sensors that employ, for each pixel, a set of discrete photodetectors such as single photon avalanche diodes (SPADs) or the like. However, various embodiments can deploy other types of photosensors. In some embodiments, 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 light emitter array **410** and/or the light sensor array **420** for redirecting the beams in the directions shown.

[0106] Each emitter can be slightly offset from its neighbor and can be configured 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 **410**(**1**) emits an illuminating beam **415**(**1**) (formed from one or more light pulses) into the circular field of view **452** (the size of which is exaggerated for the sake of clarity). Likewise, emitter **410**(**9**) emits an illuminating beam **415**(**9**) (also called an emitter channel) into the circular field of view **454**. While not shown in FIGS. **4**A and **4**B 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 (twenty one distinct fields of view in this example corresponding to the twenty one emitters, arranged in a 3×7 array, of light emitter array **410**).

[0107] 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 can 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 of view. Thus, in the example of FIGS. **4**A and **4**B, the system can sample twenty one 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.

[0108] 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.

[0109] In FIGS. **4**A and **4**B, 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.

[0110] 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 **410**(**1**) emits an illuminating beam **415**(**1**) into the circular field of view **452** and some of the illuminating beam reflects from the object **460** as reflected beam **425**(**1**). Ideally, reflected beam **425**(**1**) is detected by sensor **420**(**1**) only. Thus, emitter **410**(**1**) and sensor **420**(**1**) share the same field of view (i.e., field of view **452**) and form an emitter-sensor pair. Likewise, emitter **410**(**9**) and sensor **420**(**9**) form

an emitter-sensor pair, sharing field of view **454**. In some embodiments emitter array **410** and sensor array **420** are designed and configured (in conjunction with the bulk optics) such that the fields of view of each emitter-sensor pair are non-overlapping (beyond a threshold distance) with the fields of view of other emitter-sensor pairs.

[0111] While the emitter-sensor pairs are shown in FIGS. **4**A and **4**B 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.

[0112] 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 sensors 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.

[0113] 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.

IV. LIDAR Unit with Integrated Architecture

[0114] FIGS. **5**A-**5**B show a rotating LIDAR system **500** that employs a **360** scanning architecture, according to some embodiments of the disclosure. In some embodiments, LIDAR system **500** can spin in a clockwise or counter-clockwise direction to observe the surrounding field around a vehicle. System **500** can include a stationary base housing **502**, an optically transparent window **504**, and a stationary lid **506** for providing protection for the internal components of LIDAR system **500**. Window **504** can be made from a transparent material to allow for two-way transmission of near IR light. Stationary base housing **502**, window **504** and lid **506** make up a water-resistant or waterproof system housing or enclosure **508** that fully encloses internal components of LIDAR system **500** to protect the components from the elements. Housing/enclosure **508** can be representative, for example, of housing **220** discussed above with respect to FIG. **2**A. In some embodiments, the enclosure can have a generally cylindrical shape as shown in FIG. **5**A.

[0115] In some embodiments, window **504** can extend fully around a periphery of enclosure **508** and be attached to base housing **502** and lid **506** in a fixed relationship. In such embodiments, a light ranging device **510** (shown in FIG. **5**B), can rotate within enclosure **508** behind window **504**. In other embodiments, window **504** can rotate with light ranging device **510**. The configuration of base housing **502**, window **504** and stationary lid **506** shown in FIG. **5**A is just one example of an enclosure **508** according to embodiments of the disclosure. A person of skill in the art will recognize that other configurations of a suitable enclosure for LIDAR system **500** are possible. As one example of a different configuration, lid **506** can be part of window **504**. As another example, in embodiments where window **504** rotates with light ranging device **510**, window **504** can include two or more separate windows separated by an opaque region. For example, in some embodiments, LIDAR system **500** can include a first window aligned with an optical transmitter and a second window, spaced apart from the first window, aligned with an optical receiver. As used herein, "aligned" means that the optical transmitter or receiver transmits or receives light through the window.

[0116] The internal components (not shown in FIG. **5**A) of system **500** can include a rotary actuator and light ranging device, such as actuator **310** and light ranging device **320** described with respect to FIG. **3**. The light ranging device can be aligned with window **504** and can be spun by the rotary actuator to project pulsed beams of light through window **504** into a field surrounding LIDAR system **500** while the light ranging device is spinning continuously through 360 degrees in a clockwise or counter-clockwise direction. Light reflected from the field back through window **504** can then be detected by the light ranging device to determine distance to objects in the field as described herein.

[0117] As described in more detail below, rotating LIDAR system **500** can employ a highly integrated architecture and enables a highly compact configuration for the internal mechanical elements and circuitry. Accordingly, the overall form factor of LIDAR systems according to some embodiments of the disclosure can be smaller than many existing systems, for example, with an overall volume that is similar to or smaller than that of a coffee mug **550** as can be seen in FIG. **5**A.

[0118] FIG. **5**B shows an embodiment of LIDAR system **500** with the outer enclosure/system housing **508** (including window **504** and lid **506**) removed to highlight the integrated, stacked-board design according to some embodiments of the disclosure. As shown in FIG. **5**B, rotating LIDAR system **500** includes a light ranging device **510** that includes an optical transmitter **512** and an optical receiver **514** mounted within a housing **515** that includes a first housing portion **516** for the optical transmitter and a second housing portion **518** for the optical receiver. Light ranging device **510** is mechanically connected in a fixed relationship to a printed circuit board **522** that forms the rotating end of stacked board rotary actuator **520**. The fixed side of stacked board rotary actuator **520**, including printed circuit board **524**, is attached to base portion **502** of the enclosure.

[0119] 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 circuit boards stacked in a parallel arrangement, as shown in FIG. **5**B, e.g., circuit boards **522**, **524**, **526** and **528**. In some embodiments, the power system, electric motor, communication system, and LIDAR control system are all integrated into the one or more stacked planar circuit boards of the stacked board rotary actuator **520**. Light ranging device **510** can be conveniently attached to the top board **522** by way of one or more multi-pin connectors or the like (not shown). As will be detailed below, the boards can include a central aperture through which a central shaft passes. The upper boards can be attached to the upper portion of the shaft via one or more bearings. Each of the boards can be arranged with its planar surface perpendicular to the shaft and therefore the axis of rotation. As a result of this configuration, assembly and maintenance are much simpler relative to other systems that employ multiple boards in different orientations within the LIDAR system.

[0120] FIGS. **6**A-**6**C show cross-sectional views of LIDAR systems **600**, **650** and **660** in accordance with various embodiments of the disclosure. More specifically, the individual components shown in FIGS. **6**A-**6**C correspond generally to those already described above in reference to FIG. **3**, with the views shown FIGS. **6**A-**6**C providing examples of the geometric placement of the various circuit elements according to different embodiments. FIGS. **6**A and **6**B each show embodiments that employ optical communication between the upper and lower circuit board assemblies while FIG. **6**C shows an embodiment that employs inductive communication between the upper and lower circuit board assemblies. FIGS. **6**D-**6**E provide views of surfaces of the individual circuit boards according to some embodiments to further illustrate the concentric circumferential arrangement of a number of individual circuit elements.

[0121] Referring now to FIG. **6**A, LIDAR system **600**, which can be representative of LIDAR system **500**, can include a light ranging device **602** along with upper and lower circuit board assemblies **610** and **620**, respectively, in which upper board assembly **610** rotates with respect to lower board assembly **620** around an axis **605** that is perpendicular to the board assemblies. Circuit board assemblies **610** and **620** are each structural components of LIDAR system **600** that holding all or essentially all of the components of the LIDAR system. The two piece design enables system **600** to have reduced size and increased reliability compared to many currently available LIDAR systems and enables system **600** to be manufactured at a reduced cost.

[0122] Light ranging device **602** can be mounted to one of the circuit boards in upper board assembly **610** enabling the light ranging device to rotate with upper board assembly **610** while lower board assembly **620** can be mounted to base **604** and or sidewall **606**, each of which is a part of the stationary base of LIDAR system **600**. Rotation of upper circuit board assembly **610** and light ranging device **602** is enabled by a bearing system **607** located on a hollow shaft **606** centered along the longitudinal axis or rotation **605**.

[0123] Each of the assemblies **610**, **620** can include two or more stacked planar circuit boards arranged in a parallel relationship with each other. In the specific embodiment shown, upper assembly **610** includes a rotor communication board **612** and a rotor control board **614** while lower assembly **620** includes a stator communication board **622** and a stator control board **624**. An electric motor can be integrated directly on the board assemblies, along with an encoder, a wireless power system and optical communication system as described in more detail below. Many or all of these same elements are also integrated on the board assemblies of LIDAR systems **650** and **660** shown in FIGS. **6**B and **6**C, respectively. Thus, to simplify the description of the FIGS. **6**A-**6**C and avoid repetition, like reference numbers are used to indicate like elements and the description of such like elements is typically not repeated.

[0124] The highly integrated, stacked board design of LIDAR system **600** provides for a system that has a greatly simplified assembly process in comparison to systems that employ numerous stand-alone modules for each of the different functional elements of a LIDAR system. In alternative embodiments, LIDAR systems of the present disclosure can include upper and lower board assemblies that are each a single circuit board even further simplifying the stacked board design. For example, LIDAR system **650** shown in FIG. **6**B includes a single lower circuit board **652** and a single upper circuit board **654**.

[0125] While not shown explicitly in FIGS. **6**A-**6**C, one or more supporting power circuits, drive/control circuits, and communication circuits can be paired with each of the systems discussed below and these supporting systems can also be 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 **620**. 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., can also be mounted to one or more boards of the circuit board assemblies. Some of these elements will be discussed in further detail below but one or 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.

V. Optical Links

[0126] 1. Integrated Central Optical Downlink

[0127] In some embodiments, hollow shaft **606** 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 **620** (also referred to as the base system). The optical downlink channel can include an optical downlink transmitter **626** and an optical downlink receiver **628** each of which can be centered along rotational axis **605**. Optical downlink transmitter **626** can be attached (e.g., soldered) directly to a surface of a circuit board of upper circuit board assembly **610** and can be positioned such that it can transmit optical signals through a central hole or opening in the

hollow shaft **606**. Likewise, the optical downlink receiver **628** can be attached (e.g., soldered) directly to a surface of a circuit board of the lower circuit board assembly **620**. The optical downlink receiver **628** can be positioned on the lower end of the shaft and aligned with the optical downlink transmitter **626** such that it is able to receive optical signals transmitted from the optical downlink transmitter **626**.

[0128] The optical transmitters and receivers used for the optical downlink of the rotary actuator can be any suitable optical emitter or detector. For example IR LEDs, laser diodes, VCSELs, and the like can be used for the optical emitters. Likewise any suitable light detection technology can be used for the receivers, such as, photodiodes or the like.

[0129] 2. Integrated Optical Uplink

[0130] An optical uplink channel can be formed between a circumferential arrangement of multiple optical uplink transmitters **642** and a complementary circumferential arrangement of multiple optical uplink receivers **632**. 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 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 **606** provides for optical isolation between the uplink and downlink channels and therefore minimizes crosstalk.

[0131] The individual emitter and receivers of the circumferential arrangements can be coupled together to act together as a single composite receiver and a single composite transmitter. For example, as the system rotates, the overall optical intensity of 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 transmitters in the composite transmitter can be the same as or different from the number of individual receivers in the composite receiver.

[0132] The optical transmitters and receivers used for the optical uplink of the rotary actuator can be any suitable type of optical emitter or detector. For example, a ring of IR LEDs, laser diodes, VCSELs, or the like can be used as the composite optical transmitter. Likewise any suitable type of light detection technology can be used for the receivers, e.g., a ring of photodiodes or the like can be used as the composite optical receiver. 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.

[0133] An example of a circumferential arrangement of optical uplink transmitters **642** is shown in FIG. **6**D, which illustrates a top view of a stationary circuit board (e.g., circuit board **622** of FIG. **6**A). In this example, there are six (6) optical uplink transmitters **642** that are circumferentially arranged around the central hole **672**. The six (6) transmitters are evenly spaced around the circle **674** whose center is located at the center of the shaft (and thus the center of hole **672**) and therefore overlapped with the axis of rotation.

[0134] The opposing surface of the rotating circuit board (e.g., circuit board **612** of FIG. **6**A or circuit board **654** of FIG. **6**B) includes a corresponding circumferential arrangement of optical uplink receivers **632**, as shown in FIG. **6**E, which illustrates a bottom view of a rotating circuit board according to some embodiments. In this example, there are seven (7) optical uplink receivers that are circumferentially arranged around the central hole **672**. The seven (7) receivers are evenly spaced around the circle **684** whose center is located at center of the shaft and therefore overlapped with the axis of rotation. Accordingly, as the board rotates, the arrangement of optical uplink receivers **632** rotates about the axis of rotation. Because the radius of circle **684** is same as the radius of circle **674**, 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 is 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.

[0135] While FIGS. **6**D and **6**E depict an embodiment in which an optical downlink channel is formed within hollow shaft **606** and an optical uplink channel is formed between a circumferential arrangement of multiple optical uplink transmitters and a complementary circumferential arrangement of multiple optical uplink receivers disposed outside the shaft, in other embodiments other arrangements of optical channels are possible. For example, in some embodiments an uplink channel can be formed within hollow shaft **606** and a downlink channel can be formed outside the shaft. In still other arrangements both a downlink and an uplink channel can be formed inside shaft **606** (e.g., using separate light guides) or both a downlink channel and an uplink channel can be formed outside the shaft in separate circumferential arrangements of optical components.

VI. Inductive Communication Links

[0136] Referring back to FIG. **6**C, FIG. **6**C shows an embodiment that employs an inductive communications system **666**, **668** between the upper and lower circuit board assemblies. In this example, data uplink and downlink are provided by pairs of coils **666***a-e* and **668***a-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 **666** and lower coil housing **668** 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 **666***b* and downlink channel **1** receiver coil **668***b*, downlink channel **2** transmitter coil **666***c* and downlink channel **2** receiver coil **668***c*. In some embodiments, the downlink clock signal can be transmitted via a separate coil pair, e.g., downlink clock transmit coil **666***a* and downlink clock receiver coil **668***a*. Likewise, data uplink channels can be formed from one or more pairs of coils, e.g., by uplink transmitter coil **668***d* and uplink receiver could **666***d*. 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 **668***e* and uplink clock receiver coil **666***e*.

[0137] 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 **606** with a solid shaft **665** 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 the lower board assembly (stator) and upper board assembly/light ranging unit (rotor).

[0138] While FIG. **6**C 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 channel 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 channels can be employed without departing from the scope of the present disclosure.

VII. Integrated Electric Motor

[0139] According to certain embodiments, an electric rotary motor can be integrated directly onto the circuit boards. The motor can have 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 can be integrated onto the boards of the rotary actuator **608**, 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 LIDAR system **600**. For example, referring back to FIG. **6**D, stator assembly **644** can include an annular arrangement of multiple stator elements **644**(*i*), 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 **620** (e.g., board **622**) or to a soft magnetic core that is then affixed to the lower circuit board assembly **620**. Examples of the stator elements are shown in the top view of FIG. **6**D. Each stator element **644**(*i*) can include a solenoid coil **644***a* wound around a core **644***b* 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. In the embodiment shown in FIG. **6**D, stator assembly **644** includes eighteen (18) individual stator elements **644**(*i*) evenly spaced apart from each other, but embodiments of the disclosure are not limited to a stator assembly with any particular number of stator elements and other embodiments can include fewer or more individual stator elements **644**(*i*). For example, in some embodiments stator assembly **644** includes at least 12 individual stator elements **644**(*i*) in an annular arrangement. Also, in some embodiments, the number of individual stator elements **644**(*i*) in stator assembly **644** is a multiple of three and a motor driver circuit and controller (not shown in FIG. **6**D) provide a three-phase alternating signal to stator assembly **644** to control the rotation rate of board **622** and thus the rotation rate of light ranging device **602**.

[0140] Positioned directly opposite the motor stator assembly **644** and attached to a board of the upper circuit board assembly **610** is the motor rotor assembly **634**. In some embodiments, motor rotor assembly **634** can be a passive element that includes an annular arrangement of permanent magnets **634**(*i*), 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. **6**E. Thus, as shown in FIG. **6**E, each individual magnet **634***a* can have its poles arranged opposite to its adjacent magnets **634***b*, and each individual magnet **634***b* can have its poles arranged opposite to its adjacent magnets **634***a*. Additionally, while the embodiment of the stator assembly **644** shown in FIG. **6**E includes twenty four (24) individual magnets **634**(*i*) evenly spaced apart from each other, embodiments of the disclosure are not limited to a rotor assembly with any particular number of elements and other embodiments can include fewer or more individual magnets **634**(*i*). Further, as can be seen in FIGS. **6**D and **6**E, the motor stator assembly **644** and the motor rotor assembly **634** 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).

[0141] While the embodiments shown in FIGS. **6**D and **6**E 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 brushless DC motor can be employed, for example, 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.

VIII. Integrated Wireless Power Transmission System

[0142] To provide power to the circuit elements connected to the rotating upper circuit board assembly **610**, the rotary actuator **608** includes a wireless power system, also referred to herein as a rotary transformer. The wireless power system includes a wireless power transmission subsystem including a wireless power transmitter **648** and a wireless power receiving subsystem including a wireless power receiver

638. The wireless power transmitter **648** can be a transmitter coil in the form of a circular loop antenna (e.g., a single turn or multi-turn coil) that is attached to a surface of a circuit board of the lower circuit board assembly **620** (e.g., board **622**) as shown, for example, in FIG. **6**D. Likewise, the wireless power receiver **638** can be a receiver coil in the form of a circular loop antenna (e.g., a single turn or multi-turn coil) that is attached to a surface of a circuit board of the upper circuit board assembly **610** (e.g., board **612**) as shown in FIG. **6**E. The centers of both the wireless power transmitter **648** and the wireless power receiver **638** are positioned at the center of the hollow shaft **606** 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 can be positioned at the outermost region of the boards **622** and **612** to maximize the area (and therefore inductance) of the circular loops which maximizes power transfer efficiency and advantageously blocks light from the environment or the internals of the LIDAR system from reaching the optical encoder, uplink or downlink.

[0143] In some embodiments, the wireless power transmitter **648** and a wireless power receiver **638** 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. **6**E shows wireless power receiver **638** disposed within an annular region formed from ferrite walls **686** and **688** (not shown in FIGS. **6**A-**6**C) and an occluded ferrite bottom. Such an arrangement of ferrite materials is depicted in FIG. **6**F, which is a simplified cross-sectional view of a portion of a multi-coil wireless power receiver **638** positioned within an annular channel defined by ferrite walls **686**, **688** and a bottom ferrite wall **690**. The arrangement shown in FIG. **6**F helps channel the magnetic fields between the transmitter and receiver to improve power transfer efficiency and reduce electromagnetic radiation leaking from the system.

IX. Integrated Optical Encoder

[0144] The rotary actuator **608** further includes an integrated optical encoder assembly that allows for readout of the angular position of the upper circuit board assembly **610** relative to the lower circuit board assembly **620**. The optical encoder assembly includes a patterned annular optical encoder **646** and rotary encoder detector **636** for reading off the angular position of the assembly by, for example, detecting and counting the number of patterns that pass the rotary encoder detector **636** as the system rotates. In certain embodiments, rotary encoder detector **636** 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 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.

[0145] In some embodiments, the annular optical encoder **646** can be attached to a surface of a circuit board of the lower circuit board assembly **620** (e.g., board **622**) and the rotary encoder detector **636** can be attached to a surface of the upper circuit board assembly **610** (e.g., board **612**) as shown here, or vice versa. Regardless of which board it is placed on, the annular optical encoder **646** can be arranged to have its center at the center of the hollow shaft **606** and is therefore concentric with both the electric motor assemblies and the optical uplink receiver/transmitters as shown, for example, in FIG. **6**D. In some embodiments, the rotary encoder detector **636** is positioned on the rotating circuit board, anywhere above the annular optical encoder **646**, e.g., as shown in FIG. **6**E.

[0146] Advantageously, the encoder assembly can be 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. **6**A, in some embodiments the annular optical encoder **646** can be on the stator side of the rotary actuator **606** while the rotary encoder detector **636** 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 **636** and the light ranging device **602** 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 **636** and correlating the current ranging information with the current angular position of the rotor for increased spatial accuracy.

X. Method of Assembly

[0147] 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.

[0148] 1. Assembling the Lower Circuit Board Assembly

[0149] FIG. **7** shows an exploded view of a lower circuit board assembly **700** to illustrate an assembly process of the compact LIDAR system according to certain embodiments. In the embodiment shown in FIG. **7**, lower circuit board assembly **700** is of a two-board configuration, similar to that described above in reference to FIG. **6**A. Specifically, lower circuit board assembly **700** includes first and second subboards, referred to herein as the base control board **720** and the stator board **730**. In some embodiments, base control board **720** and stator board **730** correspond to boards **643** and board **641**, respectively, as shown in FIG. **6**A.

[0150] The assembly of lower circuit board assembly **700** can begin with base control board **720** being mechanically attached to a base housing unit **710** by way of screws **728**. As already described above in reference to FIGS. **3** and **6**A, the base control board can include a number of circuit elements, including a base controller, similar to base controller **366**. 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 **722** can be mounted to (e.g., soldered to) an

upper surface of base control board **720** in a central region of the board as described above in reference to FIG. **6**A.

[0151] In some embodiments (e.g., as described above in reference to FIG. **6**B), optical downlink receiver **722** and the other supporting circuit elements are integrated directly onto stator board **730** thereby eliminating the need for a separate base control board **720**. In such a case, assembly of lower circuit board assembly **700** can begin by attaching a heat spreading element **725** directly to the base **710** or in cases that do not employ the base or heat spreading element **725**, the assembly can begin by installing stator board **730**.

[0152] After base control board **720** is attached to base **710**, shaft **715** can be attached to base control board **720**, using screws **706**. In some embodiments, shaft **715** can be attached directly to base **710** for improved thermal conduction of heat from the upper circuit board assembly to the base **710** via the bearing system (shown in more detail in FIGS. **8**A and **8**B below). As described above in reference to FIGS. **6**A-**6**B, shaft **715** can include a central hole **716** through its length that provides an open optical path for an optical downlink channel. As such, shaft **715** can be placed directly on top of optical downlink receiver **722** located generally near the center of base **710**. In some embodiments, regardless of the shape of the outer circumference of base control board **712** or base **710**, shaft **715** defines the axis of rotation **705** of the system. Thus, the position of shaft **715** need not be directly in the center of base control board **720** or in the center of base **710**.

[0153] After shaft **715** is attached to base control board **710**, heat spreading element **725** can be attached to base control board **720** by one or more screws **716**. In some embodiments, heat spreading element **725** 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 **725** and the boards to prevent electrical shorts while providing a conductive heat path. In some embodiments, heat spreading element **725** makes thermal contact with one or more portions of the lower surface of stator board **730** and one or more portions of the upper surface of base control board **720** 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 **725** may also make thermal contact with the sides of base **710** and thus provide an improved thermal path for heat to be conducted from the boards to base **710** and eventually out of the system.

[0154] After securing heat spreading element **725**, stator board **730** can be attached by way of screws **736**. In some embodiments, stator board **730** can be electrically connected to base control board **720** by way of one or more multi-pin electrical connectors (e.g., lower connectors **724** and **726**). In some embodiments, the physical connection between the boards is made by applying a mechanical connection pressure between stator board **730** and base control board **720** (e.g., by pressing the stator board onto the base control board after it has been attached to base **710**). The connection pressure can be maintained over the life of the system by screws **736** used to secure stator board **730** to base control board **720**.

[0155] Once assembled and secured to the base **710**, one or more optional color cameras **732** can be positioned around the periphery of stator board **730** to have a clear visual path out of base **710** through one or more imaging apertures **712**, 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 **732** can be mounted directly to base **710** rather than be mounted to stator board **730**. Color cameras **732** enable LIDAR data that is accumulated by the LIDAR system to be supplemented by color imaging data such as still frames and/or video as described in U.S. application Ser. No. 15/980,509 entitled "Augmenting Panoramic LIDAR Results with Color," which is incorporated herein by reference in its entirety for all purposes.

[0156] 2. Assembling the Upper Circuit Board Assembly and Attaching to the Lower Circuit Board Assembly

[0157] FIG. **8**A is an exploded view of a compact LIDAR system **800** to illustrate an assembly process of a LIDAR system according to some embodiments of the disclosure. LIDAR system **800** can be, for example, LIDAR system **500** shown in FIG. **5**A. LIDAR system **800** includes lower circuit board assembly **700**, described above with respect to FIG. **7**, an upper circuit board assembly **810**, a light ranging device **820**, and an enclosure **830**. As shown in FIG. **8**A, LIDAR system **800** includes an upper circuit board assembly **8** that.

[0158] As shown in FIG. **8**A, upper circuit board assembly **810** is of a two-board configuration, similar to that described above in reference to FIG. **6**A and includes a ranging device control board **840** and the rotor board **850**. In some embodiments, ranging device control board **850** and rotor board **730** correspond to stator control board **624** and rotor control board **614**, respectively described above in reference to FIG. **6**A.

[0159] Rotor board **850** includes a bearing assembly **860**, shown in FIG. **8**B, which is an exploded view of rotor board **850**. Bearing assembly **860** includes bearings **862** and **864**, which are inserted into either end of a t-shaped bearing housing **865**. T-shaped bearing housing **865** can then attached to rotor board **850** with screws **866**.

[0160] Rotor board **850** can be placed on top of assembled lower circuit board assembly **700** by fitting the central portion of T-shaped bearing housing **865** over shaft **715**. A circular nut **852** can then be fitted into a circular central recess **854** in the top surface of the t-shaped bearing housing **86** and threaded onto the top of shaft **715** to securely attach rotor board **850** to lower circuit board assembly **700**. As discussed above, rotor board **850** is able to rotate relative to lower circuit board assembly **700** due to the rotational coupling made between shaft **715** and bearings **862** and **864**.

[0161] Ranging device control board **840** can then be joined to rotor board **850** by applying a downward pressure to the ranging device control board **840**. To provide an electrical connection between ranging device control board **840** and rotor board **850**, one or more electrical connectors can be attached to (e.g., soldered to) the lower surface of ranging device control board **840** (not visible in FIG. **8**A) and the upper surface of rotor board **850** (e.g., connector **856**). Ranging device control board **840** can then be secured to rotor board **850** using screws **846**.

[0162] 3. Attaching the Laser Ranging Device to the Rotary Actuator

[0163] Once the upper circuit board assembly has been assembled and secured to the lower circuit board assembly, light ranging device **820** can be electrically connected to the upper surface of ranging device control board **840**, which mechanically connects the light ranging device to T-shape

bearing housing **865**. Light ranging device **820** includes a Tx module **822** and a Rx module **824** each of which can have dedicated electrical connectors that mate with corresponding connectors **844** and **846** disposed on the upper surface of light ranging device control board **840**. As with the other boards in the system, connecting the light ranging device **820** 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 can be maintained by screws **826** mounted on either side of light ranging device **820** as shown. In addition, a u-shaped bracket **828** can secured to light ranging device **820** with additional screws **826** to provide further structure to the assembly.

[0164] Once all the internal components are assembled, enclosure **830** can be dropped over the entire assembly and affixed to base **700**, e.g., using one or more screws as well as adhesive, if required to achieve a more robust seal. Enclosure **830** can include an optically transparent window as described above with respect to FIG. **5** that enables laser pulses from Tx module **822** to be projected from the LIDAR system into the surrounding environment and enables reflected and scattered light from the pulses to be received by the LIDAR system via Rx module **824**.

[0165] 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.

XI. Optics and Optoelectronics

[0166] 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** can correspond to embodiments described above in reference to FIGS. **1-6**, e.g., light ranging device **320** described above in reference to FIG. **3** or light ranging device **510** described with respect to FIG. **5**. Light ranging device **900** includes two main modules: a light transmission (Tx) module **910** and a light sensing (Rx) module **920** spaced apart from each other within a common housing or mount **905** that includes two lens tubes, e.g., transmitter lens tube **912** and detector lens tube **922**. The light Tx module and light Rx modules each include bulk optics modules (not shown) that are positioned in front of their respective sensors/emitters, e.g., by sliding the bulk optics module into the appropriate lens tube. 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 **914**, e.g., a monolithic single-chip NIR VSCEL 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 **924**, e.g., a monolithic single-chip NIR SPAD array fabricated on a CMOS process, or the like.

[0167] Both Rx module **920** and Tx module **910** are backed by circuit boards **926** and **916**, 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 **926** 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 **926** 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 **920**.

[0168] 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 1 Hz to 30 Hz, taking range measurements at fixed angular intervals. In one embodiment, for any given full rotation ("frame"), a 64×2048 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.

[0169] 1. Optical Systems for the Tx and Rx Modules

[0170] FIG. **10** shows an optical block diagram of a light ranging device **1000** according to some embodiments of the disclosure. As shown in FIG. **10**, light ranging device **1000** includes a light transmission (Tx) module **1010** and a light sensing (Rx) module **1040**. Light transmission module **1010** can be representative of Tx module **910** while light sensing module **1040** can be representative of Rx module **920**. Embodiments of the disclosure are not limited to the specific optical configurations shown in FIG. **10**. In other embodiments, light transmission module **1010** and light sensing module **1040** can include fewer, more or different optical components. Non-limiting examples of other configurations for light transmission module **1010** and light sensing module **1040** are set forth in U.S. application Ser. No. 15/979,235 entitled "Optical Imaging Transmitter with Brightness Enhancement," filed on May 14, 2018, and U.S. application Ser. No. 15/979,266 entitled "Spinning LIDAR Unit with Micro-optics Aligned behind Stationary Window," filed on May 14, 2018, the disclosures of each of which are incorporated herein by reference in their entirety for all purposes.

[0171] Embodiments of the light ranging device **1000** can be employed within the compact LIDAR system disclosed herein as described above in reference to, e.g., FIGS. **5A-5B**. The Tx module **1010** provides active illumination of objects in the area around the LIDAR system by, e.g., transmitting pulses of narrow band light, e.g., NIR light having a spectral width of, e.g., 2 nm, 1 nm, 0.5 nm, 0.25 nm or less, into one or more fields of view, as shown in FIGS. **1A-1B** and **4** above. The Rx module **1040** detects reflected portions of the transmitted narrowband light that is reflected by the objects in the scene.

[0172] As shown in FIG. **10**, Tx module **1010** can include a TX-side micro-optics package **1020** and a bulk optical element **1030**. The TX-side micro-optics package **1020** includes a plurality of light emitters **1022**, and optionally includes a micro-lens layer **1024** and an aperture layer **1026**.

Emitters **1022** can be arranged in a one or two-dimensional array of transmitter channels, e.g., channel **1025** shown in the boxed region. Each one of the transmitter channels has one or more light emitters **1022**, e.g., NIR VCSELs or the like, capable of emitting narrowband light, and optionally, a micro-lens from lens layer **1024** and an aperture from aperture layer **1026**.

[0173] Light emitted from each one of the transmitters diverges as it approaches one of the micro-optics of the Tx-side micro-optic lens layer **1024**. Micro-lenses from micro-lens layer **1024** capture the diverging light and refocus it to a focal plane that is coincident with apertures in aperture layer **1026** that includes an array of apertures that correspond in position to the array of micro-optics and the array of emitters. Aperture array **1026** can 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 **1030**. Details of the Tx-side bulk imaging optics module **1030** are discussed in more detail below.

[0174] In some embodiments, the separation between the micro-lens layer **1024** and the Tx-side bulk imaging optics module **1030** is equal to the sum of their focal lengths, such that light focused at the aperture array **1026** appears as collimated light at the output of the Tx-side bulk imaging optics module **1030** with each collimated bundle of rays exiting the Tx-side bulk imaging optics module **1030** 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 **1030** 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 **1030** 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. In this configuration the VCSEL array advantageously 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. Without the telecentric design, light captured by the outer emitters may be reduced, scattered or refracted in an undesirable manner because of their highly oblique angle of incidence.

[0175] The Rx module **1040** includes an Rx-side bulk imaging optics module **1060** and an RX-side micro-optics package **1050**. The RX-side micro-optics package **1050** has either a one or two-dimensional array arrangement that matches the TX-side micro-optics package **1020**, with a micro-optic receiver channel **1055** for each corresponding micro-optic transmitter channel **1025**. The RX-side micro-optics package **1050** includes an Rx-side aperture array layer **1056**, an Rx-side micro-optics lens layer **1054**, a narrow band optical filter layer **1028** and a sensor array layer **1052**. The portions of the emitted light that reflect off of objects in the field, shown as light rays **1005**, enter the Rx-side bulk imaging optics module **1060** from multiple directions. The Rx-side bulk imaging optics module **1060** focuses light rays at a plane that is coincident with the Rx-side aperture array layer **1056**. The focused light then is captured by the micro-lenses of the Rx-side micro-optics lens layer **1054** and directed to a sensor array layer **1052** in a collimated fashion (i.e. having a divergence half angle of less than ten degrees).

[0176] In some embodiments, the sensor array layer **1052** 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.

[0177] In some embodiments, to remove spurious background light, a narrow band optical filter layer **1028** can be disposed within the layered structure, e.g. between the micro-optics array and the sensor array layer **1052**. The pass band of the narrow band optical filter layer **1028** 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 **1028** 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 **1056**, the focal lengths of the lenses in RX-side micro-optic lens layer **1054**, the relative positioning between RX-side aperture array layer **1056** and RX-side micro-optic lens layer **1054**, and surface quality and form precision of RX-side micro-optic lens layer **1054**. In some embodiments the narrow band optical filter layer **1028** is continuous planar layer across the entire array of sensors. In other embodiments, the narrow band optical filter layer **1028** can be fabricated as an array of micro-optical elements that correspond with the pixel geometry of the sensor array layer **1052**.

[0178] As with the Tx side, the individual elements of the Rx module **1040** form micro-optic receiver channels, e.g., receiver channel **1055**. According to certain embodiments, the array of micro-optics and receivers can have a layered monolithic structure. Each micro-optic receiver channel **1055** measures light for a different pixel in the sensor array layer **1052**, i.e., the optics of the Rx module **1040** serve to map bundles of parallel rays entering the module from different angles to different corresponding spatial positions on the sensor array layer **1052**. In some embodiments, the bulk imaging optics module **1060** 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.

[0179] In some embodiments, the micro-optic receiver channels as formed by the cooperation between the micro-optic lens layer **1054**, narrow band optical filter layer **1028**, and Rx-side aperture array layer **1056** 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 arrange-

ment 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.

[0180] The design of the micro-optical systems for the Rx module **1040** and the Tx module **1010** advantageously enable the conceptual LIDAR arrangement described above in reference to FIG. **3** 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 eliminates 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.

[0181] 2. Micro-Optics

[0182] FIG. **11**A shows a simplified top view of a micro-optics package **1100** according to certain embodiments. Micro-optics package **1100** can be applied on either or both the transmitter or detector side of the light ranging device and includes a plurality of channels **1102**. For example if implemented on the receiver side, each channel **1102** would correspond to a single micro optical receiver channel, such as channel **1055**. Similarly, if implemented on the transmitter side, each channel **1102** would correspond to a single transmitter channel, such as channel **1025**. In the example shown in FIG. **11**A, the micro-optical channels are laid out as an m×n staggered array, e.g., laid out in 16×4 array. As an example, if FIG. **11**A represents receiver channels, for a receiver channel size of 0.500 mm (diameter) the layout illustrated can be implemented in a chip of size 8.000 mm by 2.000 mm.

[0183] 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×1), a warped linear (m×1) array, a warped rectangular m×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).

[0184] FIG. **11**B shows a cross-section of a single micro-optic receiver channel **1120** according to some embodiments that can be representative of, for example, receiver channel **1055** shown in FIG. **10**. Receiver channel **1120** 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 allows a pixel (photosensor) **1171** to detect only or substantially only photons within the aforementioned narrow band of wavelengths. Embodiments of the disclosure are not limited to any particular configuration for receiver channels and channel **1120** is just one example of a receiver channel that can be implemented as receiver channel **1055**.

[0185] 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**. Aperture **1144** is configured to define a narrow field of view when placed at the focal plane of an imaging optic, such as bulk receiving optic **1060**. 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. In some embodiments, aperture layer **1140** can be formed from a optically non-transparent material that forms stop regions **1146** and apertures **1144** can be holes or openings in layer **1140**.

[0186] In some embodiments, the receiver channel **1120** includes an optical lens layer **1150** including a collimating lens **1151** characterized by a focal length. The collimating lens can be offset from the plane of 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). In this manner the collimating lens can be 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.

[0187] 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.

[0188] In some embodiments, receiver channel **1132** includes a photosensor layer **1170** including a pixel **1171** disposed behind the filter layer. The pixel can be a photosensor capable of detecting photons with a detector active area made of, e.g., a standard photodiode, an avalanche photodiode, an array of SPADs, RCPs (Resonant Cavity Photo-diodes), or other suitable photodetectors. Photosensor **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. Photosensor layer **1170** refers to a layer made of pixels and can include optional structures to improve detection efficiency and reduce cross talk with neighboring receiver structures. Photosensor layer **1170** may optionally include diffusers, converging lenses,

apertures, optically-non-transparent tube spacer structures, optically-non-transparent conical spacer structures, etc.

[0189] 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 can 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 **1120** may also feature several structures to reduce crosstalk and increase signal between receiver channels. Examples of such structures and other suitable receiver channels are described in U.S. patent application Ser. No. 15/979,295 entitled "Micro-optics for Imaging Module with Multiple Converging Lenses per Channel," filed on May 14, 2018, the disclosure of which is hereby incorporated by reference in its entirety for all purposes.

[0190] 3. Detector Array (e.g., SPADs)

[0191] FIGS. **12**A and **12**B show a top view of a SPAD-based photosensor array layer **1200** according to certain embodiments. Photosensor array layer **1200** shown in FIG. **12**A is a two-dimensional array of sensor channels **1210** where each individual sensor channel can correspond, for example, to receiver channel **1055**. Thus, each sensor channel **1210** can include a group of SPADs as described above. In the example shown in FIG. **12**A, photosensor array **1200** is an 18×4 array that includes a total of 72 individual sensor channels **1210**. Photosensor array **1200** also includes 8 calibration pixels **1220** at the top of the array. Calibration pixels **1220** can be, for example, covered by an opaque surface such that they are not exposed to any light and therefore can be used to measure dark counts.

[0192] FIG. **12**B shows a magnified view of a subset of sensor channels **1210** illustrating that each sensor channel **1210** can be formed from a group (array) of individual SPADs **1212** 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 operates to 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. That is, a single SPAD cannot detect a light intensity that is greater than one photon per quench time. Collecting multiple SPADs together as shown in FIG. **12**B 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 with N-times the dynamic range of a single SPAD.

[0193] 4. Emitter Array (e.g., VCSELs)

[0194] FIGS. **13**A and **13**B depict simplified top and side views, respectively, of an emitter array **1300** according to certain embodiments. The emitter array **1300** can include a two-dimensional array of VCSEL emitters **1310** that are fabricated on a single monolithic chip **1305** and whose pattern matches the photosensors pixels on a corresponding sensor chip. In this example, emitter array **1300** VCSEL array is 16×4 for a total of 64 emitter channels **1310** to match the middle **64** detector channels shown in FIG. **12**A above. Emitter array **1300** can also include a plurality of leads **1320** over which signals to drive the various emitters in array **1300** can be transmitted to the emitters.

[0195] As was described in reference to FIG. **12**A, the monolithic VCSEL array of optical emitters can be arranged behind the TX-side micro-optics package and behind the TX-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.

[0196] 5. Bulk Optics

[0197] In some embodiments, the present disclosure provides a telecentric light ranging device having a fast lens system (e.g., f-number=1.0, 1.2, or 1.4) and/or a lens system that is passively athermal over a specified temperature range that is likely to be encountered when the light ranging device is used for obstacle detection and avoidance in autonomous navigation for automobiles, trucks or other vehicles. In addition, the bulk optical system possesses a low focal plane distortion and one or 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.

[0198] As used herein, 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. As used herein, spot quality can be defined by a fraction of light from an extended source with angular size of 0.13 degrees that is 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.

[0199] FIG. **14** depicts a simplified schematic of a portion of an optical module **1400** that provides a thermally stable image plane over a wide range of temperatures according to some embodiments. Optical module **1400** includes an array **1410**, a bulk lens system **1420**, a lens housing **1430**, and a mount **1440** to mechanically couple the housing with the array. Optical module **1400** can be representative of an embodiment of light sensing module **330** (in which case array **1410** can be an array of photosensors) or an embodiment of light emitting module **340** (in which case array **1410** can be an array of emitters), and in some embodiments mount **1440** can representative of a portion of mount **905** shown in FIG. **9**. A light ranging device according to some embodiments of the disclosure can include a first optical

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module **1400** as a light sensing module and a second module **1400** as a light emitting module.

[0200] Array **1410** can be planar (e.g., having irregularity from a perfect plane less than 1 mm peak-to-valley over a 10 mm diameter disc) for ease in manufacturing (e.g., forming arrays in bulk on a semiconductor substrate, wherein there are a plurality of emitters or detectors in one array). In some embodiments, array **1410** can include a micro-optics structure, such as transmitter micro-optics package **1020** or receiver micro-optics package **1050** discussed above with respect to FIG. **10** depending on optical module **1400** is implemented as a light sensing module or as a light emitting module.

[0201] As shown in FIG. **14**, lens system **1420** can include a first lens **1422**, a second lens **1424**, a third lens **1426**, and a fourth lens **1428**. In some embodiments, the first lens, the second lens, the third lens, and the fourth lens are mounted in the lens housing **1430**. When implemented as part of an imager sensor (i.e., array **1410** is an array of photosensors), lens housing **1430**, lens system **1420**, and mount **1440** are configured to passively focus light from the lens system to the photosensor 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). In embodiments that include a micro-optics structure in the array, the lens system **1420** is configured to passively focus light from the lens system to the aperture layer of the micro-optics structure and the various micro-optic components in the micro-optic structure can then focus light received at each individual micro-optic channel to the corresponding photosensor for that channel.

[0202] The array can be kept at the image plane of the lens system for varying temperatures. Materials can be chosen to reduce cost, reduce weight, and/or maintain the image plane at the array. To reduce costs, first lens **1422**, second lens **1424**, the forth lens **1428** can be made of plastic (e.g., OKP-1), while third lens **1426** 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 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 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.

[0203] Lens housing **1430** (e.g., made of polycarbonate) can elongate as temperature increases. In some embodiments, mount **1440** attaches to lens housing **1430** near third lens **1426**, so that fourth lens **1428** moves to the right as temperature of the housing increases. Material of mount **1440**, which separates lens housing **1430** from array **1410**, expands with increasing temperature, moving lens housing **1430** away (e.g., left) from array **1410**. Simultaneously, lens housing **1430** expands with increasing temperature moving the fourth lens **1428** toward (e.g., right) array **1410**. Also simultaneously, the back focal 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.

[0204] In some embodiments, mount **1440** can be coupled with lens housing **1430** near the glass lens (i.e., third lens **1426** in some embodiments). In some embodiments, mount **1440** can be coupled with lens housing **1430** near the glass lens so that a lens of lens system **1410** nearest array **1410** (e.g., fourth lens **1428**) can move in relation to array **1410** (e.g., toward the array) as the focal length of lens system **1420** moves in relation to array **1410** (e.g., away from the array). In some embodiments, near can be a point or line on the outside of lens housing **1430**, nearest the glass lens, and/or or within +/−5 mm or +/−10 mm from the point or line.

[0205] The spot quality of the lens system in FIG. **14** was experimentally verified for a temperature range from −5 degrees C. to 70 degrees C. using the Zemax optical design program. In some embodiments, the inside of the LIDAR unit can be deliberately heated when the environment gets below a specific temperature. For example, when the environment is −40 degrees C., internal components of the LIDAR unit can be heated to keep the lens system at a temperature of −5 degrees C. or higher. In some embodiments a light ranging device can include a temperature sensor and a heating element (e.g., a resistive heater) that can heat the lens system when the temperature drops below a predetermined level as detected by the temperature sensor. Accordingly, system **1400** can be expected to perform well from at least temperatures ranging from −40 degrees C. to 70 degrees C. (a temperature range of 100 degrees). In various embodiments, system **1400** can provide a stable image plane over temperature ranging 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.; from −40 degrees C. to 85 degrees C.; and combinations thereof. In some embodiments, the temperature range can be from −40 degrees C. to 105 degrees C. (a temperature range of 145 degrees).

[0206] It can be often desirable to make lens housing **1430** 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 increases. In some embodiments, the material CTE of lens housing **1430** is not changed/tuned substantially to prevent reduction in optical performance. Thus, the lens 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 sufficiently different from CTEs of lenses that stress in the lenses will occur, which can result in degradation of optical performance of the lenses.

[0207] The CTE of lens housing **1430** can be matched, over a temperature range, with lens system **1420** so that a focal plane of lens system **1420** is stable relative to lens housing **1430** over the temperature range. In some embodi-

ments, a thermal coefficient of mount **1440** is matched with lens system **1420** and/or with thermal expansion of lens housing **1430** so that the focal plane is stable relative to a position of the detector (e.g., detector array) over the temperature range. As used herein, a focal plane is said to be "stable" over a range of temperatures if the focal plane maintains a predetermined resolution at the detector for the system over the given temperature range. As an example, in some embodiments a predetermined resolution requires light focused to a point at the detector to have 50% of the light in a 25 micron circle, in other embodiments a predetermined resolution requires light focused to a point at the detector to have 80% of the light in a 20 micron circle. The CTE of the material of mount **1440** can be chosen with a caveat that material of mount **1440** 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 mount **1440**.

[0208] FIGS. **15**A, **15**B, and **15**C depict an optical module **1500** according to some embodiments of the disclosure. Optical module **1500** includes a lens system **1520** with four lenses (of which only two, lenses **1522** and **1528**, are visible in FIGS. **15**A-**15**C) and a housing **1530**. Lens system **1520** can be, for example, lens system **1420**, while housing **1530** can be, for example, lens housing **1430**. Since image sensors are generally not circular, the lenses of assembly system **1500** generally do not need to be circular. For example, a photosensor array associated with lens assembly **1500** 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 (not shown in FIGS. **15**A-**15**C) 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 lens assembly **1500** can be relatively easy and cheap to manufacture.

[0209] 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 light ranging device can include 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 in some embodiments and no more than 5.0 cm in other embodiments) 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.

[0210] Lens system **1520** can be designed to be a fast lens system. In some embodiments, the f-number of lens system **1520** is between 1.0 and 2.4 (e.g., 1.2). The spot sizes on the sensor array can have 80% of the light in a 20 μm circle. Further, lens system **1520** 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.

[0211] In various instances, bulk lens systems according to the present disclosure can include: 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-optic structure can be included as part of the array as described above. The micro-optics can modify light differently for different emitters and/or detectors on the array, whereas the bulk lens system modifies light for the entire array. In some embodiments there is one or more micro-optic elements for each individual array element.

[0212] FIG. **16**A depicts a top view of an embodiment of an optical module **1600** that can be, for example, optical module **1500**. Cross section A-A is identified in FIG. **16**A. FIG. **16**B depicts an embodiment of cross section A-A. As shown in FIG. **16**B, optical module **1600** includes four optical elements, including: element **1622** (e.g., lens **1**), element **1624** (e.g., lens **2**), element **1626** (e.g., lens **3**), and element **1628** (e.g., lens **4**); and a housing **1630**. FIG. **16**C shows a magnified portion of the cross section A-A. The magnified portion shows one example of how lens **1624** and lens **1626** can be mounted in housing **1630**. The aperture stop **1625** of lens system **1600** is between lens **1624** and lens **1626**. The aperture stop **1625** can be used to secure lens **1624** within the housing.

[0213] FIG. **16**D depicts a side view of an embodiment of lens assembly **1600**. Cross section B-B is identified in FIG. **16**D. FIG. **16**E depicts an embodiment of cross section B-B. Lens **1**, lens **2**, lens **3**, lens **4**, and the housing are shown.

[0214] FIG. **17**A, depicts a cross section of an embodiment of first lens (lens **1522**). The first lens has a first surface S**1** and a second surface S**2**. The first surface S**1** of lens **1522** and the second surface S**2** of lens **1** are spherical. The first surface S**1** of the first lens can be a convex surface. The second surface S**2** 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.

[0215] FIG. **17**B, depicts a cross section of an embodiment of the second lens (lens **1524**). The second lens has a first surface S**1** and a second surface S**2**. The first surface S**1** of lens **1524** and the second surface S**2** of lens **2** are aspherical. The first surface S**1** of the second lens can be a convex surface. The second surface S**2** 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.

[0216] FIG. **17**C, depicts a cross section of an embodiment of the third lens (lens **1526**). The third lens has a first surface S**1** and a second surface S**2**. The first surface S**1** of lens **1526** and the second surface S**2** 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 S**1** of the third lens can be planar, slightly convex, or slightly concave. The second surface S**2** of the third lens can be convex. Light traveling from left to right can be collimated or slightly focused by the third lens.

[0217] FIG. **17**D, depicts a cross section of an embodiment of the fourth lens (lens **1528**). The fourth lens has a first surface S**1** and a second surface S**2**. The first surface S**1** of lens **4** and the second surface S**2** of lens **4** are aspherical. The first surface S**1** of the fourth lens can be convex. The second

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surface S2 of the third lens can be convex. Light traveling from left to right can be focused to the array.

[0218] By mixing plastic and glass lenses, as well as mixing aspherical and spherical lenses, an economical, light, compact, and/or athermal light ranging device can be made for autonomous vehicles.

[0219] 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.

[0220] FIG. **18** depicts an embodiment of an optical module **1800** with three lenses: a first lens **1822**; a second lens **1824**; and a third lens **1826**. The first lens, the second lens, and the third lens are mounted in a housing **1830**. A connecter **1805** couples the housing with a sensor **1810** (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 **1810**. Lens system **1810** 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.). Housing **1830** can be made of a high CTE material, and/or the mount **1840** attaches near lens **1822**, to hold the focal plane of lens system **1810** at the array. In the embodiment in FIG. **18**, polycarbonate (CTE=70 ppm/C) is used and mount **1840** is attached to housing **1830** 25-35 mm away from the array. A combination of mount **1840** attached to the housing 30 mm away from array **1810**, a movement of lenses of the lens system **1810** due to thermal expansion of housing **1830**, a movement of housing **1830** due to thermal expansion of mount **1840**, and/or a focal shift of lens system **1810** due to temperature change are matched to align the focal plane of the lens system with the array.

[0221] 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.

[0222] As an example, while various embodiments and examples described above have focused primarily on the application of light ranging within the context of 3D sensing for automotive or other road vehicle use cases, systems disclosed herein can be used in any application without departing from the scope of the present disclosure. The small, or even miniature, form factor of a LIDAR system according to the present disclosure enables a number of additional use cases, e.g., for solid-state light ranging systems. As specific examples, 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. As other examples, 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.

[0223] 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. 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.

[0224] As another example, while various examples above included lasers in the IR or near-IR wavelengths as the emitters in LIDAR systems according to some embodiments of the disclosure, embodiments of the disclosure are not limited to any particular wavelength of light or other types of radiation for the emitters. For example, in some embodiments, the emitters can be lasers that generate pulses having any suitable known operating wavelength including a green (532 nm) wavelength, which can be particularly well-suited for underwater applications, or UV wavelengths that can be particularly useful for atmospheric LIDAR systems. 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.

[0225] The specific details of particular embodiments described above 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. As another example, in some embodiments a curved detector and/or emitter can be used. Additionally, in some embodiments three lenses are used instead of four (e.g., two lenses plastic and one lens glass). These examples and others are included within the scope of the present disclosure.

What is claimed is:

1. A light ranging system comprising:

a shaft having a longitudinal axis;

a light ranging device configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses that are reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses;

a base subsystem that does not rotate about the shaft; and

an optical communications subsystem configured to provide an optical communications channel between the base subsystem and the light ranging device, the optical

communications subsystem including one or more turret optical communication components connected to the detector circuitry and one or more base optical communication components connected to the base subsystem.

2. The light ranging system of claim **1** wherein the optical communications subsystem comprises a downlink channel and an uplink channel, wherein the downlink channel is configured to optically transmit ranging data from the light ranging device to the base subsystem and the uplink channel is configured to optically transmit control signals from the base subsystem to the light ranging device.

3. The light ranging system of claim **2** wherein the shaft is hollow and the downlink channel comprises an optical transmitter coupled to the light ranging device and configured to optically transmit ranging data through the hollow shaft to an optical receiver coupled to the base subsystem.

4. The light ranging system of claim **3** wherein the uplink channel comprises a plurality of optical transmitters coupled to the base subsystem and disposed in an annular arrangement outside the shaft and a plurality of optical receivers coupled to the light ranging device and disposed in an annular arrangement outside the shaft.

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

6. The light ranging system of claim **1** wherein:

the one or more turret optical communication components comprise an optical downlink transmitter disposed on a turret circuit board assembly of the light ranging device that rotates around the shaft, and

the one or more base optical communication components comprise an optical downlink receiver disposed on a base circuit board assembly of the base subsystem,

the shaft is a hollow shaft having a central opening, and

the optical downlink transmitter and the optical downlink receiver are positioned to transmit and receive, respectively, an optical signal through the central opening of the shaft.

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

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

8. The light ranging system of claim **7** wherein the at least one optical uplink transmitter includes a plurality of transmitters arranged in a first ring and the at least one optical uplink receiver includes a plurality of receivers arranged in a second ring concentric with the first ring.

9. The light ranging system of claim **8** wherein the second ring is oriented in a first plane defined by the turret circuit board assembly and perpendicular the shaft, the second ring is centered on the shaft, and the turret circuit board assembly and the base circuit board assembly are spatially separated from each other along a length of the shaft.

10. The light ranging system of claim **9** wherein the first ring is oriented in a second plane defined by the base circuit board assembly of the base subsystem and perpendicular to the shaft and the first ring is centered on the shaft.

11. The light ranging system of claim **8** wherein the turret circuit board assembly comprises a single circuit board including an optical downlink transmitter and the plurality of receivers.

12. The light ranging system of claim **8** wherein the base circuit board assembly of the base subsystem comprises a single circuit board including an optical downlink receiver and the plurality of transmitters.

13. A light ranging system comprising:

a housing having an optically transparent window;

a hollow shaft having a longitudinal axis disposed within the housing;

a light ranging device disposed within the housing and configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses through the optically transparent window to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses through the optically transparent window reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses;

a base subsystem disposed within the housing that does not rotate about the shaft; and

an optical communications subsystem disposed within the housing and configured to provide an optical communications channel between the base subsystem and the light ranging device, the optical communications subsystem including a first optical channel disposed within the hollow shaft and a second optical channel arranged annularly outside the hollow shaft.

14. The light ranging system of claim **13** wherein the first optical channel comprises an optical transmitter coupled to the light ranging device and an optical receiver spaced apart from the optical transmitter and coupled to the base subsystem.

15. The light ranging system of claim **13** wherein the second optical channel comprises a plurality of optical transmitters evenly spaced in an annular arrangement configured as a composite optical transmitter coupled to the base subsystem and a plurality of optical receivers evenly spaced in an annular arrangement configured as a composite optical receiver aligned with and spaced apart from the composite optical transmitter and coupled to the light ranging device.

16. The light ranging system of claim **15** wherein the light ranging device further includes a first circuit board and the base subsystem further includes a second circuit board parallel with and spaced apart from the first circuit board, and wherein the plurality of optical transmitters are disposed on the first circuit board and the plurality of optical receivers are disposed on the second circuit board.

17. The light ranging system of claim **16** wherein the each of the optical transmitters in the plurality of optical transmitters comprises and LED and each of the optical receivers in the plurality of optical receivers comprises a photodiode.

18. The light ranging system of claim **13** wherein the first optical channel is configured to transmit ranging data from the light ranging device to the base subsystem and the

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second optical channel is configured to transmit control signals from the base subsystem to the light ranging device.

19. A light ranging system comprising:

a housing having an optically transparent window;

a hollow shaft having a longitudinal axis disposed within the housing;

a light ranging device disposed within the housing and configured to rotate about the longitudinal axis of the shaft, the light ranging device including a light source configured to transmit light pulses through the optically transparent window to objects in a surrounding environment, and detector circuitry configured to detect reflected portions of the light pulses through the optically transparent window reflected from the objects in the surrounding environment and to compute ranging data based on the reflected portion of the light pulses;

a base subsystem disposed within the housing that does not rotate about the shaft;

a first optical communication channel configured to optically transmit data between the light ranging device and the base subsystem through the hollow shaft, the first optical communication channel including a first optical component coupled to circuitry coupled to rotate with the light ranging device and a second optical component coupled to circuitry disposed on the base subsystem; and

a second, annular optical communication channel surrounding the hollow shaft and configured to optically transmit data between the light ranging device and the base subsystem, the annular optical communication channel including a first annular optical component coupled to circuitry coupled to rotate with the light ranging device and a second annular optical component coupled to circuitry disposed on the base subsystem.

20. The light ranging system of claim **19** wherein the first optical communication channel is a downlink channel configured to transmit ranging data from the light ranging device to a processor coupled to the base subsystem and the second optical communication channel is an uplink channel configured to transmit control signals from the processor to the light ranging device.

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