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Spinning LiDAR with one dimensional MEMS scanner

Abstract

Embodiments of the disclosure provide an optical sensing system for two-dimensional (2D) environmental sensing and an optical sensing method for the optical sensing system. The optical sensing system includes a rotary base and a one-dimensional (1D) optical sensing apparatus supported by the rotary base. The 1D optical sensing apparatus includes an optical source configured to emit optical signals, a 1D MEMS scanner configured to direct the optical signals towards an environment surrounding the optical sensing system, and a receiver configured to receive at least a portion of the optical signals reflected from the environment. The rotary base is configured to drive the 1D optical sensing apparatus to rotate around a first axis to scan the optical signals in a first dimension and the 1D MEMS scanner is configured to independently rotate around a second axis to scan the optical signals in a second dimension in the 2D environmental sensing.

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Background/Summary

TECHNICAL FIELD

(1) The disclosure relates to a light detection and ranging (LiDAR) system, and more particularly to, a spinning LiDAR system with a one-dimensional (1D) micro-electro-mechanical systems (MEMS) scanner for two-dimensional (2D) environmental sensing.

BACKGROUND

(2) In 2D environment sensing, conventional spinning LiDAR systems spin a laser array and a detector array to scan the laser beams and construct point cloud scenes. These spinning LiDAR systems have some drawbacks. First, these spinning LiDAR systems use a large number of laser emitters and detectors to form the arrays and require element-to-element alignment between the respective emitters and detectors, which may become time and cost prohibitive. Second, the scanning resolution and the pattern of the point clouds are fixed once the LiDAR system is assembled, and thus are not adjustable according to scanning needs after the assembly.

(3) Embodiments of the disclosure address the above problems by providing a spinning LiDAR system with a one-dimensional MEMS scanner for 2D environmental sensing.

SUMMARY

(4) Embodiments of the disclosure provide an optical sensing system for 2D environmental sensing. The optical sensing system includes a rotary base and a 1D optical sensing apparatus supported by the rotary base. The 1D optical sensing apparatus includes an optical source configured to emit optical signals, a 1D MEMS scanner configured to direct the optical signals towards an environment surrounding the optical sensing system, and a receiver configured to receive at least a portion of the optical signals reflected from the environment. The rotary base is configured to drive the 1D optical sensing apparatus to rotate around a first axis to scan the optical signals in a first dimension and the 1D MEMS scanner is configured to independently rotate around a second axis to scan the optical signals in a second dimension in the 2D environmental sensing.

(5) Embodiments of the disclosure further provide an optical sensing method for an optical sensing system. The optical sensing system includes a rotary base and a 1D optical sensing apparatus supported by the rotary base, where the 1D optical sensing apparatus further includes an optical source, a 1D MEMS scanner, and a receiver. The optical sensing method includes emitting, by the optical source, optical signals. The optical sensing method further includes controlling the rotary base to rotate around a first axis, where a rotating of the rotary base causes the 1D optical sensing apparatus to also rotate around the first axis, to allow the 1D MEMS scanner to direct the optical signals in a first dimension towards an environment. The optical sensing method additionally includes controlling the 1D MEMS scanner to independently rotate around a second axis, to direct the optical signals in a second dimension towards the environment. The optical sensing method additionally includes receiving, by the receiver, at least a portion of the optical signals reflected from the environment.

(6) It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the disclosure, as claimed.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. 1 illustrates a schematic diagram of an exemplary vehicle equipped with a spinning LiDAR system with a one-dimensional MEMS scanner, according to embodiments of the disclosure.

(2) FIG. 2 illustrates a block diagram of an exemplary spinning LiDAR system with a one-dimensional MEMS scanner, according to embodiments of the disclosure.

(3) FIG. 3 illustrates a schematic diagram of an exemplary operation of a spinning LiDAR system with a one-dimensional MEMS scanner, according to embodiments of the disclosure.

(4) FIG. 4A illustrates a schematic diagram of an exemplary operation of a one-dimensional MEMS scanner with one laser emitting module, according to embodiments of the disclosure.

(5) FIG. 4B illustrates a schematic diagram of an exemplary operation of a one-dimensional MEMS scanner with multiple laser emitting modules, according to embodiments of the disclosure.

(6) FIG. 5 illustrates a schematic diagram of an exemplary wireless connection mechanism between a first part and a second part of a spinning LiDAR system, according to embodiments of the disclosure.

(7) FIG. 6 illustrates a schematic diagram of an exemplary operation of another spinning LiDAR system with a one-dimensional MEMS scanner, according to embodiments of the disclosure.

(8) FIG. 7 is a flow chart of an exemplary optical sensing method of a spinning LiDAR system with a one-dimensional MEMS scanner, according to embodiments of the disclosure.

DETAILED DESCRIPTION

(9) Reference will now be made in detail to the exemplary embodiments, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

(10) Embodiments of the disclosure provide an exemplary spinning LiDAR system with a 1D MEMS scanner. The spinning LiDAR system may include a rotary base and a 1D optical sensing apparatus mounted on the rotary base. The rotary base may be controlled to rotate to certain degrees (e.g., ± 90 degrees, 360 degrees, etc.). The 1D optical sensing apparatus may include an optical source, a 1D MEMS scanner, and a receiver. The optical source may include one or more laser emitting modules, and the receiver may include one or more photosensors. The one or more photosensors may be aligned with the respective one or more laser emitting modules.

(11) In some embodiments, when rotating, the rotary base of the spinning LiDAR system may cause the 1D optical sensing apparatus mounted on the rotary base to rotate along its central axis. Although the optical source, 1D MEMS scanner, and receiver do not rotate by themselves, since the whole optical sensing apparatus is caused to rotate, the optical source, 1D MEMS scanner, and receiver will collectively move around the same axis circularly when the rotary base rotates. As result, the 1D MEMS scanner also moves around the same axis, thus achieving a first dimensional scanning during a scanning process. In some embodiments, the first dimensional scanning may be a horizontal scanning if the central axis of the rotary base is vertically aligned when the spinning LiDAR system is mounted on a vehicle or other device.

(12) In some embodiments, the 1D MEMS scanner itself may be actuated by an actuation mechanism, and thus may rotate around a rotational axis of the 1D MEMS scanner during a scanning process, thereby achieving a second dimensional scanning caused by the rotation of the 1D MEMS scanner itself. In some embodiments, when the spinning LiDAR system is mounted onto the rotary base, the rotational axis of the 1D MEMS scanner may be aligned in a way perpendicular to the central axis of the rotary base. Since the first dimensional scanning achieved through the rotation of the 1D optical sensing apparatus (caused by the rotary base) and the second dimensional scanning achieved by the rotation of the 1D MEMS scanner itself are perpendicular to each other, a 2D scanning may be then achieved by the disclosed spinning LiDAR system with a 1D MEMS scanner.

(13) In some embodiments, when the disclosed spinning LiDAR system with the 1D MEMS scanner rotates, the relative positions between the optical source (e.g., the one or more laser emitting modules) and the receiver (e.g., the one or more photosensors) do not change, and thus the alignment between the optical source and the receiver remains unchanged.

(14) As can be seen above, with just a very limited number of optical sources and receivers (e.g., only one laser emitting module and one photosensor), 2D scanning can be conveniently achieved through the disclosed spinning LiDAR system with a 1D MEMS scanner. Therefore, the disclosed spinning LiDAR system requires much less alignment of laser emitters and photosensors than conventional spinning LiDAR systems. As such, the disclosed spinning LiDAR system is cost-effective and easier to assemble and maintain. In addition, in the disclosed spinning LiDAR system, the whole field-of-view (FoV) (e.g., up to 360 degrees of peripheral view) may be achieved with only one emitter-detector set, which simplifies the backend circuitry (e.g., no requirement of dual-channel highly sensitive analog-to-digital converter and high-performance field-programmable gate array). Further, the scanning precision (e.g., in the vertical direction) can be improved by the disclosed spinning LiDAR system due to the MEMS actuated scanning process. The features and advantages described herein are not exhaustive and many additional features and advantages will be apparent to one of ordinary skill in the art in view of the figures and the following descriptions.

(15) The disclosed spinning LiDAR system with a 1D MEMS scanner can be used in many applications. For example, the disclosed spinning LiDAR system can be used in advanced navigation technologies, such as to aid autonomous driving or to generate high-definition maps, in

which the optical sensing system can be equipped on a vehicle.

(16) FIG. 1 illustrates a schematic diagram of an exemplary vehicle equipped with a spinning LiDAR system containing a 1D MEMS scanner, according to embodiments of the disclosure. Consistent with some embodiments, vehicle **100** may be a survey vehicle configured for acquiring data for constructing a high-definition map or three-dimensional (3D) buildings and city modeling. Vehicle **100** may also be an autonomous driving vehicle.

(17) As illustrated in FIG. 1, vehicle **100** may be equipped with an optical sensing system, e.g., a spinning LiDAR system with a 1D MEMS scanner (also referred to as “LiDAR system **102**” hereinafter) mounted to a body **104** via a mounting structure **108**. Mounting structure **108** may be an electro-mechanical device installed or otherwise attached to body **104** of vehicle **100**. In some embodiments of the present disclosure, mounting structure **108** may use screws, adhesives, or another mounting mechanism. Vehicle **100** may be additionally equipped with a sensor **110** inside or outside body **104** using any suitable mounting mechanisms. Sensor **110** may include sensors used in a navigation unit, such as a Global Positioning System (GPS) receiver and one or more Inertial Measurement Unit (IMU) sensors. It is contemplated that the manners in which LiDAR system **102** or sensor **110** can be equipped on vehicle **100** are not limited by the example shown in FIG. 1 and may be modified depending on the types of LiDAR system **102** and sensor **110** and/or vehicle **100** to achieve desirable 3D sensing performance.

(18) Consistent with some embodiments, LiDAR system **102** and sensor **110** may be configured to capture data as vehicle **100** moves along a trajectory. For example, a 1D MEMS scanner of LiDAR system **102** may be configured to scan the surrounding environment, including an up to 360-degree peripheral scanning of the surrounding environment when driven by a rotary base of LiDAR system **102**. LiDAR system **102** measures distance to a target by illuminating the target with laser beams and measuring the reflected/scattered pulses with a receiver. The laser beams used for LiDAR system **102** may be ultraviolet, visible, or near-infrared, and may be pulsed or continuous wave laser beams. In some embodiments of the present disclosure, LiDAR system **102** may capture point clouds including depth information of the objects in the surrounding environment, which may be used for constructing a high-definition map or 3D buildings and city modeling. As vehicle **100** moves along the trajectory, LiDAR system **102** may continuously capture data including the depth information of the surrounding objects (such as moving vehicles, buildings, road signs, pedestrians, etc.) for map, building, or city modeling construction.

(19) FIG. 2 illustrates a block diagram of an exemplary spinning LiDAR system **102** containing a 1D MEMS scanner, according to embodiments of the disclosure. In some embodiments, LiDAR system **102** may be a semi-coaxial LiDAR, a coaxial LiDAR, etc. As illustrated, LiDAR system **102** may include a rotary base **221**, a 1D optical sensing apparatus **201** mounted on rotary base **221**, and a controller **206** coupled to 1D optical sensing apparatus **201** and/or rotary base **221**. Controller **206** may communicate (e.g., data or power transmission) with 1D optical sensing apparatus **201** through wired or wireless connection. 1D optical sensing apparatus **201** may further include a transmitter **202** and a receiver **204**. In some embodiments, transmitter **202** may further include a laser emitter **208** for emitting an optical signal and one or more optics **210** for collimating the optical signal. In some embodiments, transmitter **202** may additionally include a 1D MEMS scanner **212** for steering the collimated optical signal according to a certain pattern. Receiver **204** may further include a receiving lens **216**, a photodetector **218**, and a readout circuit **220**.

(20) Transmitter **202** may emit optical beams (e.g., pulsed laser beams, continuous wave (CW) beams, frequency modulated continuous wave (FMCW) beams) along multiple directions, e.g., up to a 360-degree peripheral field of view when rotary base **221** causes 1D optical sensing apparatus **201** to rotate in a scanning process. According to one example, transmitter **202** may sequentially emit a stream of laser beams in a vertical field-of-view (FOV) that can be up to 360 degrees in horizontal directions.

(21) Laser emitter **208** may be configured to emit laser beams **207** (also referred to as “native laser

beams”) to optics **210**. For instance, laser emitter **208** may generate laser beams in the ultraviolet, visible, or near-infrared wavelength range, and provide the generated laser beams to optics **210**. In some embodiments of the disclosure, depending on underlying laser technology used for generating laser beams, laser emitter **208** may include one or more of a double heterostructure (DH) laser emitter, a quantum well laser emitter, a quantum cascade laser emitter, an interband cascade (ICL) laser emitter, a separate confinement heterostructure (SCH) laser emitter, a distributed Bragg reflector (DBR) laser emitter, a distributed feedback (DFB) laser emitter, a vertical-cavity surface-emitting laser (VCSEL) emitter, a vertical-external-cavity surface-emitting laser (VECSEL) emitter, an external-cavity diode laser emitter, etc., or any combination thereof. Depending on the number of laser emitting units or modules in a package, laser emitter **208** may include a single emitter containing a single light-emitting unit, a multi-emitter unit containing multiple single emitters packaged in a single chip, an emitter array or laser diode bar containing multiple (e.g., 10, 20, 30, 40, 50, etc.) single emitters in a single substrate, an emitter stack containing multiple laser diode bars or emitter arrays vertically and/or horizontally built up in a single package, etc., or any combination thereof. Depending on the operating time, laser emitter **208** may include one or more of a pulsed laser diode (PLD), a CW laser diode, a Quasi-CW laser diode, etc., or any combination thereof. Depending on the semiconductor materials of diodes in laser emitter **208**, the wavelength of incident laser beams **207** may be at different values, such as 760 nm, 785 nm, 808 nm, 848 nm, 870 nm, 905 nm, 940 nm, 980 nm, 1064 nm, 1083 nm, 1310 nm, 1370 nm, 1480 nm, 1512 nm, 1550 nm, 1625 nm, 1654 nm, 1877 nm, 1940 nm, 2000 nm, etc. It is understood that any suitable laser source may be used as laser emitter **208** for emitting laser beams **207** at a proper wavelength.

(22) Optics **210** may include optical components (e.g., lenses, mirrors) that can shape the laser light and collimate the laser light into a narrow laser beam **209** to increase the scan resolution and the range to scan object(s) **214**. 1D MEMS scanner **212** may include various optical elements such as prisms, mirrors, gratings, optical phased array (e.g., liquid crystal-controlled grating), or any combination thereof. Consistent with embodiments of the disclosure, 1D MEMS scanner **212** in transmitter **202** may include a MEMS actuation mechanism and a mirror driven by the MEMS actuation mechanism. In some embodiments, object(s) **214** may be made of a wide range of materials including, for example, non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds, and even single molecules. In some embodiments, at each time point during a scanning process, the rotary base **221** and the MEMS actuation mechanism may cooperatively control the mirror of 1D MEMS scanner **212** to steer laser beams **211** to object(s) **214** in a 2D scanning pattern, as described in more detail in FIGS. 3-7.

(23) Receiver **204** may be configured to detect returned laser beams **213** returned from object **214**. Upon contact, laser light can be reflected/scattered by object **214** via backscattering, such as Raman scattering, and fluorescence. Returned laser beams **213** may be in a same or different direction from laser beams **211**. In some embodiments, receiver **204** may collect at least a portion of laser beams returned from object **214** and output signals reflecting the intensity of the returned laser beams.

(24) As illustrated in FIG. 2, receiver **204** may include one or more receiving lenses **216**, a photodetector **218**, and a readout circuit **220**. Receiving lens(es) **216** may be configured to converge and focus the returning optical signal on photodetector **218** as a focused laser beam **215**.

(25) Photodetector **218** may be configured to detect the focused laser beams **215**. In some embodiments, photodetector **218** may convert a laser beam **215** into an electrical signal **217** (e.g., a current or a voltage signal). Electrical signal **217** may be an analog signal which is generated when photons are absorbed in a photodiode included in photodetector **218**. In some embodiments, photodetector **218** may include a PIN detector, an avalanche photodiode (APD) detector, a single photon avalanche diode (SPAD) detector, a silicon photo multiplier (SiPM) detector, or the like. In some embodiments, photodetector **218** may include a plurality of photosensors or pixels arranged in a one-dimensional, two-dimensional array, or even three-dimensional array.

(26) Readout circuit **220** may be configured to integrate, amplify, filter, and/or multiplex signal detected by photodetector **218** and transfer the integrated, amplified, filtered, and/or multiplexed signal **219** onto an output port (e.g., controller **206**) for readout. In some embodiments, readout circuit **220** may act as an interface between photodetector **218** and a signal processing unit (e.g., controller **206**). Depending on the configurations, readout circuit **220** may include one or more of a transimpedance amplifier (TIA), an analog-to-digital converter (ADC), a time-to-digital converter (TDC), or the like.

(27) Controller **206** may be configured to control transmitter **202** and/or receiver **204** to perform detection/sensing operations, and/or to control rotary base **221** to rotate according to a certain pattern. In one example, controller **206** may control laser emitter **208** to emit laser beams **207**, or control 1D MEMS scanner **212** to rotate along its rotational axis to achieve a one-dimensional scanning. In another example, controller **206** may control rotary base **221** to rotate according to a certain pattern (e.g., ± 90 degrees, 360 degrees, etc.).

(28) In some embodiments, controller **206** may also control data acquisition and perform data analysis. For instance, controller **206** may collect digitalized signal information from readout circuit **220**, determine the distance of object **214** from LiDAR system **102** according to the travel time of laser beams, and construct a high-definition map or 3D buildings and city modeling surrounding LiDAR system **102** based on the distance information of object(s) **214**.

(29) In some embodiments, controller **206** may be external to 1D optical sensing apparatus **201**, to save the weight and space of the 1D optical sensing apparatus. That is, controller **206** may not be mounted on rotary base **221** as other components of 1D optical sensing apparatus **201**. To implement respective functions, controller **206** may communicate with 1D optical sensing apparatus **201** through wired or wireless connection. For instance, if rotary base **221** is configured to rotate continuously (e.g., 360-degree rotation), a wired (e.g., through a slip ring) or wireless connection may be set up between controller **206** and 1D optical sensing apparatus **201** for data and/or power transmission. For another instance, if rotary base **221** is configured to rotate less than 360 degrees (e.g., ± 90 -degree rotation), a wired connection may be set up between controller **206** and 1D optical sensing apparatus **201**. In some embodiments, controller **206** may also communicate with rotary base **221** through wired or wireless connection.

(30) In some embodiments, one or more controllers **206** may be included in LiDAR system **102**, each of which may implement different functions. For instance, there may be a specific controller (not shown) for controlling the rotation of rotary base **221**, or there may be another different controller (not shown) for controlling the rotation of 1D MEMS scanner **212**, or there may be even another different controller (not shown) to perform data analysis and map construction, etc. In some embodiments, one or more controllers **206** may be located within 1D optical sensing apparatus **201** mounted on rotary base **221**. For instance, a controller for controlling the rotation of 1D MEMS scanner **212** may be included inside 1D optical sensing apparatus **201** mounted on rotary base **221**. Other configurations of the one or more controllers **206**, including their specific locations, for controlling the operation of the disclosed spinning LiDAR system with a 1D MEMS scanner are also possible and contemplated in the present disclosure, as further described below in FIGS. 3-7.

(31) FIG. 3 illustrates a schematic diagram of an exemplary operation of one spinning LiDAR system with a 1D MEMS scanner (also referred to as “LiDAR system **300**” hereinafter). As illustrated, LiDAR system **300** may include a rotary base **321** and a 1D optical sensing apparatus **301** mounted on rotary base **321**. 1D optical sensing apparatus **301** may further include a laser emitter **308**, a 1D MEMS scanner **312**, a receiving lens **316**, and a photodetector **318**. The components **321**, **308**, **312**, **316**, and **318** may have similar configurations and functions to those components described in FIG. 2. Although not specifically illustrated, the exemplary LiDAR system **300** may further include one or more controllers for controlling the operation and/or for achieving certain other functions of LiDAR system **300**. These controllers may communicate with

rotary base **321** and/or 1D optical sensing apparatus **301** through wired or wireless connection.

(32) As illustrated in FIG. 3, in some embodiments, LiDAR system **300** may further include a beam splitter **322** configured to prevent emitted laser power from being backscattered into photodetector **318** during a sensing process. To achieve this, laser polarization may be exploited, and thus LiDAR system **300** may further include a quarter-wave plate **324**. When a linearly polarized laser beam is transmitted by laser emitter **308**, a polarizing beam splitter **322** may isolate it. Specifically, quarter-wave plate **324** may convert linear polarization to circular polarization. When that circular polarization bounces off of an object **314**, most of the light will reverse its handedness. In return, the opposite-handedness circular-polarization beam may be converted to the opposite linear polarization of the laser and may be transmitted through the polarizing beam splitter **322** to photodetector **318**. This polarization method of transmit/receive isolation can achieve up to 40-45 dB of isolation with proper design, which is proper for LiDAR applications.

(33) As described in FIG. 2, 1D MEMS scanner **312** may be a one-dimensional scanner. That is, 1D MEMS scanner **312** may be controlled to rotate along one axis (e.g., a horizontal axis). For instance, as illustrated in FIG. 4A, 1D MEMS scanner **312** may be controlled to rotate along a rotational axis **402** of the 1D MEMS scanner. The rotational axis of the 1D MEMS scanner may be an axis perpendicular to a central axis of rotary base **321**, when 1D optical sensing apparatus **301** is mounted onto rotary base **321**. For instance, if the central axis of rotary base **321** is vertical when mounted onto a vehicle **100**, the rotational axis **402** of 1D MEMS scanner **312** may be then a horizontal axis. On the other hand, if the central axis of rotary base **321** is horizontal when mounted on a vehicle **100**, the rotational axis **402** of 1D MEMS scanner **312** may be then a vertical axis.

(34) As also illustrated in FIG. 4A, when 1D MEMS scanner **312** is controlled to rotate to certain angles, the reflected laser beams may be directed towards the environment in different directions. Accordingly, when 1D MEMS scanner **312** is controlled to rotate within a certain angle range along rotational axis **402**, the reflected laser beams may be directed to certain coverage in the environment in one dimension. For instance, if 1D MEMS scanner **312** is controlled to rotate within 30 degrees along a horizontal rotational axis **402**, the reflected laser beams may have a 60-degree coverage in the environment in the vertical dimension, as shown in FIG. 4A.

(35) In some embodiments, there may be multiple laser emitting modules in LiDAR system **300**. To achieve a same coverage as shown in FIG. 4A (in which there is only one laser emitting module), 1D MEMS scanner **312** may be controlled to rotate within a smaller angle range. For instance, if there are two laser emitting modules, to cover a vertical dimension of 60-degree coverage in the environment, 1D MEMS scanner **312** may be controlled to rotate within a 15-degree angle range (which is half than that is in FIG. 4A), since each laser emitting module is just responsible for covering half of the area, as shown in FIG. 4B. Similarly, if there are three laser emitting modules in laser emitter **308**, a 10-degree angle range may achieve the same as shown in FIG. 4A. That is, the more laser emitting modules in LiDAR system **300**, the smaller angle range the 1D MEMS scanner **312** may need to rotate, to cover a same area in the environment.

(36) As previously described, one obvious advantage of the disclosed LiDAR system is that a very limited number of transmitters/receivers are used in such a LiDAR system to achieve 2D environmental sensing. In its simplest form, only one laser emitting module and one photosensor are used to achieve a target 2D environment sensing. In another form, only very few laser emitting modules (e.g., less than a first threshold, which may be 2, 4, 6, 8, etc.) and very few photosensors (e.g., less than a second threshold, which may be also 2, 4, 6, 8, etc.) are used to achieve a 2D scanning. Since the number of laser emitting modules and photosensors used in the disclosed spinning LiDAR system is very limited and much smaller than other existing spinning LiDAR systems, the alignment between the laser emitting module(s) and photosensor(s) is much easier to achieve, as previously described. In some embodiments, a monolithic emitter array and a monolithic detector array may be applied to a LiDAR system that contains a number of emitters and detectors, which may further simplify an alignment process and lower the cost.

(37) Referring back to FIG. 3, in some embodiments, different drive forces may be applied to control the rotation of 1D MEMS scanner **312** along the rotational axis **402** of the 1D MEMS scanner. These drive forces may be generated by different electromagnetic, electrostatic, thermo-electric, and piezo-electric effects, etc. According to one example, magnetic actuators may be used here due to their good linearity of the tilt angle versus the applied signal amplitude in static and dynamic operations. To drive the mirror in the 1D MEMS scanner to tilt, a metallic coil may be placed on the 1D MEMS scanner or mirror itself. As the mirror is placed in a magnetic field, the alternating current flowing in the coil may generate Lorentz force that tilts the mirror. A magnetically actuated mirror requires a low voltage (e.g., below 5V), making this actuation compatible with standard complementary metal-oxide-semiconductor (CMOS) voltage. Another advantage of such actuation type is that MEMS behavior does not present hysteresis, as opposed to electrostatic actuated MEMS mirrors, which makes it very simple to control. Apparently, under proper configurations, certain electrostatically, thermo-electrically, or piezo-electrically actuated scanners may be also used in place of 1D MEMS scanner **312** to achieve a one-dimensional (e.g., vertical dimension) scanning by the rotation of the 1D MEMS scanner.

(38) In some embodiments, to achieve a 2D scanning for LiDAR system **300**, rotary base **321** may be controlled to rotate according to a certain pattern (e.g., rotate horizontally along a vertical axis). As previously described, the rotation of rotary base **321** may cause 1D optical sensing apparatus **301** to rotate synchronously (e.g., at a same rotational speed) with it during a scanning process. This then causes the 1D MEMS scanner **312** to circularly move around a same axis of rotary base **321**. As previously described, the central axis of rotary base **321** may be perpendicular to the rotational axis of 1D MEMS scanner **312** when 1D MEMS scanner **312** is mounted with other components of 1D optical sensing apparatus **301** onto rotary base **321**. Accordingly, during a scanning process, LiDAR system **300** may achieve a 2D scanning, with scanning in the one dimension realized by the rotation of 1D MEMS scanner **312** itself, and scanning in the other dimension realized by the circular movement of 1D MEMS scanner **312** around the central axis of rotary base **321**.

(39) In some embodiments, depending on the maximum rotation angles configured for rotary base **321**, LiDAR system **300** may be controlled to cover a certain angle range during a scanning process. For instance, a controller may control rotary base **321** to horizontally rotate ± 30 , ± 45 , ± 60 , ± 75 , ± 90 , ± 105 degrees, and so on. In this way, LiDAR system **300** may be then controlled to cover a partial coverage around a vehicle on which LiDAR system **300** is mounted. For instance, if LiDAR system **300** is mounted on the front (e.g., along with a front plate of a vehicle) of the vehicle, a ± 90 -degree rotation of rotary base **321** may allow LiDAR system **300** to cover a front half FOV in front of the vehicle. For another instance, if LiDAR system **300** is mounted along with a front left lamp, a ± 45 -degree rotation of rotary base **321** may allow LiDAR system **300** to have a quarter coverage on the front-left of the vehicle. Other instances of rotation configuration for rotary base **321** and respective coverages are also possible and contemplated in the disclosure.

(40) In some embodiments, a controller may control rotary base **321** to continuously rotate 360-degrees in one direction without back and forth (also referred to as “spin”). In this way, LiDAR system **300** may achieve coverage that covers all horizontal directions around a vehicle. For instance, for a LiDAR system **300** that is mounted on top of a vehicle **100**, rotary base **321** may be controlled to rotate continuously (clockwise or anti-clockwise) during a scanning process, to achieve a 360-degree horizontal FOV around the vehicle.

(41) In some embodiments, different connection methods may be applied for a specific LiDAR system **300**, depending on the rotation configuration of the respective rotary base. For instance, if rotary base **321** of LiDAR system **300** is configured to rotate less than 360 degrees (e.g., ± 45 , ± 90 degrees), wired data and/or power transmission to/from 1D optical sensing apparatus **301** may be configured for such a LiDAR system (e.g., a LiDAR system for mounting in front of a vehicle or on one side of a vehicle). In one example, slip rings may be used to establish physical connections

between components in the rotatable 1D optical sensing apparatus **301** and other components (e.g., controller(s) and power suppl(ies)) of LiDAR system **300** external to the rotatable 1D optical sensing apparatus. This can be properly achieved if rotary base **321** and 1D optical sensing apparatus **301** do not continuously rotate (i.e., less than a full circle), as that leaves space for a wired connection to be established between components in 1D optical sensing apparatus **301** and other components in LiDAR system **300**.

(42) On the other hand, if rotary base **321** of LiDAR system **300** is configured to continuously rotate (e.g., 360-degree rotation), wireless data and/or power transmission to/from the rotatable 1D optical sensing apparatus **301** may be implemented for such a LiDAR system (e.g., a LiDAR system for mounting on top of a vehicle). In some embodiments, the slip ring-based data and/or power transmission is also possible and thus contemplated in the disclosure, although such wired transmission has drawbacks of wear and tear and thus less reliable lifetime. In some embodiments, different mechanisms may be applied to set up the wireless transmission to/from the continuously rotating 1D optical sensing apparatus **301**. For instance, electrical or magnetic signals may be applied to establish a wireless connection through electromagnetic coupling. In some embodiments, due to the low transmission speed as well as signal interference problems in electromagnetic coupling, optical signals may be applied instead, to establish a wireless connection, as further described below in FIG. 5.

(43) FIG. 5 illustrates a schematic diagram of an exemplary wireless connection mechanism between a first part and a second part of a spinning LiDAR system **300**, according to embodiments of the disclosure. According to one embodiment, the first part **502** (represented by a circle) may correspond to 1D optical sensing apparatus **301**, and may include an optical transceiver **503** that includes at least one light emitter **506** and at least one detector **508**. The second part **504** (represented by a circle) may correspond to other components in LiDAR system **300** except 1D optical sensing apparatus **301**. Similar to the first part **502**, the second part **504** may also include an optical transceiver **505** that includes at least one light emitter **512** and at least one detector **510**.

(44) Optical transceivers **503** and **505** may be configured to be wirelessly coupled to each other and simultaneously transmit signals to each other. For example, optical transceivers **503** and **505** may transmit optical signals to each other using the light emitter-detector pairs, thus establishing a wireless connection. The wireless connection between parts **502** and **504** avoids the physical contact commonly found in conventional LiDAR sensing devices using slip rings as the means to establish a connection between moving and stationary parts. Because no physical abrasion is involved, the lifespan of a spinning LiDAR system can be improved.

(45) Optical transceivers **503** and **505** may be configured to simultaneously transmit signals to each other using non-interfering light signals to achieve full-duplex signal/data communication. For example, light emitters **506** and **512** may emit non-interfering light signals based on different wavelengths to transmit information between parts **502** and **504**. For instance, light emitter **506** may be configured to emit a first light signal **514** at a first wavelength, such as a wavelength in the ultraviolet range for transmitting signals to detector **510** of part **504**. Light emitter **512** may be configured to emit a second light signal **516** at a second wavelength, such as a wavelength in the visible light range or infrared range for transmitting signals to detector **508** of part **502**. It is understood that other non-interfering wavelength ranges may also be used, as long as the base bands of light signals **514** and **516** are significantly non-overlapping. For example, different colors in the visible light range may be used (e.g., red and blue, red and green, etc.) in the present disclosure.

(46) Detectors **508** and **510** may be configured to detect light signals within differing target wavelength ranges. For example, detector **508** may be configured to react to or be sensitive to the wavelengths of the light signals emitted by light emitter **512**, but insensitive to the wavelengths of the light signals emitted by light emitter **506**. Similarly, detector **510** may be configured to react to or be sensitive to the wavelengths of the light signals emitted by light emitter **506**, but insensitive

to the wavelengths of the light signals emitted by light emitter **512**. In this way, emission and detection of light signals in both directions (from part **502** to part **504** and from part **504** to part **502**) can be simultaneously performed, thereby improving transmission efficiency.

(47) In some embodiments, information related to the sensing signal may be embedded or encoded in the beam of light signal **514** using signal processing technologies (e.g., using Orthogonal Frequency Division Multiplexing or other modulation techniques to modulate the frequency, phase, and/or magnitude of the light wave emitted by light emitter **506**) and may be transmitted to detector **510**. Detector **510** may convert the light signals into a data stream by first converting the light signals into electrical signals and then demodulating the electrical signals into a digital data stream. Control information may be transmitted in a similar manner by light signal **516** from part **504** to part **502**. It is to be noted that the signal transmission between parts **502** and **504** can be in analog or digital form, and may or may not involve signal modulation.

(48) In some embodiments, parts **502** and **504** may also use light signals **514** and/or **516** for wireless power transfer. For example, light emitters **506** and/or **512** may convert electrical power into optical power for the transmission of energy. Detectors **508** and/or **510** may convert the optical power back to electrical power, such as DC or AC electric current which may drive electrical loads.

(49) Accordingly, by using the wireless connection mechanism illustrated in FIG. 5, data and/or power transmission can be effectively set up between components in 1D optical sensing apparatus **301** and other components in LiDAR system **300** when rotary base **321** is configured to continuously rotate. This may then allow 1D optical sensing apparatus **301** to continuously rotate without interfering with the data and/or power transmission to/from a continuously rotating 1D optical sensing apparatus **301**.

(50) Referring back to FIG. 3, during a scanning process, different rotation speeds may be configured for rotary base **321** and/or 1D MEMS scanner **312**. In one implementation, rotary base **321** may be configured to rotate slower while 1D MEMS scanner **312** is configured to rotate faster. In such implementation, LiDAR system **300** may be controlled to vertically scan the surrounding areas (e.g., up and down), where vertically scanning laser beams continue clockwise or anticlockwise. In another implementation, rotary base **321** may be configured to rotate faster (e.g., along its central axis) while 1D MEMS scanner **312** is configured to rotate slower (e.g., along its rotational axis). Accordingly, during a scanning process, LiDAR system **300** may scan the surrounding areas in a horizontal circle (if rotary base **321** rotates continuously) or arc (if rotary base **321** rotates less than 360 degrees) by gradually moving horizontal circles or arcs up or down, thereby forming a spiral pattern or partial (e.g., a quarter) of a spiral pattern. Accordingly, by controlling the respective rotation speeds of rotary base **321** and/or 1D MEMS scanner **312**, different scanning patterns may be achieved by LiDAR system **300**.

(51) In some embodiments, by controlling the rotation speed of rotary base **321**, the resolution for the 2D environmental sensing may be further controlled. For instance, to achieve a high resolution, the rotation speed of rotary base **321** may be controlled to be slow. On the other hand, if the resolution is not so important, but rather the time for scanning the environment is more important, the rotation speed of rotary base **321** may be controlled to be fast. Accordingly, in some embodiments, LiDAR system **300** may further include a controller (which may be similar to one of the controllers previously described) configured to control a rotation speed of the rotary base according to a target resolution for the 2D environmental sensing. In some embodiments, other approaches for controlling the resolution of the 2D environmental sensing are also possible. For instance, the firing time of the laser emitter(s) of a LiDAR system **300** may be controlled alternatively or additionally, to adjust the resolution of the 2D environmental sensing. It is to be noted that when controlling the different scanning patterns, the relative rotation speeds between rotary base **321** and 1D MEMS scanner **312** are more important. When controlling the target resolution for the 2D environmental sensing, the absolute rotation speed of rotary base **321** becomes more important. Accordingly, the terms “slow” and “fast” in the above descriptions may

correspond to different speeds under different circumstances.

(52) FIG. 3 merely illustrates one exemplary spinning LiDAR system containing a 1D MEMS scanner. In FIG. 6, another exemplary spinning LiDAR system **600** with a 1D MEMS scanner is further provided. As illustrated, LiDAR system **600** may include a rotary base **621** and a 1D optical sensing apparatus **601**. 1D optical sensing apparatus **601** may further include a laser emitter **608**, a receiving lens **616**, a photodetector **618**, and a MEMS mirror **612**, which may be a 1D MEMS array or a monolithic mirror as long as the aperture is large enough. In some embodiments, the 1D MEMS array may include a number of 1D MEMS elements organized in an array. It is to be noted that, while only one laser emitter **608** and one photodetector **618** are illustrated in spinning LiDAR system **600**, it is contemplated, as described above, they can each be replaced by a small array of emitters and photodetectors. It is also to be noted that, the use of a laser array or detector array does not require the use of a 1D MEMS array. For instance, a monolithic MEMS mirror may also be paired with the laser and detector arrays in LiDAR system **600**.

(53) Different from LiDAR system **300** in which a beam splitter is used to separate returning laser beams from transmitting laser beams, in LiDAR system **600**, MEMS mirror **612** is used for separating transmitting laser beams from returning laser beams. For instance, one portion of MEMS **612** may be used for laser transmitter(s) while the remaining portion of MEMS **612** may be used for photosensor(s), so as to separate light paths for transmitting laser beams and returning laser beams. In some embodiments, MEMS mirror **612** may be mounted on a rotating module for 1D rotation (e.g., rotation along a horizontal axis). Accordingly, during a scanning process, MEMS mirror **612** may be controlled to rotate to achieve one dimensional scanning, while rotary base **621** may be controlled to rotate 1D optical sensing apparatus **601** including the MEMS mirror **612** to achieve the other dimensional scanning in a 2D scanning process. In addition, by controlling the rotation speeds of MEMS mirror **612** and rotary base **621**, different scanning patterns may be also achieved. Further, by controlling the rotation speed of rotary base **621** and/or firing time of the laser emitter(s) of LiDAR system **600**, the resolution of the 2D environmental sensing may be also controlled, as discussed in FIG. 3.

(54) It is to be noted that spinning LiDAR systems illustrated in FIGS. 3 and 6 are merely two exemplary spinning LiDAR systems that combine a rotary base with a 1D MEMS scanner to achieve a 2D scanning. In actual applications, many different spinning LiDAR systems that contain a 1D MEMS scanner may be applied to achieve a target 2D scan of the environment in optical sensing.

(55) FIG. 7 is a flow chart of an exemplary optical sensing method of an optical sensing system (e.g., a spinning LiDAR system **102** containing a 1D MEMS scanner), according to embodiments of the disclosure. In some embodiments, method **700** may be performed by various components of LiDAR system **102**, e.g., rotary base **221**, 1D optical sensing apparatus **201** mounted on rotary base **221**, and controller(s) **106**. In some embodiments, method **700** may include steps **S702-S708**. It is to be appreciated that some of the steps may be optional. Further, some of the steps may be performed simultaneously, or in a different order than that shown in FIG. 7.

(56) In step **S702**, an optical source (e.g., laser emitter **208** inside 1D optical sensing apparatus **201** mounted on rotary base **221**) may sequentially emit a series of optical signals. Here, the series of optical signals may be emitted by the optical source at a predefined time interval. In addition, the series of signals may have a same wavelength and have a same power during a certain period when the optical sensing system is sensing an environment surrounding the system.

(57) In some embodiments, besides the optical source that emits the optical signals, the 1D optical sensing apparatus mounted on the rotary base may further include a 1D MEMS scanner (e.g., 1D MEMS scanner **212** of LiDAR system **102**) for scanning the optical signals towards the environment, and a receiver (e.g., receiver **204** of LiDAR system **102**) for receiving at least a portion of the optical signals reflected from the environment surrounding the LiDAR system.

(58) In step **S704**, the rotary base of the optical sensing system may be controlled to rotate around a

first axis, where the first axis may be a central axis of the rotary base. When the rotary base is mounted horizontally on a vehicle (e.g., vehicle **100**), and the 1D optical sensing apparatus is mounted vertically on top of the rotary base, the first axis may be a vertical axis. In some embodiments, the rotation of the rotary base may also cause the 1D optical sensing apparatus to rotate along a same axis (e.g., a same vertical axis or central axis of the rotary base). Since the 1D optical sensing apparatus is caused to rotate around the central axis, the 1D MEMS scanner is also caused to move circularly around the same central axis of the rotary base, thereby achieving a first dimension of scanning due to the circular movement of the 1D MEMS scanner. The first dimension may be a horizontal dimension if the central axis of the rotary base is vertically aligned when the optical sensing system is mounted on the vehicle.

(59) In step **S706**, the 1D MEMS scanner may be controlled to independently rotate around a second axis. The independent rotation of the 1D MEMS scanner may cause the 1D scanner to further direct the optical signals towards the environment in a second dimension. In some embodiments, the second axis of the 1D MEMS scanner may be the rotational axis of the 1D MEMS scanner, and may be perpendicular to the central axis of the rotary base. Accordingly, the second dimension may be perpendicular to the first dimension. For instance, if the first dimension is a horizontal dimension, the second dimension is then a vertical dimension. Accordingly, the 1D MEMS scanner may achieve a 2D scanning of the environment, driven by its own rotation along the rotational axis and by its circular movement around the central axis of the rotary base, which is perpendicular to the rotational axis of the 1D MEMS scanner.

(60) In step **S708**, the receiver of the optical sensing system may receive at least a portion of the optical signals reflected from the environment. The received portion of optical signals may follow a same path (e.g., in a coaxial LiDAR) or a different path (e.g., in a semi-coaxial LiDAR). When following a same path, a beam splitter may be disposed along the optical path, to transmit the reflected optical signals towards the receiver. In some embodiments, a quarter-wave plate may be also disposed along the optical path, to convert linear polarization to circular polarization for the beam splitter to transmit the reflected optical signals as expected. When following a different path, a reflecting mirror may reflect the returning laser beams towards the receiver. After receiving the returned portion of optical signals, the receiver may convert the received portion of optical signals to digital signals, which may be used for further analysis, e.g., for constructing a high-definition map or 3D buildings and city modeling. Depending on the rotation angles configured for the rotary base of the optical sensing system, the constructed high-definition map or 3D buildings and city modeling may cover a specific part of the areas around the vehicle, or cover more complete areas surrounding the vehicle.

(61) Although the disclosure is made using a LiDAR system as an example, the disclosed embodiments may be adapted and implemented to other types of optical sensing systems that use receivers to receive optical signals not limited to laser beams. For example, the embodiments may be readily adapted for optical imaging systems or radar detection systems that use electromagnetic waves to scan objects.

(62) It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed system and related methods. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed system and related methods.

(63) It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

Claims

1. An optical sensing system for two-dimensional (2D) environmental sensing, comprising: a rotary base; and a one-dimensional (1D) optical sensing apparatus supported by the rotary base, wherein

the 1D optical sensing apparatus comprises: an optical source, configured to emit optical signals; a quarter-wave plate, configured to convert a linearly polarized laser beam in the optical signal to circularly polarized or a circularly polarized laser beam in the optical signals to linearly polarized; a 1D micro-electro-mechanical systems (MEMS) scanner, configured to direct the optical signals towards an environment surrounding the optical sensing system; and a receiver, configured to receive at least a portion of the optical signals reflected from the environment, wherein the rotary base is configured to drive the 1D optical sensing apparatus to rotate around a first axis to scan the optical signals in a first dimension in the 2D environmental sensing and the 1D MEMS scanner is configured to independently rotate around a second axis to scan the optical signals in a second dimension in the 2D environmental sensing.

2. The optical sensing system of claim 1, wherein the first axis is a central axis of the rotary base.

3. The optical sensing system of claim 1, wherein the first dimension is perpendicular to the second dimension.

4. The optical sensing system of claim 1, wherein the optical source, the 1D MEMS scanner, and the receiver inside the 1D optical sensing apparatus synchronously move circularly around the first axis when driven by the rotary base.

5. The optical sensing system of claim 1, wherein an alignment between the optical source and the receiver remains unchanged when the 1D optical sensing apparatus is caused to rotate.

6. The optical sensing system of claim 1, wherein the 1D MEMS scanner comprises an array of MEMS mirrors each driven by a MEMS actuator coupled thereto to rotate around the second axis.

7. The optical sensing system of claim 1, wherein the 1D optical sensing apparatus further comprises a beam splitter that is configured to allow the emitted optical signals to pass through the beam splitter while transmitting the at least a portion of the optical signals towards the receiver.

8. The optical sensing system of claim 1, wherein the optical source comprises a single laser emitting module.

9. The optical sensing system of claim 1, wherein the optical source comprises a limited number of laser emitting modules less than a first predetermined threshold.

10. The optical sensing system of claim 1, wherein the receiver comprises a single photosensing detector.

11. The optical sensing system of claim 1, wherein the receiver comprises a number of photosensing detectors less than a second predetermined threshold.

12. The optical sensing system of claim 1, further comprising a controller configured to control a rotation speed of the rotary base according to a target resolution for the 2D environmental sensing.

13. An optical sensing method for an optical sensing system, the optical sensing system comprising a rotary base and a 1D optical sensing apparatus supported by the rotary base, the 1D optical sensing apparatus further comprising an optical source, a quarter-wave plate, a 1D MEMS scanner, and a receiver, the method comprising: emitting, by the optical source, optical signals; converting, by the quarter-wave plate, a linearly polarized laser beam in the optical signal to circularly polarized or a circularly polarized laser beam in the optical signals to linearly polarized; controlling the rotary base to rotate around a first axis, a rotating of the rotary base causing the 1D optical sensing apparatus to also rotate around the first axis, allow the 1D MEMS scanner to direct the optical signals in a first dimension towards an environment; controlling the 1D MEMS scanner to independently rotate around a second axis, to direct the optical signals in a second dimension towards the environment; and receiving, by the receiver, at least a portion of the optical signals reflected from the environment.

14. The optical sensing method of claim 13, wherein, before receiving the at least a portion of the optical signals, the method further comprises: transmitting, by a beam splitter, the at least a portion of the optical signals towards the receiver.

15. The optical sensing method of claim 13, wherein, before receiving the at least a portion of the optical signals, the method further comprises: reflecting, by a portion of a MEMS mirror, the at

least a portion of the optical signals towards the receiver.

16. The optical sensing method of claim 13, wherein an alignment between the optical source and the receiver remains unchanged when the 1D optical sensing architecture is caused to rotate by the rotary base.

17. The optical sensing method of claim 13, wherein the optical source comprises a single laser emitting module.

18. The optical sensing method of claim 13, wherein the optical source comprises a limited number of laser emitting modules less than a first predetermined threshold.

19. The optical sensing method of claim 13, wherein the receiver comprises a single photosensing detector.

20. The optical sensing method of claim 13, wherein the receiver comprises a number of photosensing detectors less than a second predetermined threshold.
