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MOTORS FOR DRIVING MULTI-ELEMENT OPTICAL SCANNING DEVICES, AND ASSOCIATED SYSTEMS AND METHODS

Abstract

An optical system includes at least one optical element positionable along an optical path to receive radiation, a shaft extending through a center of the at least one optical element, and an emitter configured to emit light along an emitted light axis. The emitted light axis does not coincide with a shaft axis of the shaft.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of application Ser. No. 17/651,864, filed on Feb. 21, 2022, which is a continuation of International Application No. PCT/CN2019/102069, filed Aug. 22, 2019, the entire contents of both of which are incorporated herein by reference.

TECHNICAL FIELD
[0002] The present technology is directed generally to motors for driving multi-element optical scanning devices, and associated systems and methods.
BACKGROUND
[0003] Optical scanners have many applications including applications directed to autonomous driving. The environment of a mobile platform can typically be scanned or otherwise detected using one or more sensors such as LiDAR sensors which typically transmit a pulsed signal (e.g., laser signal) and detect reflections of the pulsed signal. Three-dimensional information about the environment can be determined in this way (e.g., at laser scanning points). While existing LiDAR sensors are typically suitable for their intended purpose, there is a continual user-driven demand for more compact, lightweight, long-lasting, and/or integratable LiDAR sensors for use on a wide variety of mobile platforms. Aspects of the technology described herein are directed to meeting these demands.
SUMMARY
[0004] Representative systems in accordance with the present technology include an optical system, comprising at least one optical element positionable along an optical path to receive radiation, the at least one optical element having an opening therethrough. The system can further include a shaft extending through the opening, a bearing operably coupled to the shaft, and a motor coupled to the at least one optical element to rotate the at least one optical element. The motor can include a stator and a rotor, and the system can further comprise a yoke coupled between the rotor and the at least one optical element.
[0005] In further representative embodiments, the shaft is fixed, with the bearing positioned in the opening. The stator can be positioned in the opening, and the rotor can be positioned either within or outside the opening.
[0006] The shaft can be supported via a shaft support, which can include, for example, a hub, a rim, and one or more spokes between the hub and rim. In representative embodiments, at least one of the shaft support or the shaft include a surface inclined at a non-orthogonal angle relative to the optical path to direct light off the optical path. The inclined surface can be provided in addition to, or in lieu of, a light-absorptive material.
[0007] In particular embodiments, the optical element has a weight distribution that is not axis symmetric relative to the shaft, and the system can further include a yoke carrying and positioned around the optical element, with the yoke having a weight distribution that is complementary to the weight distribution of the optical element.
[0008] In further particular embodiments, the bearing is axially loaded to at least reduce axial motion between elements of the bearing. For example, the system can include a pedestal having an inwardly facing step engaged with the bearing and an outwardly facing step engaged with the at

least one optical element. The bearing can include two bearing elements, each bearing element including an inner race and an outer race, with the outer races of each bearing element positioned on opposite sides of the inwardly facing step and engaged with the inwardly facing step.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a schematic block diagram of a system for sensing an environment around a vehicle or other moving object, in accordance with embodiments of the present technology.

[0010] FIG. **2** is a partially schematic illustration of a system having optical elements positioned to transmit and receive light or other radiation, in accordance with embodiments of the present technology.

[0011] FIG. **3**A is a partially schematic illustration of a representative light path configured in accordance with embodiments of the present technology.

[0012] FIG. **3**B is a partially schematic illustration of an emitter having one or more emitter elements configured in accordance with embodiments of the present technology.

[0013] FIG. **3**C is a partially schematic illustration of a receiver having one or more receiver elements configured in accordance with embodiments of the present technology.

[0014] FIG. **4** is a partially schematic illustration of a system having multiple optical elements with bearings configured in accordance with embodiments of the present technology.

[0015] FIG. **5**A is a partially schematic illustration of a system having components with occluded areas, and corresponding light paths, in accordance with embodiments of the present technology.

[0016] FIG. **5**B is a partially schematic illustration of a collimation element with a light extinction treatment configured in accordance with embodiments of the present technology.

[0017] FIG. **5**C is a partially schematic illustration of a collimation element having another light extinction treatment configured in accordance with embodiments of the present technology.

[0018] FIG. **6** is a partially schematic illustration of a system having an angularly offset emitted light axis configured in accordance with embodiments of the present technology.

[0019] FIG. **7** is a partially schematic illustration of a system having a laterally offset emitted light axis configured in accordance with embodiments of the present technology.

[0020] FIG. **8**A is a partially schematic illustration of a system having a laterally offset optical axis configured in accordance with further embodiments of the present technology.

[0021] FIGS. **8**B and **8**C illustrate systems having at least three optical elements configured in accordance with representative embodiments of the present technology.

[0022] FIG. **9** is a partially schematic illustration of an actuator having bearing elements arranged in accordance with representative embodiments of the present technology.

[0023] FIG. **10**A is a partially schematic illustration of an actuator having an optical element and yoke arranged in accordance with representative embodiments of the present technology.

[0024] FIG. **10**B is a partially schematic illustration of an actuator having a yoke and bearings configured in accordance with further representative embodiments of the present technology.

[0025] FIG. **11** is a partially schematic illustration of an actuator having a rotor positioned within an optical element in accordance with representative embodiments of the present technology.

[0026] FIG. **12**A is a partially schematic illustration of an actuator having bearing elements and a yoke carrying an optical element in accordance with embodiments of the present technology.

[0027] FIG. **12**B is a partially schematic illustration of a representative stator of the type shown in FIG. **12**A.

[0028] FIG. **12**C is a partially schematic, isometric illustration of a stator configured in accordance with representative embodiments of the present technology.

[0029] FIG. **12**D is a partially schematic, isometric illustration of a rotor carried by a yoke and

configured in accordance with representative embodiments of the present technology.
[0030] FIGS. **13**A and **13**B are partially schematic illustrations of actuators having shaft supports configured in accordance with representative embodiments of the present technology.
[0031] FIGS. **14**A and **14**B are partially schematic illustrations of actuators having shaft supports and/or other representative elements inclined in accordance with representative embodiments of the present technology.
[0032] FIGS. **15**A and **15**B illustrate details of representative inclined surfaces in accordance with embodiments of the present technology.
[0033] FIGS. **16**A and **16**B illustrate optical elements and corresponding yokes configured in a rotationally balanced combination in accordance with representative embodiments of the present technology.
[0034] FIGS. **17**A and **17**B illustrate representative systems configurations with preload forces applied to corresponding bearing elements in accordance with representative embodiments of the present technology.
[0035] FIGS. **18**A-**18**E illustrate representative configurations of optical elements having sloped, angled, or inclined surfaces arranged in accordance with embodiments of the present technology.
[0036] FIG. **19** is a partially schematic illustration of representative vehicles and/or other devices on which sensing systems described herein are included, in accordance with representative embodiments of the present technology.

DETAILED DESCRIPTION

[0037] The present technology is directed generally to small bearings and motors for driving multi-element optical scanning devices, and associated systems and methods. In representative embodiments, the bearings are configured to be positioned within openings of the optical elements, as opposed to at the outer edges of the optical elements. This arrangement can reduce the velocities associated with the bearing components, thereby reducing component wear and extending the lifetime of the devices. The motors can be integrated with the bearings and the optical elements in manners that are more compact than traditional devices, allowing these devices to be used in contexts where low weight and low volume provide significant overall system advantages.
[0038] Representative ranging devices (e.g., LiDAR devices) are described under Heading 1 below (“Introduction”). Representative devices and systems that incorporate the small bearings and/or motors into multi-element devices are described in further detail under Heading 2 below (“Representative Systems and Methods”).

1. Introduction

[0039] Representative devices in accordance with the present technology include LiDAR devices, laser ranging equipment and other electronic equipment. In representative implementations, a ranging device is used to sense the external environment and obtain corresponding information, for example, the distance to a target, the azimuth angle of an object or component, the strength of reflected light or other radiation, the speed of an object, among others. For example, the ranging device can detect the distance from the detector to a target object by measuring the light propagation time between the ranging device and the object, that is, the light flight time (time-of-flight, or “TOF”). The ranging device can use other techniques in addition to or in lieu of TOF to detect the distance from the ranging device to the object, such as a ranging method based on phase movement (phase shift) measurements, or a ranging method based on frequency movement (frequency shift) measurements.
[0040] Throughout the discussion of the present technology, the radiation emitted and received by the ranging device may be referred to as light, laser light, beams, etc. Unless otherwise noted, such terms are used as representative examples of electromagnetic radiation. Accordingly, the present technology includes all suitable electromagnetic radiation, whether in the visible spectrum or not.
[0041] FIG. **1** illustrates a representative system **100** (e.g., for performing ranging tasks) that can include a transmitting (or emitting) circuit **101**, a receiving (or detecting) circuit **102**, a sampling

circuit **103**, and an operation circuit **104**. The transmitting or emitting circuit **101** can emit light, or other electromagnetic, pulse sequences (such as laser pulse sequences), e.g., in the form of a beam. The receiving circuit **102** can receive the light pulse sequence reflected by the detected object, and convert the light pulses to an electrical signal (e.g., via the photoelectric effect). The electrical signal can be processed and then output to the sampling circuit **103**. The sampling circuit **103** directs sampling results to an operation circuit **106** which can determine the distance between the ranging system **100** and the detected object, and/or other useful information.

[0042] Optionally, the ranging system **100** can also include a control circuit **105** that controls one or more of the illustrated circuits, for example, the working time of each circuit and/or the operational parameters of each circuit.

[0043] Although the illustrated ranging system shown in FIG. **1** includes a transmission circuit, a receiving circuit, a sampling circuit and an operation circuit for detecting reflections from the emitted beam, in other embodiments, the number of transmission circuits, receiving circuits, sampling circuits, and/or computing circuits can be greater, e.g., for emitting/detecting multiple beams in the same direction or in different directions. The multiple beams (e.g., at least two beams) can be emitted at the same time, or they can be emitted at different times. In one example, the circuitry chips for at least two emitting circuits are encapsulated in the same module. For example, multiple laser emitting chips can be encapsulated together and placed in the same encapsulation space, as described later with reference to FIG. **3**B.

[0044] In some implementations, in addition to the circuit shown in FIG. **1**, the ranging system **100** can also include a scanning module (described further below with reference to FIG. **2**), which is used to change the propagation direction of at least one laser pulse sequence emitted by the transmitting circuit.

[0045] In some implementations, modules including the emitting circuit **101**, receiving circuit **102**, sampling circuit **103** and operation circuit **104**, optionally further including the control circuit **105**, are referred to as a ranging module. The ranging module can be independent of other modules, for example, the scanning module.

[0046] The beam emitted by the ranging device and the beam reflected by an object in the environment can share at least part of the same optical path in the ranging device, e.g., in a coaxial arrangement. Alternatively, the ranging device can include a heterogeneous optical path, that is, the beam emitted by the ranging device and the reflected beam are transmitted along different optical paths in the ranging device. FIG. **2**, described further below, is a schematic diagram of an embodiment of the measuring device of the present technology that includes a coaxial light path.

[0047] Referring now to FIG. **2**, a representative system **200** includes a ranging device **208**. The ranging device **208** can include the transmitter (or emitter) **201** (which can include the transmitting circuit **101** described above), a collimation element **270**, a receiver or detector **202** (which can include the receiving circuit **102**, sampling circuit **103** and operation circuit **106** described above), and an optical path change element **210**. The ranging device **208** is used to transmit a beam **212** and receive the reflected beam, converting the returned beam into an electrical signal. Accordingly, the transmitter **201** and receiver **202** may be referred to collectively as a transceiver **207**. In some embodiments, the transmitter **201** can emit a laser pulse sequence, e.g., in the form of a laser beam. The laser beam can be a narrow bandwidth beam with wavelengths within or outside the visible light range. The collimation element **270** is arranged along an emitted light path or optical axis **272** of the transmitter **201** and is used to direct the beam **212** emitted from the transmitter **201**, e.g., to straighten the beam to include parallel components before it reaches the associated scanner **204**. The collimation element **270** can also be used to converge at least part of the reflected radiation **215** before it reaches the receiver **202**. The collimation element **270** can include a collimation lens or other component configured to collimate the beam(s).

[0048] In an embodiment shown in FIG. **2**, the paths along which the emitted light and the received light pass, merge in the ranging device **208** between the scanner **204** and the collimation element

270, so that the emitted light and the received light can share the same collimation element **270**, making the light paths more compact. In other implementations, the system can include two collimation elements: one for emitted light and one for received light.

[0049] In the embodiment shown in FIG. **2**, the beam aperture of the transmitter **201** is relatively small, and the beam aperture of the returned light received by the ranging device **208** is larger, so the optical path change element **210** can use a small area reflector to merge the paths of the emitted light and the received light. In other implementations, the optical path change element **210** can use a reflector with a through hole, wherein the through hole is used to pass the emitted light, and the reflector is used to reflect the returned light to the receiver **202**.

[0050] The scanner **204** is placed along the path of the emitted light (e.g., beam) **212**, and changes the direction of the beam collimated by the collimation element **270**. The beam is then directed into the external environment, and the returned or reflected beam is directed by the scanner **204** back to the collimation element **270**.

[0051] In some embodiments, the scanner **204** can include at least one optical element to change the propagation path of the beam, by reflection, refraction, diffraction, and/or other techniques. For example, the scanner **204** can include one or more lenses, mirrors, prisms, vibrators, gratings, liquid crystals, optical phased arrays, and/or any suitable combination of the foregoing optical elements. In one example, at least part of the optical element moves. In some embodiments, multiple optical elements of the scanner **204** can rotate or vibrate relative to a common axis (e.g., a rotation axis) **209**, and each rotating and/or vibrating optical element can continuously alter the propagation direction of the emitted beam. In some embodiments, multiple optical elements of the scanner **204** can rotate and/or vibrate at different speeds, or at the same speed. In some embodiments, multiple optical elements of the scanner **204** can rotate/vibrate about different axes. In some embodiments, the multiple optical elements can rotate and/or vibrate in the same direction or in different directions.

[0052] In some embodiments, the scanner **204** includes a first optical element **120**, coupled to a first actuator **280***a* to rotate the first optical element **120** around the rotation axis **209**, thus changing the direction of the emitted beam **212**. The angle between the direction of the beam **212** after passing through the first optical element **120** varies with the rotation of the first optical element **120**. In one embodiment, the first optical element includes non-parallel opposing surfaces, e.g., a wedge-shaped prism with a thickness variation along at least one axis.

[0053] The scanner **204** can also include a second optical element **130**, coupled to a second actuator **280***b* to rotate about the rotation axis **209**, e.g., at a speed different than the rotation speed of the first optical element **120**. The second optical element **130** changes the direction of the beam exiting the first optical element **120**. Depending upon the configuration, the first optical element **120** and the second optical element **130** can be driven by the same or different actuators, but in either case, can direct the emitted beam **212** into different directions, thus scanning a larger space. The second optical element **130** can include any of the foregoing elements described above with reference to the first optical element **120**, and can be the same as or different than the first element **120**. In some embodiments, the scanner **204** further includes a third optical element (not shown in FIG. **2**) and associated actuator.

[0054] Regardless of the number of optical elements included in the scanner **204**, the scanner **204** can receive the incoming beam **212** (e.g., from the collimation element **270**) and, as a result of rotating, vibrating, and/or undergoing other movement, redirect the incoming light in multiple directions, shown in FIG. **2** as a first direction **213** and a second direction **214**. The emitted light strikes an object **211** in the environment, creating reflected light **215**, some of which is directed in a third direction **216**. Accordingly, at least a portion of the reflected light returns to the scanner **204**, passes through the one or more optical elements, through the collimation element **270**, and to the receiver **202**. The receiver **202** generates an electrical signal which provides an input **291** to a controller **290**. The controller **290** processes the input, along with other inputs, and directs an output **292**. The output **292** can be used to control any of a variety of functions, including, but not limited to, the direction, speed, and/or orientation or pose of an autonomous or other vehicle.

[0055] FIG. **3**A is a partially schematic illustration of a representative system **300** illustrating selected elements in further detail. The system **300** includes a transmitter or emitter **301** that directs emitted light **312** to a first mirror **310***a*. The first mirror **310***a* redirects the light to a collimation element **370**, which in turn directs emitted light **312** to a scanner (not shown in FIG. **3**A). Reflected light **315** is returned to the collimation element **370** where it passes through a splitter **317**. A portion of the reflected light **315** impinges on a second mirror **310***b*, which redirects the reflected light to a receiver or detector **302**. The receiver **302** generates the electrical signal which is directed to the controller **290** (FIG. **2**).

[0056] FIG. **3**B illustrates a representative emitter **301** that includes multiple emitter elements **301***a*, which can be encapsulated together. FIG. **3**C illustrates a representative receiver **302**, which includes multiple receiver elements **302***a*. The emitter elements **301***a* and receiver elements **302***a* can include any of a variety of suitable solid state devices, and/or other devices configured to emit and receive radiation inside or outside the visible spectrum. For example, the emitter elements **301***a* can include laser diodes, and the receiver elements **302***a* can include photodiodes.

[0057] The resulting information obtained from the receiver **302** can be used to generate distance and/or azimuth data corresponding to the detected object **211** (FIG. **1**). This information can in turn be used for remote sensing, obstacle avoidance, mapping, modeling, navigation and/or other functions. The ranging devices in accordance with the present technology can be applied to a mobile platform, e.g., an autonomous or partially autonomous vehicle.

2. Representative Systems and Methods

[0058] One drawback associated with some conventional sensor systems is that they are large and bulky, which makes them difficult to integrate into smaller and/or weight-sensitive platforms. One cause for the additional bulk is the bearings that are used to provide smooth, low-friction rotation for the optical devices. For example, such bearings are typically placed around the outside of the optical devices. The optical devices are also typically driven from a radially outward position, so as to avoid interfering with the optical light paths within the scanner. Aspects of the present technology are directed to, instead, providing apertures or openings within the optical elements and placing the bearings and/or other elements of the drive mechanism within the openings. While this approach results in occluded regions along the optical path, the technology further includes techniques to address the occlusion, resulting in devices that are compact, lightweight, and yet still provide suitable ranging and detection functions.

[0059] FIG. **4** illustrates a representative system **400** having a housing **440** in which a first optical element **420** (e.g., a first prism) and a second optical element **430** (e.g., a second prism) are positioned. Each optical element includes a corresponding opening, illustrated as a first opening **422** and a second opening **432**. A shaft **460** extends along a shaft axis **461** and passes through the first and second openings **422**, **432**. One or more bearings **450**, for example, each including multiple bearing elements **451**, are positioned within the corresponding openings to stabilize the rotary motion of the first and second optical elements **420**, **430** relative to the shaft **460**. Accordingly, the shaft **461**, in combination with the bearing(s) **450**, can act as a mandrel to keep the optical elements **420**, **430** centered as they smoothly rotate. By placing the bearings **450** close to the radial centers of the optical elements, the bearings **450** can be made smaller than bearings in typical conventional installations. In addition, the linear velocities near the radial centers of the optical elements are lower than at the tips of the optical elements, which reduces the wear and tear on the bearings and therefore can extend the operational life of the system **400**. The bearings **450** can have a ball bearing configuration, for example, with an inner race, an outer race, and multiple balls between the races, optionally further including one or more retainers, and/or other suitable types of bearings. Such bearings can typically include oil or grease which, if the bearing heats up significantly, breaks down or otherwise suffers a reduction in efficacy. Accordingly, reducing the velocity of the bearing components can increase bearing efficiency and life by reducing the likelihood for adversely affecting the lubricant. Furthermore, at low temperatures, the lubricant becomes more viscous, and, with the greater moment arm resulting from the bearings being positioned at the outer periphery of the optical elements, can create so much friction that the optical elements are unable to rotate, and/or the actuators that drive the optical elements draw so much current that the associated circuitry fails. Again, positioning the bearings closer to the radial centers of the optical elements can reduce or eliminate this undesirable effect. Still further, by reducing frictional loads on the bearings, the amount of power required by the motors or other actuators driving the optical elements can be reduced, not only at start up, but also during normal operating conditions.

[0060] FIG. **5**A illustrates further elements of a representative system **500**. The system includes a transceiver **507** that transmits emitted light and receives reflected light to detect information corresponding to the external environment. The emitted light **512** proceeds from a focal plane **519**, oriented along an orthogonal axis **562**, to a collimation element **570** that collimates the light directed to the scanner **504**. At the scanner **504**, a first optical element **520** and a second optical element **530** receive the incoming emitted light **512**, and rotate about a shaft axis **561**. Each optical element includes a corresponding opening **522**, **532** which houses a bearing, and which presents one or more occlusion surfaces **523** and produces a corresponding occlusion area **524**. The occlusion area **524** results in an emitted light gap **525**. The emitted light **512** proceeds along an optical path **518** to an object (not shown in FIG. **5**A) which reflects the light, producing reflected light **515** that passes along the optical path **518** in the reverse direction. This arrangement is compact, and the light reduction resulting from the occlusion area **524** can be at or below acceptable levels.

[0061] The emitted light **512** passing from the collimation element to the scanner **504** can impinge upon, and reflect from, the occlusion areas **524** of the first and/or second optical elements **520**, **530**. Accordingly, typical designs will include occlusion areas **524** that are as small as possible, while providing enough area to accommodate the associated bearings and/or other elements. To reduce or eliminate such reflections which could otherwise create optical noise or other interference within the scanner **504**, the collimation element **570** can (optionally) include light extinction treatments, described further below with reference to FIGS. **5**B and **5**C.

[0062] Referring first to FIG. **5**B, the collimation element **570** can include a light extinction treatment **571** facing toward the focal plane **519** shown in FIG. **5**A. Suitable light extinction treatments **571** can include materials that are highly absorptive of the emitted light (and/or have low reflectivity), thus reducing internal reflections within the scanner **504**. Suitable materials include matt black oxidation, and/or coatings with light extinction paint. Such paint or other coatings can be applied to specific parts of the optical (or other) elements to prevent the emitted light striking such parts and producing undesirable reflections. As described later with reference to FIGS. **14**A-**15**B, the device can include inclined or sloped surfaces to redirect internal reflections for absorption or attenuation. The light extraction treatment can have different patterns and/or arrangements, depending upon the shape of the occlusion areas **524** shown in FIG. **5**A. For example, the light extraction treatment **571** shown in FIG. **5**B has a generally circular shape located at the center of the collimation element **570**, corresponding to a similarly-shaped occlusion area. In FIG. **5**C, the light extinction treatment **571** includes a first generally circular region **571***a*, and a second region **571***b* that extends radially outwardly from the first region **571***a*. The second region **571***b* can account for other structures within the scanner (e.g., spokes or other support structures, described later with reference to FIGS. **13**A, **13**B) that may otherwise also reflect light within the scanner, creating optical noise.

[0063] In addition to, or in lieu of, the light extraction treatments described above, representative systems can include configurations that direct the emitted light in a way that avoids impinging on the occlusion areas, thus reducing or eliminating the need for light extinction treatments. FIGS. **6**-

8C illustrate representative systems having such configurations.
[0064] Referring first to FIG. **6**, a representative system **600** includes an optical path **618** that extends from a corresponding focal plane **619**, at a non-zero inclination angle A relative to an orthogonal axis **662**. In FIG. **6**, the orthogonal axis **662** is orthogonal to the collimation element **670** and/or the focal plane **619**, and is aligned with a shaft axis **661** passing through openings **622**, **632** in the corresponding first and second optical elements **620**, **630**. Because the emitted light **612** is directed radially outwardly from the occlusion areas **624** of the optical elements **620**, **630**, the optical elements need not include (or need not include as much) light extinction treatment. While the amount of light emitted by the system **600** may be reduced relative to an arrangement that utilizes the full radial extent of the optical elements outside the occlusion areas **624**, the light reduction is not expected to significantly affect system performance.
[0065] As discussed above with reference to FIG. **6**, the illustrated emitted light axis **672** is oriented at an angle relative to the orthogonal axis **662**. In other embodiments, the optical elements can be oriented at such an angle. For example, referring now to FIG. **7**, a representative system **700** include a focal plane **719** and a corresponding emitted light axis **772** that is offset by an offset distance D from a corresponding orthogonal axis **762** of the corresponding collimation element **770** and/or focal plane **719**. The first and second optical elements **720**, **730** each have corresponding openings **722**, **732** and occlusion areas **724**. The optical elements **720**, **730** are positioned for rotation about a shaft axis **761**, which is oriented at a non-zero inclination angle B relative to the orthogonal axis **762**. Accordingly, the emitted light **712** passes along the corresponding emitted light axis **772** in a manner that avoids or reduces impingement on the occlusion areas **724**.
[0066] FIGS. **8**A-**8**C illustrate further representative embodiments of systems for which the emitted light is directed (at least in part) around or away from the corresponding occlusion areas. Referring first to FIG. **8**A, a system **800***a* directs emitted light **812***a* from a corresponding focal plane **819** along an emitted light axis **872** that is offset by an offset distance D from the corresponding orthogonal axis **862** of the collimation element **870** and/or focal plane **819**. The system **800***a* includes first and second optical elements **820***a*, **830***a* that rotate relative to the shaft axis **861**, while the emitted light **812***a* bypasses (at least in part) the corresponding occlusion areas **824**.
[0067] Similar arrangements can be used for systems that include more than two optical elements. For example, FIG. **8**B illustrates a representative system **800***b* that produces emitted light **812***b* passing through a first optical element **820***b* to a first plane **826***b*. The first optical element **820***b* can be supported using one or more centrally-located small bearings **850**, e.g. of the type shown in FIG. **4**. The corresponding emitted light axis **872** is offset from the occlusion area **824** associated with the first optical device **820***b*. The system **800***b* can further include multiple second optical elements **830***b*, shown as second optical elements **830***b***1** and **830***b***2**. The second optical elements **830***b* redirect the emitted light **812***b* to a second plane **836***b*, and can be supported by larger bearings **850***b* positioned outwardly around the optical elements **830***b*.
[0068] Referring next to FIG. **8**C, a representative system **800***c* includes a shaft **860** carried by multiple first optical elements **820***c*, illustrated as first optical elements **820***cl* and **820***c***2**. The emitted light passes through a first plane **826***c*, through a corresponding second optical element **830***c* and to a second optical plane **836***c*. In this configuration, the first optical elements **820***c***1**, **820***c***2** are supported by one or more small, centrally-located bearings **850**, and the second optical element **830***c* is supported by a larger, outwardly positioned bearing **850***b*.
[0069] One feature of the representative embodiments shown in FIGS. **8**B and **8**C is that they can include more than two optical elements. Another feature of the representative embodiments shown in FIGS. **8**B and **8**C is that they can include a combination of bearing arrangements. For example, the first optical elements in FIGS. **8**B and **8**C include small bearings **850** positioned close to the rotation axis of the first optical elements, while the second optical elements include larger bearings **850***b* positioned around the outsides of the second optical elements. The smaller bearings can be used for components having relatively high rotation speeds, and the larger bearings can be used for

components having slower rotation speeds. Even if fewer than all the optical elements include bearing arrangements located near the rotation axis (as shown in FIGS. **8**B and **8**C), the devices nevertheless are expected to provide an overall lighter and more efficient arrangement. In other embodiments (not shown in FIGS. **8**B and **8**C), all the optical elements, or at least more of the optical elements, can include bearing arrangements with the bearing elements located close to the rotation axis. Further details of the bearing arrangements and associated drive mechanisms are described in further detail below with reference to FIGS. **9**-**17**B.

[0070] FIG. **9** is a partially schematic, cross-sectional illustration of a system **900** that includes a housing **940** in which is positioned an actuator **980** that drives an optical element **920** supported relative to a fixed shaft **960** to rotate as indicated by arrow R. The optical element **920** includes an opening **922** through which the shaft **960** passes, and the actuator **980** includes a rotor **982** driven by an outwardly positioned stator **981**. The rotor **982** carries a rotor magnet **983** and is attached to a rotor yoke **984**. The rotor yoke **984** carries and rotates the optical element **920**. A bearing **950** is positioned between the shaft **960** and the optical element **920** (e.g., at least partially within the opening **922**) and can include one or more bearing elements **951**. Further details of arrangements for supporting and pre-loading the bearing components are described later with reference to FIG. **17**A-**17**B.

[0071] FIG. **10**A illustrates a representative optical element **1020** driven by a corresponding actuator **1080** having a stator positioned radially inwardly from the corresponding rotor. The optical element **1020** can correspond to any of the optical elements described above. The actuator **1080** drives the optical element **1020** to rotate relative to a fixed shaft **1060**, as indicated by rotation direction arrow R. The optical element **1020** is supported relative to the shaft **1060** by a bearing **1050** that includes one or more bearing elements **1051**. The illustrated actuator **1080** includes a fixed stator **1081**, and a rotor **1082** that includes a rotor magnet **1083** that is positioned outwardly from the stator **1081**. The rotor **1082** is coupled to the optical element **1020** via a yoke **1084**. Accordingly, when energized, the rotor **1082** spins the optical element **1020** about a rotation axis **1009** in the rotation direction R, while the optical element **1020** is stabilized relative to the shaft **1060** via the bearing **1050**. As described above, the bearing **1050** is positioned within an opening **1022** positioned along the rotation axis **1009** to reduce the velocities experienced by the bearing elements **1051** and thus reduce heating and wear. The bearing elements **1051** can include ball bearings, and/or other suitable rotary bearing components.

[0072] In FIG. **10**A, the optical element **1020** is positioned within the ring-shaped stator **1081**. In other embodiments, the optical element **1020** can have other positions relative to the stator **1081**. For example, referring now to FIG. **10**B, the optical element **1020** is positioned axially outside the stator **1081**, and outside the rotor magnet **1083**. The rotor magnet **1083** is carried by the rotor **1082**, which is connected to the optical element **1020** via the yoke **1084** in a manner generally similar to that described above with reference to FIG. **10**A. An advantage of the arrangement shown in FIG. **10**A is that the “nested” arrangement of the optical element **1020** within the stator **1081** and rotor **1082** can provide for a compact arrangement.

[0073] FIG. **11** is a partially schematic illustration of another actuator **1180** having the optical element **1020** positioned axially away from the corresponding stator **1181** and rotor **1182**. In addition, in this embodiment, the corresponding shaft **1160** is supported relative to a housing **1140** via a bearing **1150**. The rotor **1182** is connected to the optical element **1020** to rotate the optical element **1020**, and is connected to the shaft **1160** which stabilizes the optical element **1020** relative to the housing **1140** via the bearing **1150**.

[0074] FIG. **12**A illustrates a representative actuator **1280** having a housing **1240** carrying a fixed stator **1281** and a fixed shaft **1260**. The stator **1281** drives a corresponding rotor **1282**, which carries the optical element **1020** via a yoke **1284**. The optical element **1020** is stabilized relative to the shaft **1260** via a corresponding bearing **1250** having one or more bearing elements **1251**.

[0075] FIG. **12**B illustrates several of the elements described above with reference to FIG. **12**A, including the shaft **1260**, the stator **1281**, and the rotor **1282**. The stator **1281** includes a stator core **1285** having stator windings **1286**. The core **1285** and windings **1286** are shown in further detail in FIG. **12**C. FIG. **12**D illustrates an isometric view of the shaft **1260**, the bearing **1250** (positioned outwardly from the shaft **1260**), the optical element **1220** (positioned outwardly from the bearing **1250**), the rotor **1282** (positioned outwardly from the optical element **1220**), and the yoke **1284** (positioned outwardly from the rotor **1282**). The yoke **1284** can be a part of the rotor **1282**, or can be attached to the rotor. The yoke **1284**/rotor **1282** can carry a magnet, which is driven by the electrical current carried by the stator windings **1286**.

[0076] FIGS. **13**A-**15**B illustrate representative arrangements for supporting shafts and for reducing optical noise in a scanner via inclined, sloped, or angled surfaces. Referring first to FIG. **13**A, a representative scanner **1304** include a first optical element **1320** driven by a corresponding first actuator **1380***a*, and a second optical element **1330** driven by a second actuator **1380***b*. The scanner **1304** can further include a shaft **1360** which stabilizes the optical elements **1320**, **1330** as they rotate, and a shaft support **1363** that supports the shaft **1360**. The shaft support **1363** can include (or form a part of) an overall housing **1340** in which the optical elements **1320**, **1330** are positioned. The shaft support **1363** can further include a rim **1364** carrying one or more spokes **1366**. The spokes **1366** in turn carry a hub **1365** in which the shaft **1360** is received. The spokes **1366** can be thicker or deeper than they are wide, to provide increased strength (e.g., against bending) while reducing optical interference. In the illustrated embodiment, the shaft **1360** is fixed relative to the shaft support **1363**. In other embodiments, the shaft **1360** can rotate, and can accordingly include bearings of the type described herein.

[0077] FIG. **13**B illustrates an arrangement similar to that shown in FIG. **13**A, with the shaft support **1363** including two spokes **1366** rather than three. The reduced number of spokes **1366** shown in FIG. **13**B can reduce optical interference in the scanner **1304**, while the increased number of spokes **1366** shown in FIG. **13**A can improve the stability of the shaft **1360**.

[0078] FIG. **14**A illustrates an arrangement similar to that shown in FIG. **13**B, but with selected elements including sloped, angled, or inclined surfaces so as to avoid or attenuate optical reflections within the scanner **1304**. For example, several elements can include sloped surfaces **1367** (e.g., chamfers), including first sloped surfaces **1367***a* carried by the spokes **1366**, second sloped surfaces **1367***b* carried by the hub **1365**, and/or third sloped surfaces **1367***c* carried by the shaft **1360**. The sloped surfaces can redirect emitted light **1312** exiting the collimation element **1370** so as to be absorbed by other elements in the scanner **1304** (e.g., the surfaces of the rim **1364** or the housing **1340**) before reaching the first optical element **1320**.

[0079] In an embodiment shown in FIG. **14**A, the sloped surfaces form a peak or inverted "V" shape. In other embodiments, for example as shown in FIG. **14**B, the sloped surfaces can be sloped in a single direction. In particular, the hub sloped surface **1367***b* is sloped in a single direction, as is the shaft sloped surface **1367***c*. In other embodiments, the sloped surfaces can have orientations and/or configurations other than those shown in FIGS. **14**A-**14**B.

[0080] FIG. **15**A illustrates a representative sloped surface **1567** having a "V" shaped configuration. Emitted light **1512** forms incident radiation **1568**, which is then redirected by the sloped surfaces **1567** to form reflected radiation **1569**, which can be absorbed internally by other elements of the scanner **1304** (FIG. **14**A).

[0081] In FIG. **15**B, the sloped surfaces **1567** are positioned adjacent to corresponding absorptive surfaces **1559**. The absorptive surfaces **1559** receive and absorb or extinguish the reflected radiation **1569**. This arrangement can further reduce the optical noise within the associated scanner by capturing and absorbing reflected radiation before it is transmitted further within the scanner.

[0082] FIGS. **16**A and **16**B illustrate arrangements for balancing optical devices so as to reduce the tendency for the optical devices to wobble when rotated, and therefore reduce the loads on the associated bearings. Because the optical element **1020** can have a wedge or prism shape (see, e.g., FIG. **12**A), the optical element **1020** can include a lighter region **1627** (toward the narrower side of the wedge) and a heavier region **1628** (toward the thicker side of the wedge). To account for this asymmetry, the yoke **1684** can include a complementary heavier region **1678** (positioned adjacent the lighter region **1627** of the optical element **1020**) and a lighter region **1677** (positioned adjacent the heavier region **1628** of the optical element **1020**). In particular embodiments shown in FIGS. **16**A and **16**B, the lighter region **1677** of the rim **1687** can be made lighter via one or more apertures **1688**. In other embodiments, other techniques (e.g., using materials of different densities) can be used to provide a relative weight difference between the heavier region **1678** and the lighter region **1677**. In any of these embodiments, as described above, the complementary lighter and heavier regions **1677**, **1678** can balance the corresponding heavier and lighter regions **1628**, **1627** of the optical element **1020** to provide an overall balanced assembly.

[0083] FIGS. **17**A and **17**B illustrate techniques for applying a preload to the bearings that stabilize the rotary motion of the optical elements. Referring first to FIG. **17**A, a representative scanner **1704** includes a first optical element **1020** and second optical element **1030**, each supported by corresponding bearings **1750**. The bearings can include one or more bearing elements, including first and second bearing elements **1751***a*, **1751***b* carried by one bearing **1750** (e.g., a bearing retainer or pedestal **1752**), and third and fourth bearing elements **1751***c*, **1751***d* carried by the other bearing **1750**. Each bearing **1750** (e.g., the bearing elements **1751***a*, **1751***b*, **1751***c*, **1751***d*) can include an inner race, outer race, and multiple balls between the inner and outer races. The inner races are fixed relative to the shaft **1760**, and the outer races are fixed relative to the corresponding bearing retainer or pedestal **1752**, which is in turn fixed relative to the corresponding optical element **1020**, **1030**. Two stator couplings **1779** support the fixed shaft **1760** (aligned along a shaft axis **1761**) within the bearings **1750**. An optional shaft sleeve **1758** provides a mechanical connection between the two bearings **1750**. Accordingly, when an applied preload PL is applied to one stator coupling **1779**, the force is transmitted to the other bearing **1750** (via the shaft sleeve **1758**) to keep the bearings in position along the shaft **1760**. In addition, an inwardly-facing step or projection **1749** of the bearing retainer **1752** can form two-oppositely facing recesses in which the bearing outer races are positioned, with the inwardly-facing step engaged with each bearing outer race. The shaft sleeve **1758** can engage the bearing inner races, causing the inner and outer races to be biased in opposite directions. The bearing retainer **1752** can also include one or more outwardly-facing steps or projections **1759** that engage with the corresponding first or second optical element **1720**, **1730**. The outer surface of the shaft **1760**, and the inner surfaces of the bearings **1750**, can be coated with an adhesive which is dried or cured before the preload PL is released. Accordingly, the adhesive can preserve the preload after manufacture. In another embodiment, shown in FIG. **17**B, the shaft sleeve **1758** can be replaced by a biasing element **1753** (e.g., a spring) that biases the two bearings **1750** away from each other, as an alternate technique for preloading the bearings and keeping the bearings in fixed positions relative to the shaft **1760**.

[0084] As discussed above, representative optical elements have a wedge or prism shape. This shape can be formed by an orthogonal surface (orthogonal to the incoming or outgoing optical path, or to the shaft axis **1761**), and an inclined surface (inclined relative to the same path or optical axis). Multiple optical elements can have these surfaces arranged relative to each other in any of a number of suitable configurations, as illustrated below with reference to FIGS. **18**A-**18**B.

[0085] Referring first to FIG. **18**A, a representative system **1800** includes a transceiver **1807** and a scanner **1804**. The transceiver **1807** includes an emitter and receiver (not shown in FIG. **18**A) with a corresponding focal plane **1819** and optical path **1872**. A collimator **1870** collimates the emitted radiation and directs it to the scanning module **1804**. The scanning module **1804** houses the first optical element **1020** and the second optical element **1030** that rotate relative to a shaft or rotation axis **1861**. The first optical element **1020** can include an orthogonal surface **1821** (orthogonal relative to the optical path **1872** and/or rotation axis **1861**) and an inclined surface **1829** (oriented at a non-orthogonal angle relative to the optical path **1872** and/or rotation axis **1861**). Similarly, the second optical element **1030** can include an orthogonal surface **1831** and an inclined surface **1839**.

In an embodiment shown in FIG. **18**A, the inclined surface **1829** of the first optical element **1020** faces toward the orthogonal surface **1831** of the second optical element **1030**.

[0086] In an embodiment shown in FIG. **18**B, the inclined surface **1829** of the first optical element **1020** faces toward the inclined surface **1839** of the second optical element **1030**. In FIG. **18**C, the orthogonal surface **1821** of the first optical element **1020** faces toward the inclined surface **1839** of the second optical element **1030**. In FIG. **18**D, the orthogonal surface **1821** of the first optical element **1020** faces toward the corresponding orthogonal surface **1831** of the second optical element **1030**. In FIG. **18**E, each of the first and second elements **1020** includes multiple (e.g., two) inclined surfaces. Accordingly, the first optical element **1020** includes two opposing inclined surfaces **1829**, and the second optical element **1030** includes two inclined surfaces **1839**. In still further embodiments, the optical elements can have different arrangements of surfaces and/or orientations. In any of these embodiments, the optical elements can be supported by bearings and/or driven by motors having any suitable one (or more) of the configurations described herein. As discussed above, such arrangements can provide lightweight, compact, long-lasting reduced power, and/or otherwise beneficial devices for scanning the environment around a mobile platform.

[0087] FIG. **19** illustrates examples of mobile platforms configured in accordance with various embodiments of the presently disclosed technology. As illustrated, a representative mobile platform as disclosed herein may include at least one of an unmanned aerial vehicle (UAV) **1902**, a manned aircraft **1904**, an autonomous vehicle **1906**, a self-balancing vehicle **808**, a terrestrial robot **1910**, a smart wearable device **1912**, a virtual reality (VR) head-mounted display **1914**, or an augmented reality (AR) head-mounted display **1916**.

[0088] From the foregoing, it will be appreciated that specific embodiments of the present technology have been described herein for purposes of illustration, but that various modification may be made without deviating from the technology. For example, the components described herein can have suitable shapes and/or dimensions that deviate from those expressly shown in the figures, while still providing one or more of the associated benefits described above. In a particular example, while the openings in the optical elements are shown in the Figures as circular, in other embodiments, the openings can have other shapes, as can the corresponding shafts. In general, the associated bearings will still have radial symmetry so as to allow for rotation.

[0089] Certain aspects of the technology described in the context of particular embodiments may be combined or eliminated in other embodiments. For example, embodiments showing two optical elements may, in at least some representative examples, include one optical element, or more than two optical elements. Further, while advantages associated with certain embodiments of the technology have been described in the context of those embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the present technology. Accordingly, the present disclosure and associated technology can encompass other embodiments not expressly shown or described herein.

Claims

1. An optical system, comprising: at least one optical element positionable along an optical path to receive radiation; a shaft extending through a center of the at least one optical element; and an emitter configured to emit light along an emitted light axis, wherein the emitted light axis does not coincide with a shaft axis of the shaft.

2. The optical system of claim 1, wherein the at least one optical element includes a refractive element having opposing, non-parallel surfaces.

3. The optical system of claim 1, wherein an angle between the shaft axis of the shaft and the emitted light axis is non-zero.

4. The optical system of claim 3, further comprising: a collimation element provided between the emitter and the at least one optical element, and configured to collimate emitted light from the

emitter.
5. The optical system of claim 4, wherein the collimation element is perpendicular to the shaft axis of the shaft.
6. The optical system of claim 4, wherein the emitter is provided at a focal plane of the optical system, the focal plane is perpendicular to an orthogonal axis of the optical system.
7. The optical system of claim 6, wherein the collimation element is perpendicular to the orthogonal axis, the orthogonal axis is parallel to the emitted light axis, and the emitted light axis is offset by a predetermined offset distance from the orthogonal axis.
8. The optical system of claim 1, wherein the shaft axis of the shaft is parallel to the emitted light axis, and the emitted light axis is offset by a predetermined offset distance from the shaft axis of the shaft.
9. The optical system of claim 1, wherein the at least one optical element has an opening therethrough, and the shaft extends through the opening.
10. The optical system of claim 1, wherein the at least one optical element includes a first optical element and a second optical element, and the first optical element and the second optical element are rotatable relative to each other.
11. The optical system of claim 1, further comprising: at least one bearing operably coupled to the shaft; and a motor operably coupled to the at least one optical element to rotate the at least one optical element.
12. The optical system of claim 11, further comprising: a shaft support positioned to support the shaft relative to the motor.
13. The optical system of claim 12, wherein the shaft support includes a hub engaged with the shaft, a rim carried by the motor, and a plurality of spokes between the hub and the rim.
14. The optical system of claim 13, wherein at least one of the plurality of spokes includes a sloped surface inclined at a non-orthogonal angle relative to the optical path to direct light off the optical path.
15. The optical system of claim 12, wherein at least one of the shaft support or the shaft includes a surface inclined at a non-orthogonal angle relative to the optical path to direct light off the optical path.
16. The optical system of claim 12, wherein the shaft includes an end surface inclined at a non-orthogonal angle relative to the optical path to direct light off the optical path.
17. The optical system of claim 16, wherein the end surface of the shaft is conical, or the end surface of the shaft is sloped.
18. The optical system of claim 11, wherein at least one of the shaft or the at least one bearing includes a light-absorptive material.
19. The optical system of claim 1, further comprising: a yoke carrying and positioned around the at least one optical element, wherein the at least one optical element has a weight distribution that is not axisymmetric relative to the shaft, and the yoke has a weight distribution that is complementary to the weight distribution of the at least one optical element.
20. A mobile platform system comprising: a mobile platform; and an optical system carried by the mobile platform, and including: at least one optical element positionable along an optical path to receive radiation; a shaft extending through a center of the at least one optical element; and an emitter configured to emit light along an emitted light axis, wherein the emitted light axis does not coincide with a shaft axis of the shaft.