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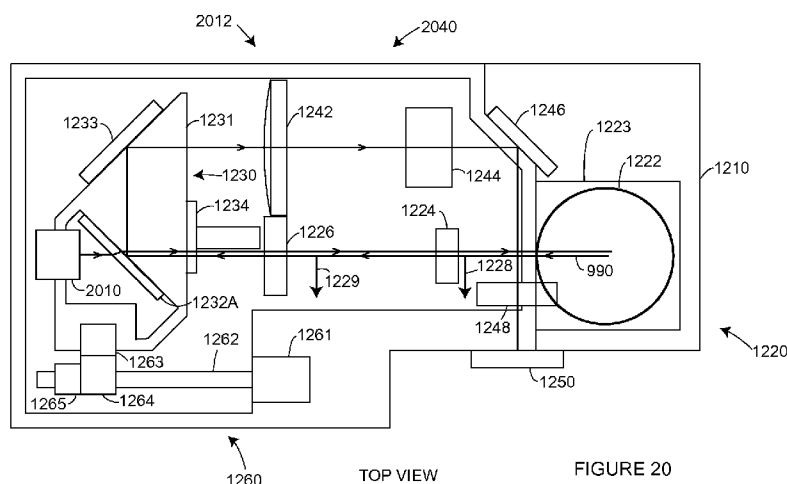


FIGURE 20

(57) Abstract: A device including a zoom-camera assembly having a first lens group, a magnifier lens group, a beam splitter, an imaging sensor, a motor, and an illuminator, the illuminator generating a first beam of light and cooperating with the beam splitter to send the beam of light through the first lens group to a retroreflector, the first lens group receiving the second beam of light and cooperating with the beam splitter to pass the received second beam of light through the magnifier lens group onto the imaging sensor, the motor adjusting a spacing between the first lens group and the magnifier lens group.

ZOOM CAMERA ASSEMBLY HAVING INTEGRATED ILLUMINATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a Non-Provisional Patent Application that claims the benefit of United States Provisional Patent Application Serial No. 62/017,865, filed on June 27, 2014, the contents of which are incorporated by reference herein in its entirety.

BACKGROUND

[0002] The present disclosure relates to a coordinate-measuring device having the ability to determine three orientational degrees of freedom (DOF). Such a coordinate-measuring device may be used in conjunction with a device having the ability to measure three translational DOF, thereby enabling determination of the position and orientation of a rigid body in space.

[0003] Some coordinate-measuring devices have the ability to measure the three-dimensional (3D) coordinates of a point (the three translational degrees of freedom of the point) by sending a beam of light to the point. Some such devices send the beam of light onto a retroreflector target in contact with the point. The instrument determines the coordinates of the point by measuring the distance and the two angles to the target. The distance is measured with a distance-measuring device such as an absolute distance meter (ADM) or an interferometer. The angles are measured with an angle-measuring device such as an angular encoder. The device may include a gimbaled beam-steering mechanism to direct the beam of light to the point of interest.

[0004] The laser tracker is a particular type of coordinate-measuring device that tracks the retroreflector target with one or more beams of light it emits. A coordinate-measuring device closely related to the laser tracker is the total station. In many cases, the total station, which is most often used in surveying applications, may be used to measure the coordinates of a retroreflector. Hereinafter, the term laser tracker is used in a broad sense to include total stations.

[0005] Ordinarily the laser tracker sends a beam of light to a retroreflector target. A common type of retroreflector target is the spherically mounted retroreflector (SMR), which comprises a cube-corner retroreflector embedded within a metal sphere. The cube-corner retroreflector comprises three mutually perpendicular mirrors that intersect in a common vertex point. For the case of a “hollow” SMR having reflecting surface in contact with air, the

vertex is located at the center of the sphere. Because of this placement of the cube corner within the sphere, the perpendicular distance from the vertex to a surface on which the SMR rests remains constant, even as the SMR is rotated. Consequently, the laser tracker can measure the 3D coordinates of a surface by following the position of an SMR as it is moved over the surface. Stating this another way, the laser tracker needs to measure only three degrees of freedom (one radial distance and two angles) to fully characterize the 3D coordinates of a surface.

[0006] One type of laser tracker contains only an interferometer (IFM) without an ADM. If an object blocks the path of the beam of light from one of these trackers, the IFM loses its distance reference. The operator must then track the retroreflector to a known location to reset to a reference distance before continuing the measurement. A way around this limitation is to put an ADM in the tracker. The ADM can measure distance in a point-and-shoot manner, as described in more detail below. Some laser trackers contain only an ADM without an interferometer. U.S. Patent No. 7,352,446 ('446) to Bridges et al., the contents of which are herein incorporated by reference, describes a laser tracker having only an ADM (and no IFM) that is able to accurately scan a moving target. Prior to the '446 patent, absolute distance meters were too slow to accurately find the position of a moving target.

[0007] A gimbal mechanism within the laser tracker may be used to direct the beam of light from the tracker to the SMR. Part of the light retroreflected by the SMR enters the laser tracker and passes onto a position detector. A control system within the laser tracker can use the position of the light on the position detector to adjust the rotation angles of the mechanical axes of the laser tracker to keep the laser beam centered on the SMR. In this way, the tracker is able to follow (track) an SMR that is moved over the surface of an object of interest. The gimbal mechanism used for a laser tracker may be used for a variety of other applications. As a simple example, the laser tracker may be used in a gimbal steering device having a visible pointer beam but no distance meter to steer a light beam to series of retroreflector targets and measure the angles of each of the targets.

[0008] Angle-measuring devices such as angular encoders are attached to the mechanical axes of the tracker. The one distance measurement and two angle measurements performed by the laser tracker are sufficient to completely specify the three-dimensional location of the SMR.

[0009] Several laser trackers are available or have been proposed for measuring six, rather than the ordinary three, degrees of freedom. Such laser trackers combine measurement

of three orientational DOF with measurement of three translational DOF to obtain measurement of six DOFs. Exemplary six-DOF systems are described by U.S. Patent No. 7,800,758 ('758) to Bridges et al., the contents of which are herein incorporated by reference, and U.S. Patent No. 5,267,014 to Prenninger, the contents of which are herein incorporated by reference.

[0010] One method of measuring three orientational DOF of a retroreflector is to project light onto a retroreflector that includes marks. The marks, which are captured by a camera, are evaluated to determine the three orientational DOF. Prior art methods have, in some cases, only partially illuminated the retroreflector target, thereby failing to capture the full extent of all the marks. Prior art methods usually involve projection of a Gaussian beam of laser light. The Gaussian profile causes portions of the image to be dimly illuminated, and the high coherence of the laser light causes speckle. While existing laser tracker measurement methods may be suitable for their intended purpose, the art relating to laser tracker measurement methods would be advanced with a method that overcomes the aforementioned limitations

SUMMARY

[0011] According to an embodiment of the present invention, a device comprises a zoom-camera assembly, the zoom-camera assembly including a first lens group, a magnifier lens group, a beam splitter, an imaging sensor, a first motor, and an illuminator, the illuminator configured to generate a first beam of light and to cooperate with the beam splitter to send the first beam of light through the first lens group to a retroreflector, the retroreflector configured to reflect the first beam of light as a second beam of light, the first lens group configured to receive the second beam of light and to cooperate with the beam splitter to pass the received second beam of light through the magnifier lens group onto the imaging sensor, the imaging sensor including a plurality of photosensitive pixel elements, the first motor configured to adjust a spacing between the first lens group and the magnifier lens group.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Referring now to the drawings, exemplary embodiments are shown which should not be construed to be limiting regarding the entire scope of the disclosure, and wherein the elements are numbered alike in several FIGURES:

[0013] FIG. 1 is a perspective view of a laser tracker system with a retroreflector target in accordance with an embodiment of the present invention;

[0014] FIG. 2 is a perspective view of a laser tracker system with a six-DOF target in accordance with an embodiment of the present invention;

[0015] FIG. 3 is a block diagram describing elements of laser tracker optics and electronics in accordance with an embodiment of the present invention;

[0016] FIG. 4, which includes FIGs. 4A and 4B, shows two types of prior art afocal beam expanders;

[0017] FIG. 5 shows a prior art fiber-optic beam launch;

[0018] FIGs. 6A-D are schematic figures that show four types of prior art position detector assemblies;

[0019] FIGs. 6E and 6F are schematic figures showing position detector assemblies in accordance with embodiments of the present invention;

[0020] FIG. 7 is a block diagram of electrical and electro-optical elements within a prior art ADM;

[0021] FIGs. 8A and 8B are schematic figures showing fiber-optic elements within a prior art fiber-optic network;

[0022] FIG. 8C is a schematic figure showing fiber-optic elements within a fiber-optic network in accordance with an embodiment of the present invention;

[0023] FIG. 9 is an exploded view of a prior art laser tracker;

[0024] FIG. 10 is a cross-sectional view of a prior art laser tracker;

[0025] FIG. 11 is a block diagram of the computing and communication elements of a laser tracker according to an embodiment of the present invention;

[0026] FIG. 12A is a block diagram of elements in a laser tracker that uses a single wavelength according to an embodiment of the present invention;

[0027] FIG. 12B is a block diagram of elements in a laser tracker that uses a single wavelength according to an embodiment of the present invention;

[0028] FIG. 13 is a block diagram of elements in a laser tracker with six-DOF capability according to an embodiment of the present invention;

[0029] FIG. 14 is a top view of an orientation camera;

[0030] FIG. 15 is a perspective view of a laser tracker with covers off and optics block removed according to an embodiment of the present invention;

[0031] FIG. 16 is an exploded view showing an optics bench in relation to other elements of a laser tracker according to an embodiment of the present invention;

[0032] FIG. 17 is a perspective view of a zenith shaft, an optics bench, and a second optics assembly assembled together in accordance with an embodiment of the present invention;

[0033] FIG. 18 is a top view of an orientation-camera optics assembly;

[0034] FIG. 19 is a cross-sectional view of an optics bench, an optics assembly, and a position detector assembly;

[0035] FIG. 20 is a top view of an orientation camera that includes an integrated illuminator according to an embodiment of the present invention; and

[0036] FIG. 21 is a block diagram showing elements included in the integrated illuminator according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0037] An exemplary laser tracker system 5 illustrated in FIG. 1 includes a laser tracker 10, a retroreflector target 26, an optional auxiliary unit processor 50, and an optional auxiliary computer 60. An exemplary gimbaled beam-steering mechanism 12 of laser tracker 10 comprises a zenith carriage 14 mounted on an azimuth base 16 and rotated about an azimuth axis 20. A payload 15 is mounted on the zenith carriage 14 and rotated about a zenith axis 18. Zenith axis 18 and azimuth axis 20 intersect orthogonally, internally to tracker 10, at gimbal point 22, which is typically the origin for distance measurements. A beam of light 46 virtually passes through the gimbal point 22 and is pointed orthogonal to zenith axis 18. In other words, beam of light 46 lies in a plane approximately perpendicular to the zenith axis 18 and that passes through the azimuth axis 20. Outgoing beam of light 46 is pointed in the desired direction by rotation of payload 15 about zenith axis 18 and by rotation of zenith carriage 14 about azimuth axis 20. A zenith angular encoder, internal to the tracker, is attached to a zenith mechanical axis aligned to the zenith axis 18. An azimuth angular encoder, internal to the tracker, is attached to an azimuth mechanical axis aligned to the azimuth axis 20. The zenith and azimuth angular encoders measure the zenith and azimuth angles of rotation to relatively high accuracy. Outgoing beam of light 46 travels to the retroreflector target 26, which might be, for example, an SMR as described above. By

measuring the radial distance between gimbal point 22 and retroreflector 26, the rotation angle about the zenith axis 18, and the rotation angle about the azimuth axis 20, the position of retroreflector 26 is found within the spherical coordinate system of the tracker.

[0038] Outgoing beam of light 46 may include one or more wavelengths, as described hereinafter. For the sake of clarity and simplicity, a steering mechanism of the sort shown in FIG. 1 is assumed in the following discussion. However, other types of steering mechanisms are possible. For example, it is possible to reflect a laser beam off a mirror rotated about the azimuth and zenith axes. The techniques described herein are applicable, regardless of the type of steering mechanism.

[0039] Magnetic nests 17 may be included on the laser tracker for resetting the laser tracker to a “home” position for different sized SMRs – for example, 1.5, 7/8, and ½ inch SMRs. An on-tracker retroreflector 19 may be used to reset the tracker to a reference distance. In addition, an on-tracker mirror, not visible from the view of FIG. 1, may be used in combination with the on-tracker retroreflector to enable performance of a self-compensation, as described in U.S. Patent No. 7,327,446, the contents of which are herein incorporated by reference.

[0040] FIG. 2 shows an exemplary laser tracker system 7 that is like the laser tracker system 5 of FIG. 1 except that retroreflector target 26 is replaced with a six-DOF probe 1000. In FIG. 1, other types of retroreflector targets may be used. For example, a catseye retroreflector, which is a glass retroreflector in which light focuses to a small spot of light on a reflective rear surface of the glass structure, is sometimes used.

[0041] FIG. 3 is a block diagram showing optical and electrical elements in a laser tracker embodiment. It shows elements of a laser tracker that emit two wavelengths of light – a first wavelength for an ADM and a second wavelength for a visible pointer and for tracking. The visible pointer enables the user to see the position of the laser beam spot emitted by the tracker. The two different wavelengths are combined using a free-space beam splitter. Electrooptic (EO) system 100 includes visible light source 110, isolator 115, optional first fiber launch 170, optional IFM 120, beam expander 140, first beam splitter 145, position detector assembly 150, second beam splitter 155, ADM 160, and second fiber launch 170.

[0042] Visible light source 110 may be a laser, superluminescent diode, or other light emitting device. The isolator 115 may be a Faraday isolator, attenuator, or other device capable of reducing the light that passes back into the light source to prevent instability in the visible light source 110.

[0043] Optional IFM may be configured in a variety of ways. As a specific example of a possible implementation, the IFM may include a beam splitter 122, a retroreflector 126, quarter waveplates 124, 130, and a phase analyzer 128. The visible light source 110 may launch the light into free space, the light then traveling in free space through the isolator 115, and optional IFM 120. Alternatively, the isolator 115 may be coupled to the visible light source 110 by a fiber optic cable. In this case, the light from the isolator may be launched into free space through the first fiber-optic launch 170, as discussed hereinbelow with reference to FIG. 5.

[0044] In some cases such as in FIG. 3, the fiber launch may emit a collimated beam of light less than a millimeter in diameter. It is expanded to a larger beam, for example 5 mm in diameter, by the beam expander 140. In other cases, a fiber launch may emit a relatively large beam. For example, the beam leaving the ADM fiber launch 170 in FIG. 3 might be eight millimeters in diameter. The two beams of light are combined by beam splitter 155 to produce a composite beam 188. Beam expander 140 may be set up using a variety of lens configurations, but two commonly used prior-art configurations are shown in FIGs. 4A and 4B. FIG. 4A shows a configuration 140A based on the use of a negative lens 141A and a positive lens 142A. A beam of collimated light 220A incident on the negative lens 141A emerges from the positive lens 142A as a larger beam of collimated light 230A. FIG. 4B shows a configuration 140B based on the use of two positive lenses 141B, 142B. A beam of collimated light 220B incident on a first positive lens 141B emerges from a second positive lens 142B as a larger beam of collimated light 230B. Of the light leaving the beam expander 140, a small amount reflects off the beam splitters 145, 155 on the way out of the tracker and is lost. That part of the light that passes through the beam splitter 155 is combined with light from the ADM 160 to form a composite beam of light 188 that leaves that laser tracker and travels to the retroreflector 90.

[0045] In an embodiment, the ADM 160 includes a light source 162, ADM electronics 164, a fiber network 166, an interconnecting electrical cable 165, and interconnecting optical fibers 168, 169, 184, 186. ADM electronics send electrical modulation and bias voltages to light source 162, which may, for example, be a distributed feedback laser that operates at a wavelength of approximately 1550 nm. In an embodiment, the fiber network 166 may be the prior art fiber-optic network 420A shown in FIG. 8A. In this embodiment, light from the light source 162 in FIG. 3 travels over the optical fiber 184, which is equivalent to the optical fiber 432 in FIG. 8A.

[0046] The fiber network of FIG. 8A includes a first fiber coupler 430, a second fiber coupler 436, and low-reflectance terminators 435, 440. The light travels through the first fiber coupler 430 and splits between two paths, the first path through optical fiber 433 to the second fiber coupler 436 and the second path through optical fiber 422 and fiber length equalizer 423. Fiber length equalizer 423 connects to fiber length 168 in FIG. 3, which travels to the reference channel of the ADM electronics 164. The purpose of fiber length equalizer 423 is to match the length of optical fibers traversed by light in the reference channel to the length of optical fibers traversed by light in the measure channel. Matching the fiber lengths in this way reduces ADM errors caused by changes in the ambient temperature. Such errors may arise because the effective optical path length of an optical fiber is equal to the average index of refraction of the optical fiber times the length of the fiber. Since the index of refraction of the optical fibers depends on the temperature of the fiber, a change in the temperature of the optical fibers causes changes in the effective optical path lengths of the measure and reference channels. If the effective optical path length of the optical fiber in the measure channel changes relative to the effective optical path length of the optical fiber in the reference channel, the result will be an apparent shift in the position of the retroreflector target 90, even if the retroreflector target 90 is kept stationary. To get around this problem, two steps are taken. First, the length of the fiber in the reference channel is matched, as nearly as possible, to the length of the fiber in the measure channel. Second, the measure and reference fibers are routed side by side to the extent possible to ensure that the optical fibers in the two channels see nearly the same changes in temperature.

[0047] The light travels through the second fiber optic coupler 436 and splits into two paths, the first path to the low-reflection fiber terminator 440 and the second path to optical fiber 438, from which it travels to optical fiber 186 in FIG. 3. The light on optical fiber 186 travels through to the second fiber launch 170.

[0048] In an embodiment, fiber launch 170 is shown in prior art FIG. 5. The light from optical fiber 186 of FIG. 3 goes to fiber 172 in FIG. 5. The fiber launch 170 includes optical fiber 172, ferrule 174, and lens 176. The optical fiber 172 is attached to ferrule 174, which is stably attached to a structure within the laser tracker 10. If desired, the end of the optical fiber may be polished at an angle to reduce back reflections. The light 250 emerges from the core of the fiber, which may be a single mode optical fiber with a diameter of between 4 and 12 micrometers, depending on the wavelength of the light being used and the particular type of optical fiber. The light 250 diverges at an angle and intercepts lens 176,

which collimates it. The method of launching and receiving an optical signal through a single optical fiber in an ADM system was described in reference to FIG. 3 in patent '758.

[0049] Referring to FIG. 3, the beam splitter 155 may be a dichroic beam splitter, which transmits different wavelengths than it reflects. In an embodiment, the light from the ADM 160 reflects off dichroic beam splitter 155 and combines with the light from the visible light source 110, which is transmitted through the dichroic beam splitter 155. The composite beam of light 188 travels out of the laser tracker to retroreflector 90 as a first beam, which returns a portion of the light as a second beam. That portion of the second beam that is at the ADM wavelength reflects off the dichroic beam splitter 155 and returns to the second fiber launch 170, which couples the light back into the optical fiber 186.

[0050] In an embodiment, the optical fiber 186 corresponds to the optical fiber 438 in FIG. 8A. The returning light travels from optical fiber 438 through the second fiber coupler 436 and splits between two paths. A first path leads to optical fiber 424 that, in an embodiment, corresponds to optical fiber 169 that leads to the measure channel of the ADM electronics 164 in FIG. 3. A second path leads to optical fiber 433 and then to the first fiber coupler 430. The light leaving the first fiber coupler 430 splits between two paths, a first path to the optical fiber 432 and a second path to the low reflectance termination 435. In an embodiment, optical fiber 432 corresponds to the optical fiber 184, which leads to the light source 162 in FIG. 3. In most cases, the light source 162 contains a built-in Faraday isolator that minimizes the amount of light that enters the light source from optical fiber 432. Excessive light fed into a laser in the reverse direction can destabilize the laser.

[0051] The light from the fiber network 166 enters ADM electronics 164 through optical fibers 168, 169. An embodiment of prior art ADM electronics is shown in FIG. 7. Optical fiber 168 in FIG. 3 corresponds to optical fiber 3232 in FIG. 7, and optical fiber 169 in FIG. 3 corresponds to optical fiber 3230 in FIG. 7. Referring now to FIG. 7, ADM electronics 3300 includes a frequency reference 3302, a synthesizer 3304, a measure detector 3306, a reference detector 3308, a measure mixer 3310, a reference mixer 3312, conditioning electronics 3314, 3316, 3318, 3320, a divide-by-N prescaler 3324, and an analog-to-digital converter (ADC) 3322. The frequency reference, which might be an oven-controlled crystal oscillator (OCXO), for example, sends a reference frequency f_{REF} , which might be 10 MHz, for example, to the synthesizer, which generates two electrical signals – one signal at a frequency f_{RF} and two signals at frequency f_{LO} . The signal f_{RF} goes to the light source 3102, which corresponds to the light source 162 in FIG. 3. The two signals at frequency f_{LO} go to the measure mixer 3310 and the reference mixer 3312. The light from optical fibers 168, 169

in FIG. 3 appear on fibers 3232, 3230 in FIG. 7, respectively, and enter the reference and measure channels, respectively. Reference detector 3308 and measure detector 3306 convert the optical signals into electrical signals. These signals are conditioned by electrical components 3316, 3314, respectively, and are sent to mixers 3312, 3310, respectively. The mixers produce a frequency f_{IF} equal to the absolute value of $f_{LO} - f_{RF}$. The signal f_{RF} may be a relatively high frequency, for example, 2 GHz, while the signal f_{IF} may have a relatively low frequency, for example, 10 kHz.

[0052] The reference frequency f_{REF} is sent to the prescaler 3324, which divides the frequency by an integer value. For example, a frequency of 10 MHz might be divided by 40 to obtain an output frequency of 250 kHz. In this example, the 10 kHz signals entering the ADC 3322 would be sampled at a rate of 250 kHz, thereby producing 25 samples per cycle. The signals from the ADC 3322 are sent to a data processor 3400, which might, for example, be one or more digital signal processor (DSP) units located in ADM electronics 164 of FIG. 3.

[0053] The method for extracting a distance is based on the calculation of phase of the ADC signals for the reference and measure channels. This method is described in detail in U.S. Patent No. 7,701,559 ('559) to Bridges et al., the contents of which are herein incorporated by reference. Calculation includes use of equations (1) – (8) of patent '559. In addition, when the ADM first begins to measure a retroreflector, the frequencies generated by the synthesizer are changed some number of times (for example, three times), and the possible ADM distances calculated in each case. By comparing the possible ADM distances for each of the selected frequencies, an ambiguity in the ADM measurement is removed. The equations (1) – (8) of patent '559 combined with synchronization methods described with respect to FIG. 5 of patent '559 and the Kalman filter methods described in patent '559 enable the ADM to measure a moving target. In other embodiments, other methods of obtaining absolute distance measurements, for example, by using pulsed time-of-flight rather than phase differences, may be used.

[0054] The part of the return light beam 190 that passes through the beam splitter 155 arrives at the beam splitter 145, which sends part of the light to the beam expander 140 and another part of the light to the position detector assembly 150. The light emerging from the laser tracker 10 or EO system 100 may be thought of as a first beam and the portion of that light reflecting off the retroreflector 90 or 26 as a second beam. Portions of the reflected beam are sent to different functional elements of the EO system 100. For example, a first portion may be sent to a distance meter such as an ADM 160 in FIG. 3. A second portion

may be sent to a position detector assembly 150. In some cases, a third portion may be sent to other functional units such as an optional interferometer 120. It is important to understand that, although, in the example of FIG. 3, the first portion and the second portion of the second beam are sent to the distance meter and the position detector after reflecting off beam splitters 155 and 145, respectively, it would have been possible to transmit, rather than reflect, the light onto a distance meter or position detector.

[0055] Four examples of prior art position detector assemblies 150A – 150D are shown in FIGs. 6A-D. FIG. 6A depicts the simplest implementation, with the position detector assembly including a position sensor 151 mounted on a circuit board 152 that obtains power from and returns signals to electronics box 350, which may represent electronic processing capability at any location within the laser tracker 10, auxiliary unit 50, or external computer 60. FIG. 6B includes an optical filter 154 that blocks unwanted optical wavelengths from reaching the position sensor 151. The unwanted optical wavelengths may also be blocked, for example, by coating the beam splitter 145 or the surface of the position sensor 151 with an appropriate film. FIG. 6C includes a lens 153 that reduces the size of the beam of light. FIG. 6D includes both an optical filter 154 and a lens 153.

[0056] FIG. 6E shows a position detector assembly according to an embodiment of the present invention that includes an optical conditioner 149E. Optical conditioner contains a lens 153 and may also contain optional wavelength filter 154. In addition, it includes at least one of a diffuser 156 and a spatial filter 157. As explained hereinabove, a popular type of retroreflector is the cube-corner retroreflector. One type of cube corner retroreflector is made of three mirrors, each joined at right angles to the other two mirrors. Lines of intersection at which these three mirrors are joined may have a finite thickness in which light is not perfectly reflected back to the tracker. The lines of finite thickness are diffracted as they propagate so that upon reaching the position detector they may not appear exactly the same as at the position detector. However, the diffracted light pattern will generally depart from perfect symmetry. As a result, the light that strikes the position detector 151 may have, for example, dips or rises in optical power (hot spots) in the vicinity of the diffracted lines. Because the uniformity of the light from the retroreflector may vary from retroreflector to retroreflector and also because the distribution of light on the position detector may vary as the retroreflector is rotated or tilted, it may be advantageous to include a diffuser 156 to improve the smoothness of the light that strikes the position detector 151. It might be argued that, because an ideal position detector should respond to a centroid and an ideal diffuser should spread a spot symmetrically, there should be no effect on the resulting position given by the

position detector. However, in practice the diffuser is observed to improve performance of the position detector assembly, probably because the effects of nonlinearities (imperfections) in the position detector 151 and the lens 153. Cube corner retroreflectors made of glass may also produce non-uniform spots of light at the position detector 151. Variations in a spot of light at a position detector may be particularly prominent from light reflected from cube corners in six-DOF targets, as may be understood more clearly from commonly assigned U.S. Patent Nos. 8,740,396 ('396) to Brown et al., and 8,467,072 ('072) to Cramer et al., the contents of each of which are herein incorporated by reference. In an embodiment, the diffuser 156 is a holographic diffuser. A holographic diffuser provides controlled, homogeneous light over a specified diffusing angle. In other embodiments, other types of diffusers such as ground glass or "opal" diffusers are used.

[0057] The purpose of the spatial filter 157 of the position detector assembly 150E is to block ghost beams that may be the result, for example, of unwanted reflections off optical surfaces, from striking the position detector 151. A spatial filter includes a plate 157 that has an aperture. By placing the spatial filter 157 a distance away from the lens equal approximately to the focal length of the lens, the returning light 243E passes through the spatial filter when it is near its narrowest – at the waist of the beam. Beams that are traveling at a different angle, for example, as a result of reflection of an optical element strike the spatial filter away from the aperture and are blocked from reaching the position detector 151. An example is shown in FIG. 6E, where an unwanted ghost beam 244E reflects off a surface of the beam splitter 145 and travels to spatial filter 157, where it is blocked. Without the spatial filter, the ghost beam 244E would have intercepted the position detector 151, thereby causing the position of the beam 243E on the position detector 151 to be incorrectly determined. Even a weak ghost beam may significantly change the position of the centroid on the position detector 151 if the ghost beam is located a relatively large distance from the main spot of light.

[0058] A retroreflector of the sort discussed here, a cube corner or a cateye retroreflector, for example, has the property of reflecting a ray of light that enters the retroreflector in a direction parallel to the incident ray. In addition, the incident and reflected rays are symmetrically placed about the point of symmetry of the retroreflector. For example, in an open-air cube corner retroreflector, the point of symmetry of the retroreflector is the vertex of the cube corner. In a glass cube corner retroreflector, the point of symmetry is also the vertex, but one must consider the bending of the light at the glass-air interface in this case. In a cateye retroreflector having an index of refraction of 2.0, the point of symmetry is

the center of the sphere. In a catenoid retroreflector made of two glass hemispheres symmetrically seated on a common plane, the point of symmetry is a point lying on the plane and at the spherical center of each hemisphere. The main point is that, for the type of retroreflectors ordinarily used with laser trackers, the light returned by a retroreflector to the tracker is shifted to the other side of the vertex relative to the incident laser beam.

[0059] This behavior of a retroreflector 90 in FIG. 3 is the basis for the tracking of the retroreflector by the laser tracker. The position sensor has on its surface an ideal retrace point. The ideal retrace point is the point at which a laser beam sent to the point of symmetry of a retroreflector (e.g., the vertex of the cube corner retroreflector in an SMR) will return. Usually the retrace point is near the center of the position sensor. If the laser beam is sent to one side of the retroreflector, it reflects back on the other side and appears off the retrace point on the position sensor. By noting the position of the returning beam of light on the position sensor, the control system of the laser tracker 10 can cause the motors to move the light beam toward the point of symmetry of the retroreflector.

[0060] If the retroreflector is moved transverse to the tracker at a constant velocity, the light beam at the retroreflector will strike the retroreflector (after transients have settled) a fixed offset distance from the point of symmetry of the retroreflector. The laser tracker makes a correction to account for this offset distance at the retroreflector based on scale factor obtained from controlled measurements and based on the distance from the light beam on the position sensor to the ideal retrace point.

[0061] As explained hereinabove, the position detector performs two important functions – enabling tracking and correcting measurements to account for the movement of the retroreflector. The position sensor within the position detector may be any type of device capable of measuring a position. For example, the position sensor might be a position sensitive detector or a photosensitive array. The position sensitive detector might be lateral effect detector or a quadrant detector, for example. The photosensitive array might be a CMOS or CCD array, for example.

[0062] In an embodiment, the return light that does not reflect off beam splitter 145 passes through beam expander 140, thereby becoming smaller. In another embodiment, the positions of the position detector and the distance meter are reversed so that the light reflected by the beam splitter 145 travels to the distance meter and the light transmitted by the beam splitter travels to the position detector.

[0063] The light continues through optional IFM, through the isolator and into the visible light source 110. At this stage, the optical power should be small enough so that it does not destabilize the visible light source 110.

[0064] In an embodiment, the light from visible light source 110 is launched through a beam launch 170 of FIG. 5. The fiber launch may be attached to the output of light source 110 or a fiber optic output of the isolator 115.

[0065] In an embodiment, the fiber network 166 of FIG. 3 is prior art fiber network 420B of FIG. 8B. Here the optical fibers 184, 186, 168, 169 of FIG. 3 correspond to optical fibers 443, 444, 424, 422 of FIG. 8B. The fiber network of FIG. 8B is like the fiber network of FIG. 8A except that the fiber network of FIG. 8B has a single fiber coupler instead of two fiber couplers. The advantage of FIG. 8B over FIG. 8A is simplicity; however, FIG. 8B is more likely to have unwanted optical back reflections entering the optical fibers 422 and 424.

[0066] In an embodiment, the fiber network 166 of FIG. 3 is fiber network 420C of FIG. 8C. Here the optical fibers 184, 186, 168, 169 of FIG. 3 correspond to optical fibers 447, 455, 423, 424 of FIG. 8C. The fiber network 420C includes a first fiber coupler 445 and a second fiber coupler 451. The first fiber coupler 445 is a 2 x 2 coupler having two input ports and two output ports. Couplers of this type are usually made by placing two fiber cores in close proximity and then drawing the fibers while heated. In this way, evanescent coupling between the fibers can split off a desired fraction of the light to the adjacent fiber. The second fiber coupler 451 is of the type called a circulator. It has three ports, each having the capability of transmitting or receiving light, but only in the designated direction. For example, the light on optical fiber 448 enters port 453 and is transported toward port 454 as indicated by the arrow. At port 454, light may be transmitted to optical fiber 455. Similarly, light traveling on port 455 may enter port 454 and travel in the direction of the arrow to port 456, where some light may be transmitted to the optical fiber 424. If only three ports are needed, then the circulator 451 may suffer less losses of optical power than the 2 x 2 coupler. On the other hand, a circulator 451 may be more expensive than a 2 x 2 coupler, and it may experience polarization mode dispersion, which can be problematic in some situations.

[0067] FIGs. 9 and 10 show exploded and cross sectional views, respectively, of a prior art laser tracker 2100, which is depicted in FIGs. 2 and 3 of U.S. Patent No. 8,525,983 to Bridges et al., which is incorporated by reference herein. Azimuth assembly 2110 includes post housing 2112, azimuth encoder assembly 2120, lower and upper azimuth bearings 2114A, 2114B, azimuth motor assembly 2125, azimuth slip ring assembly 2130, and azimuth circuit boards 2135.

[0068] The purpose of azimuth encoder assembly 2120 is to accurately measure the angle of rotation of yoke 2142 with respect to the post housing 2112. Azimuth encoder assembly 2120 includes encoder disk 2121 and read-head assembly 2122. Encoder disk 2121 is attached to the shaft of yoke housing 2142, and read head assembly 2122 is attached to post assembly 2110. Read head assembly 2122 comprises a circuit board onto which one or more read heads are fastened. Laser light sent from read heads reflect off fine grating lines on encoder disk 2121. Reflected light picked up by detectors on encoder read head(s) is processed to find the angle of the rotating encoder disk in relation to the fixed read heads.

[0069] Azimuth motor assembly 2125 includes azimuth motor rotor 2126 and azimuth motor stator 2127. Azimuth motor rotor comprises permanent magnets attached directly to the shaft of yoke housing 2142. Azimuth motor stator 2127 comprises field windings that generate a prescribed magnetic field. This magnetic field interacts with the magnets of azimuth motor rotor 2126 to produce the desired rotary motion. Azimuth motor stator 2127 is attached to post frame 2112.

[0070] Azimuth circuit boards 2135 represent one or more circuit boards that provide electrical functions required by azimuth components such as the encoder and motor. Azimuth slip ring assembly 2130 includes outer part 2131 and inner part 2132. In an embodiment, wire bundle 2138 emerges from auxiliary unit processor 50. Wire bundle 2138 may carry power to the tracker or signals to and from the tracker. Some of the wires of wire bundle 2138 may be directed to connectors on circuit boards. In the example shown in FIG. 10, wires are routed to azimuth circuit board 2135, encoder read head assembly 2122, and azimuth motor assembly 2125. Other wires are routed to inner part 2132 of slip ring assembly 2130. Inner part 2132 is attached to post assembly 2110 and consequently remains stationary. Outer part 2131 is attached to yoke assembly 2140 and consequently rotates with respect to inner part 2132. Slip ring assembly 2130 is designed to permit low impedance electrical contact as outer part 2131 rotates with respect to the inner part 2132.

[0071] Zenith assembly 2140 comprises yoke housing 2142, zenith encoder assembly 2150, left and right zenith bearings 2144A, 2144B, zenith motor assembly 2155, zenith slip ring assembly 2160, and zenith circuit board 2165.

[0072] The purpose of zenith encoder assembly 2150 is to accurately measure the angle of rotation of payload frame 2172 with respect to yoke housing 2142. Zenith encoder assembly 2150 comprises zenith encoder disk 2151 and zenith read-head assembly 2152. Encoder disk 2151 is attached to payload housing 2142, and read head assembly 2152 is attached to yoke housing 2142. Zenith read head assembly 2152 comprises a circuit board

onto which one or more read heads are fastened. Laser light sent from read heads reflect off fine grating lines on encoder disk 2151. Reflected light picked up by detectors on encoder read head(s) is processed to find the angle of the rotating encoder disk in relation to the fixed read heads.

[0073] Zenith motor assembly 2155 comprises azimuth motor rotor 2156 and azimuth motor stator 2157. Zenith motor rotor 2156 comprises permanent magnets attached directly to the shaft of payload frame 2172. Zenith motor stator 2157 comprises field windings that generate a prescribed magnetic field. This magnetic field interacts with the rotor magnets to produce the desired rotary motion. Zenith motor stator 2157 is attached to yoke frame 2142.

[0074] Zenith circuit board 2165 represents one or more circuit boards that provide electrical functions required by zenith components such as the encoder and motor. Zenith slip ring assembly 2160 comprises outer part 2161 and inner part 2162. Wire bundle 2168 emerges from azimuth outer slip ring 2131 and may carry power or signals. Some of the wires of wire bundle 2168 may be directed to connectors on circuit board. In the example shown in FIG. 10, wires are routed to zenith circuit board 2165, zenith motor assembly 2150, and encoder read head assembly 2152. Other wires are routed to inner part 2162 of slip ring assembly 2160. Inner part 2162 is attached to yoke frame 2142 and consequently rotates in azimuth angle only, but not in zenith angle. Outer part 2161 is attached to payload frame 2172 and consequently rotates in both zenith and azimuth angles. Slip ring assembly 2160 is designed to permit low impedance electrical contact as outer part 2161 rotates with respect to the inner part 2162. Payload assembly 2170 includes a main optics assembly 2180 and a secondary optics assembly 2190.

[0075] FIG. 11 is a block diagram depicting a dimensional measurement electronics processing system 1500 that includes a laser tracker electronics processing system 1510, processing systems of peripheral elements 1582, 1584, 1586, computer 1590, and other networked components 1600, represented here as a cloud. Exemplary laser tracker electronics processing system 1510 includes a master processor 1520, payload functions electronics 1530, azimuth encoder electronics 1540, zenith encoder electronics 1550, display and user interface (UI) electronics 1560, removable storage hardware 1565, radio frequency identification (RFID) electronics, and an antenna 1572. The payload functions electronics 1530 includes a number of subfunctions including the six-DOF electronics 1531, the camera electronics 1532, the ADM electronics 1533, the position detector (PSD) electronics 1534, and the level electronics 1535. Most of the subfunctions have at least one processor unit, which might be a digital signal processor (DSP) or field programmable gate array (FPGA),

for example. The electronics units 1530, 1540, and 1550 are separated as shown because of their location within the laser tracker. In an embodiment, the payload functions 1530 are located in the payload 2170 of FIGs. 9 and 10, while the azimuth encoder electronics 1540 is located in the azimuth assembly 2110 and the zenith encoder electronics 1550 is located in the zenith assembly 2140.

[0076] Many types of peripheral devices are possible, but here three such devices are shown: a temperature sensor 1582, a six-DOF probe 1584, and a personal digital assistant, 1586, which might be a smart phone, for example. The laser tracker may communicate with peripheral devices in a variety of means, including wireless communication over the antenna 1572, by means of a vision system such as a camera, and by means of distance and angular readings of the laser tracker to a cooperative target such as the six-DOF probe 1584.

Peripheral devices may contain processors. The six-DOF accessories may include six-DOF probing systems, six-DOF scanners, six-DOF projectors, six-DOF sensors, and six-DOF indicators. The processors in these six-DOF devices may be used in conjunction with processing devices in the laser tracker as well as an external computer and cloud processing resources. Generally, when the term laser tracker processor or measurement device processor is used, it is meant to include possible external computer and cloud support.

[0077] In an embodiment, a separate communications bus goes from the master processor 1520 to each of the electronics units 1530, 1540, 1550, 1560, 1565, and 1570. Each communications line may have, for example, three serial lines that include the data line, clock line, and frame line. The frame line indicates whether or not the electronics unit should pay attention to the clock line. If it indicates that attention should be given, the electronics unit reads the current value of the data line at each clock signal. The clock-signal may correspond, for example, to a rising edge of a clock pulse. In an embodiment, information is transmitted over the data line in the form of a packet. In an embodiment, each packet includes an address, a numeric value, a data message, and a checksum. The address indicates where, within the electronics unit, the data message is to be directed. The location may, for example, correspond to a processor subroutine within the electronics unit. The numeric value indicates the length of the data message. The data message contains data or instructions for the electronics unit to carry out. The checksum is a numeric value that is used to minimize the chance that errors are transmitted over the communications line.

[0078] In an embodiment, the master processor 1520 sends packets of information over bus 1610 to payload functions electronics 1530, over bus 1611 to azimuth encoder electronics 1540, over bus 1612 to zenith encoder electronics 1550, over bus 1613 to display

and UI electronics 1560, over bus 1614 to removable storage hardware 1565, and over bus 1616 to RFID and wireless electronics 1570.

[0079] In an embodiment, master processor 1520 also sends a synch (synchronization) pulse over the synch bus 1630 to each of the electronics units at the same time. The synch pulse provides a way of synchronizing values collected by the measurement functions of the laser tracker. For example, the azimuth encoder electronics 1540 and the zenith electronics 1550 latch their encoder values as soon as the synch pulse is received. Similarly, the payload functions electronics 1530 latch the data collected by the electronics contained within the payload. The six-DOF, ADM, and position detector all latch data when the synch pulse is given. In most cases, the camera and inclinometer collect data at a slower rate than the synch pulse rate but may latch data at multiples of the synch pulse period.

[0080] The azimuth encoder electronics 1540 and zenith encoder electronics 1550 are separated from one another and from the payload electronics 1530 by the slip rings 2130, 2160 shown in FIGs. 9 and 10. This is why the bus lines 1610, 1611, and 1612 are depicted as separate bus line in FIG. 11.

[0081] The laser tracker electronics processing system 1510 may communicate with an external computer 1590, or it may provide computation, display, and UI functions within the laser tracker. The laser tracker communicates with computer 1590 over communications link 1606, which might be, for example, an Ethernet line or a wireless connection. The laser tracker may also communicate with other elements 1600, represented by the cloud, over communications link 1602, which might include one or more electrical cables, such as Ethernet cables, and one or more wireless connections. An example of an element 1600 is another three dimensional test instrument – for example, an articulated arm CMM, which may be relocated by the laser tracker. A communication link 1604 between the computer 1590 and the elements 1600 may be wired (e.g., Ethernet) or wireless. An operator sitting on a remote computer 1590 may make a connection to the Internet, represented by the cloud 1600, over an Ethernet or wireless line, which in turn connects to the master processor 1520 over an Ethernet or wireless line. In this way, a user may control the action of a remote laser tracker.

[0082] Laser trackers today use one visible wavelength (usually red) and one infrared wavelength for the ADM. The red wavelength may be provided by a frequency stabilized helium-neon (HeNe) laser suitable for use in an IFM and also for use as a red pointer beam. Alternatively, the red wavelength may be provided by a diode laser that serves just as a pointer beam. A disadvantage in using two light sources is the extra space and added cost

required for the extra light sources, beam splitters, isolators, and other components. Another disadvantage in using two light sources is that it is difficult to perfectly align the two light beams along the entire paths the beams travel. This may result in a variety of problems including inability to simultaneously obtain good performance from different subsystems that operate at different wavelengths. A system that uses a single light source, thereby eliminating these disadvantages, is shown in opto-electronic system 500 of FIG. 12A.

[0083] FIG. 12A includes a visible light source 110, an isolator 115, a fiber network 420, ADM electronics 530, a fiber launch 170, a beam splitter 145, and a position detector 150. The visible light source 110 might be, for example, a red or green diode laser or a vertical cavity surface emitting laser (VCSEL). The isolator might be a Faraday isolator, an attenuator, or any other device capable of sufficiently reducing the amount of light fed back into the light source. The light from the isolator 115 travels into the fiber network 420, which in an embodiment is the fiber network 420A of FIG. 8A.

[0084] FIG. 12B shows an embodiment of an optoelectronic system 400 in which a single wavelength of light is used but wherein modulation is achieved by means of electro-optic modulation of the light rather than by direct modulation of a light source. The optoelectronic system 400 includes a visible light source 110, an isolator 115, an electrooptic modulator 410, ADM electronics 475, a fiber network 420, a fiber launch 170, a beam splitter 145, and a position detector 150. The visible light source 110 may be, for example, a red or green laser diode. Laser light is sent through an isolator 115, which may be a Faraday isolator or an attenuator, for example. The isolator 115 may be fiber coupled at its input and output ports. The isolator 115 sends the light to the electrooptic modulator 410, which modulates the light to a selected frequency, which may be up to 10 GHz or higher if desired. An electrical signal 476 from ADM electronics 475 drives the modulation in the electrooptic modulator 410. The modulated light from the electrooptic modulator 410 travels to the fiber network 420, which might be the fiber network 420A, 420B, 420C, or 420D discussed hereinabove. Some of the light travels over optical fiber 422 to the reference channel of the ADM electronics 475. Another portion of the light travels out of the tracker, reflects off retroreflector 90, returns to the tracker, and arrives at the beam splitter 145. A small amount of the light reflects off the beam splitter and travels to position detector 150, which has been discussed hereinabove with reference to FIGs. 6A-F. A portion of the light passes through the beam splitter 145 into the fiber launch 170, through the fiber network 420 into the optical fiber 424, and into the measure channel of the ADM electronics 475. In general, the system 500 of FIG. 12A can be manufactured for less money than system 400 of FIG. 12B; however,

the electro-optic modulator 410 may be able to achieve a higher modulation frequency, which can be advantageous in some situations.

[0085] FIG. 13 shows an embodiment of a locator camera system 950 and an optoelectronic system 900 in which an orientation camera 910 is combined with the optoelectronic functionality of a 3D laser tracker to measure six degrees of freedom. The optoelectronic system 900 includes a visible light source 905, an isolator 908, an optional electrooptic modulator 410, ADM electronics 715, a fiber network 420, a fiber launch 170, a beam splitter 145, a position detector 150, a beam splitter 922, and an orientation camera 910. The light from the visible light source is emitted in optical fiber 980 and travels through isolator 908, which may have optical fibers coupled on the input and output ports. The light may travel through the electrooptic modulator 410 modulated by an electrical signal 716 from the ADM electronics 715. Alternatively, the ADM electronics 715 may send an electrical signal over cable 717 to modulate the visible light source 905. Some of the light entering the fiber network travels through the fiber length equalizer 423 and the optical fiber 422 to enter the reference channel of the ADM electronics 715. An electrical signal 469 may optionally be applied to the fiber network 420 to provide a switching signal to a fiber optic switch within the fiber network 420. A part of the light travels from the fiber network to the fiber launch 170, which sends the light on the optical fiber into free space as light beam 982. A small amount of the light reflects off the beamsplitter 145 and is lost. A portion of the light passes through the beam splitter 145, through the beam splitter 922, and travels out of the tracker to six degree-of-freedom (DOF) device 4000. The six-DOF device 4000 may be a probe, a scanner, a projector, a sensor, or other device.

[0086] On its return path, the light from the six-DOF device 4000 enters the optoelectronic system 900 and arrives at beamsplitter 922. Part of the light is reflected off the beamsplitter 922 and enters the orientation camera 910. The orientation camera 910 records the positions of some marks placed on the retroreflector target. From these marks, the orientation angle (i.e., three degrees of freedom) of the six-DOF probe is found. The principles of the orientation camera are described hereinafter in the present application and also in patent '758. A portion of the light at beam splitter 145 travels through the beamsplitter and is put onto an optical fiber by the fiber launch 170. The light travels to fiber network 420. Part of this light travels to optical fiber 424, from which it enters the measure channel of the ADM electronics 715.

[0087] The locator camera system 950 includes a camera 960 and one or more light sources 970. The locator camera system is also shown in FIG. 1, where the cameras are

elements 52 and the light sources are elements 54. The camera includes a lens system 962, a photosensitive array 964, and a body 966. One use of the locator camera system 950 is to locate retroreflector targets in the work volume. It does this by flashing the light source 970, which the camera picks up as a bright spot on the photosensitive array 964. A second use of the locator camera system 950 is establish a coarse orientation of the six-DOF device 4000 based on the observed location of a reflector spot or LED on the six-DOF device 4000. If two or more locator camera systems are available on the laser tracker, the direction to each retroreflector target in the work volume may be calculated using the principles of triangulation. If a single locator camera is located to pick up light reflected along the optical axis of the laser tracker, the direction to each retroreflector target may be found. If a single camera is located off the optical axis of the laser tracker, then approximate directions to the retroreflector targets may be immediately obtained from the image on the photosensitive array. In this case, a more accurate direction to a target may be found by rotating the mechanical axes of the laser to more than one direction and observing the change in the spot position on the photosensitive array.

[0088] FIG. 14 shows an embodiment of an orientation camera 910, which may be used in the optoelectronic systems of FIG. 13. The general principles of the orientation camera are described in patent '758 and are generally adhered to in orientation camera 912. In an embodiment, the orientation camera 910 includes a body 1210, an afocal beam reducer 1220, a magnifier 1240, a path length adjuster 1230, an actuator assembly 1260, and a photosensitive array 1250. The afocal beam reducer includes a positive lens 1222, a mirror 1223, and negative lenses 1224, 1226. The afocal beam reducer has the property that a ray of light that enters lens 1222 parallel to an optical axis – an axis that passes through the center of the lenses – emerges from lens 1226 also parallel to the optical axis. The afocal beam reducer also has the property that an image has a constant size regardless of the distance from the lens to an object. Another way of describing an afocal lens assembly is to say that it has an infinite effective focal length, which is to say that an object placed an infinite distance from the afocal lens will form an image of the object on the other side of the lens with the image sensor an infinite distance from the lens.

[0089] The magnifier 1240 includes a positive lens 1242, negative lenses 1244, 1248, and a mirror 1246. The magnifier has the same function as a microscope objective but is scaled to provide a larger image. The photosensitive array 1250 may, for example, be a CMOS or CCD array that converts the light that strikes it into an array of digital values representing the irradiance of the light at each pixel of the photosensitive array. The pattern

of irradiance may reveal, for example, the marks on a six-DOF target. The path length adjuster 1230 includes a platform 1231, two mirrors 1232, 1233, and a ball slide 1234. The mirrors 1232, 1233 are mounted on the platform 1231 so that when the platform 1231 is moved, the distance between the afocal beam reducer 1220 and the magnifier 1240 is changed. This change in distance is needed to keep a clear image on the photosensitive array 1250 for a changing distance from the laser tracker to the target. The platform 1231 is mounted on the ball slide 1234, which provides the platform with low friction linear motion. In an embodiment, the actuator assembly 1260 includes a motor 1261, a motor shaft 1262, a flexible coupling 1263, an adapter 1264, and a motor nut 1265. The motor nut 1265 is fixedly attached to the adapter. As the threaded motor shaft 1262 is rotated by the motor 1261, the motor nut 1265 is moved either farther from or nearer to the motor, depending on the direction of rotation of the motor shaft. The flexible coupler 1263, which is attached to the adapter 1264, allows the platform to move freely even if the motor shaft 1262 and the ball slide 1234 are not parallel to one another.

[0090] In an embodiment, the orientation camera 910 provides constant transverse magnification for different distances to the target. Here transverse magnification is defined as the image size divided by the object size. The lenses shown in FIG. 14 were selected to produce a constant image size on the photosensitive array 1250 of 3 mm for an object size of 13 mm. In this instance, the transverse magnification is $3 \text{ mm} / 13 \text{ mm} = 0.23$. This transverse magnification is held constant for a target placed a distance from the tracker of between 0.5 meter and 30 meters. This image size of 3 mm might be appropriate for a ¼ inch CCD or CMOS array. In an embodiment, the transverse magnification is four times this amount, making it appropriate for a one inch CCD or CMOS array. An orientation camera with this increased transverse magnification can be obtained in the same size body 1210, by changing the focal lengths and spacings of the three lenses in the magnifier 1240.

[0091] In an embodiment shown in FIG. 14, the effective focal lengths of the three lens elements 1222, 1224, and 1226 of the beam reducer 1220 are 85.9 mm, -29.6 mm, and -7.2 mm, respectively. A virtual image is formed after the light from the object passes through these three lens elements. For an object placed 0.5 meter from the laser tracker, the virtual image 1229 has a size of 0.44 mm and is located 7 mm from the lens 1226. For an object placed 30 meters from the laser tracker, the virtual image 1228 has a size of 0.44 mm and is located 1.8 mm from the lens 1224. The distance between the virtual image 1228 and the virtual image 1129 is 39.8 mm, which means that the platform needs a maximum travel range

of half this amount, or 19.9 mm. The transverse magnification of the beam reducer 1220 is $0.44 \text{ mm}/13 \text{ mm} = 0.034$.

[0092] The three lens elements 1242, 1244, and 1228 comprise a magnifier lens assembly. In the embodiment of FIG. 14, the effective focal lengths of the three lens elements 1242, 1244, and 1228 are 28.3 mm, -8.8 mm, and -8.8 mm, respectively. The size of the image at the photosensitive array 1250 is 3 mm for a target located 0.5 meter from the laser tracker, 30 meters from the laser tracker, or any distance in between. The transverse magnification of the magnifier lens assembly is $3 \text{ mm}/0.44 \text{ mm} = 6.8$. The overall transverse magnification of the orientation camera is $3 \text{ mm}/13 \text{ mm} = 0.23$. In another embodiment, the transverse magnification of the magnifier lens assembly is increased by a factor of 4 to $4 \times 6.8 = 27$, thereby producing an overall transverse magnification of $12 \text{ mm}/13 \text{ mm} = 0.92$ for any distance from 0.5 to 30 meters.

[0093] Other combinations of lenses can be combined to make an orientation camera having a constant transverse magnification. Furthermore, although having constant transverse magnification is helpful, other lens systems are also useable. To make a zoom camera not having constant magnification, the lens elements 1222, 1224, and 1226 may be replaced by a lens assembly that is not afocal. The path length adjuster 1230 and the actuator assembly 1260 are provided to retain the zoom capability.

[0094] FIG. 15 shows an embodiment of a laser tracker 3600 with front covers removed and some optical and electrical components omitted for clarity. As shown in FIG. 16, in an embodiment, the optics bench assembly 3620 includes a mating tube 3622. FIG. 16 shows a gimbal assembly 3610, which includes a zenith shaft 3630, and the optics bench assembly 3620. The zenith shaft includes a shaft 3634 and a mating sleeve 3632. The zenith shaft 3630 may be fabricated of a single piece of metal in order to improve rigidity and temperature stability.

[0095] FIG. 17 shows an isometric view of an embodiment of the optics bench assembly 3620 and the zenith shaft 3630. The optics bench assembly 3620 includes the main optics assembly 3650 and secondary optics assembly 912. FIG. 18 shows a top view of the orientation camera of the secondary optics assembly 912. These elements were previously described with reference to FIG. 14. FIG. 19 shows a cross sectional view 3800 along line A-A of FIG. 18. In an embodiment, visible laser light is sent through an optical fiber 3812. The light source that puts light into the optical fiber, the fiber network (if any) over which the light is routed, and the optical fiber 3812 all rotate along with the optics bench assembly 3620. In an embodiment, the optical fiber 3812 includes a connector, which enables quick

disconnect from the optical fiber originating at the light source. If the light source provides visible light, then the light can serve as both a pointer beam visible to an operator and as a measurement beam that can be used for measurements of distances, angles, and the like. The laser light is launched from a ferrule 3814, which may be mechanically adjusted to point the laser beam in the desired direction. In an embodiment, the ferrule 3814 and the face of the fiber held by the ferrule and polished at an angle of approximately 8 degrees to reduce backreflection of light in the optical fiber. The ferrule is adjusted to cause the beam emitted by the optical fiber to travel parallel to the central axis 55 of the mating tube 3622. The cross sectional view 3800 shows that light from the ferrule 3814 passes through lenses 3822 and 3824 in this case, although many different lens arrangements could be used. The light passes through beam splitter 3832 and beam splitter 3834 out of the tracker to a retroreflector target (not shown). On the return path from the retroreflector target, some of the light reflects off the beam splitter 3834, passes through lens 1222, reflects off mirror 1223 and continues through a variety of optical elements as explained hereinabove with reference to FIG. 14. The rest of the light passes through beam splitter 3834 and travels to beam splitter 3832, where some of it reflects, travels through optical diffuser/filter 3847, through lens 3844, and strikes position detector 3846. The light may also pass through an aperture placed between the lens 3844 and the position detector 3846. The purpose of such an aperture is to block ghost beams. In this case, the position detector is moved farther from the lens 3844 so that the aperture can be placed at a focal position of the beam of light (as shown in FIG. 6E). In an embodiment, the position detector 3846 is tilted so as to cause the backreflected light to be reflected at an angle, thereby reducing the chance that light reflected off the surface of the position detector 3846 will bounce off another surface (for example, the surface of an aperture/spatial filter 157) and return to the position detector. Position detector leads 3848 are attached by means of pass-through sockets (not shown) to a circuit board (not shown) that rotates with the optics bench assembly. Pass through sockets are spring loaded sockets that allow electrical connection to be made without soldering components. These sockets are advantageous because they enable the optics bench to be easily removed and replaced in a quick repair operation. The light that does not travel to the position detector 3846 continues through beam splitter 3832, optical elements 3824, 3822, which focuses it into the optical fiber 3812 within the ferrule 3814.

[0096] FIG. 20 shows an orientation camera 2012 that is like the orientation camera 912 of FIG. 14 except that the orientation camera 2012 includes an illuminator 2010. The illuminator 2010 projects a beam of light through the beam splitter 1232A along the optical

axis and passing through the afocal lens assembly toward the retroreflector. In an embodiment, the illuminator is not moved by the actuator assembly 1260.

[0097] In general, there may be several marks on or near the retroreflector target. In an embodiment, the retroreflector target is a cube-corner retroreflector made of glass. In an embodiment, a mark is placed on each of the three intersection lines between the planar reflective surfaces of the glass cube corner. In further embodiments, additional lines are added to the front face of the cube corner retroreflector. In other embodiments, additional reflective features or illuminated features are placed outside the retroreflector body. To capture all of the marks on the retroreflector or near the retroreflector, it is often desirable to overfill the retroreflector with projected light. The captured image will then represent all the marks on the retroreflector. To obtain the best performance for distance measurement and tracking, the composite beam 188 in FIG. 3 is usually relatively small, typically a few millimeters in diameter. In contrast, to overfill the retroreflector, a beam having a diameter of 25 mm or more may be desirable. To produce such a large beam in the main optics assembly 3650 of FIG. 17 would require the assembly 3650 to be expanded to hold the required optics. It is therefore desirable to find an alternative way to launch a beam of light that does not require so much space.

[0098] In addition, it is frequently desirable to use a different type of beam than that provided in the composite beam 188. Whereas composite beam 188 is typically one or more beams of laser light, the beam of light that overfills the target to capture the target features may be a beam from light emitting diodes (LEDs) or superluminescent diodes, which have lower coherence length than laser light sources and hence tend to produce smaller of the undesirable diffraction effects. Hence it is desirable to find a way to launch a beam that may have relatively low coherence without taking up a lot of extra space in the assembly shown in FIG. 17.

[0099] FIG. 21 shows an embodiment of the illuminator 2010. A light source 2210 may be a superluminescent diode (SLD), which has reduced coherence compared to a laser. The reduced coherence length of an SLD relative to a laser is the result of the relatively larger linewidth of the SLD. A benefit of the reduced coherence length is a reduction in speckle, which results in clearer and less noisy images of marks on the illuminated retroreflector. In other embodiments, the light is provided by an LED, which may be launched, for example, out of a multimode optical fiber.

[0100] In an embodiment, the light source 2210 is transmitted through a single mode fiber 2215. The SLD light emerges from the single mode fiber with a cross sectional

irradiance profile that is approximately Gaussian in shape. In an embodiment, the single mode fiber is attached to a multimode fiber 2225, which is a fiber having a larger core diameter enabling it to support multiple transverse modes of the SLD light. In an embodiment, the single mode fiber and multiple mode fiber are butt coupled (adjoined with each fiber having perpendicular cuts) at a coupling location 2220. The length of the multimode fiber includes a length 2230 sufficient to allow the profile of the beam to evolve from Gaussian to approximately flat-topped. A flat topped beam is a beam having approximately equal optical power per unit area over a specified region, which in this case is an area that is approximately circular.

[0101] To increase the uniformity of the beam, the light projected from the light source 2210 through the beam splitter 2210 may be sized to overfill the lens 1226, thereby selecting the centermost and flattest part of the beam. After reflecting off the beam splitter 3834 (as shown in FIG. 19), the beam of SLD light passing out of the laser tracker may be collimated or it may be diverging. If the SLD light 2254 passes through an afocal lens assembly before passing out of the tracker, the light will be collimated in leaving the tracker if it is collimated when it passes through the beam splitter 3834. To obtain such collimated light, the lens 2240 of FIG. 21 is placed a distance equal to the lens focal length away from the end 2235 of the multi-mode fiber 2225. If the SLD light 2254 passes through an afocal lens assembly before passing out of the tracker, the light will be diverging if the fiber end 2235 is placed slightly nearer the lens 2240 than the focal length of the lens.

[0102] Other types of light besides SLD light may be used. Laser light and LED light, for example, are other possible choices. In most cases, it is a good idea to project a different wavelength of light from the illuminator than from the 3D measuring device. This ensures that the light returned to the photosensitive array is reflected from a region of relatively uniform illumination over the entire retroreflector. It also ensures that noise effects, for example, resulting from speckle, are minimized.

[0103] While the invention has been described with reference to example embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

Moreover, the use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another.

Furthermore, the use of the terms a, an, etc. do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item.

CLAIMS

What is claimed is:

1. A device comprising:

a zoom-camera assembly, the zoom-camera assembly including a first lens group, a magnifier lens group, a beam splitter, an imaging sensor, a first motor, and an illuminator, the illuminator configured to generate a first beam of light and to cooperate with the beam splitter to send the first beam of light through the first lens group to a retroreflector, the retroreflector configured to reflect the first beam of light as a second beam of light, the first lens group configured to receive the second beam of light and to cooperate with the beam splitter to pass the received second beam of light through the magnifier lens group onto the imaging sensor, the imaging sensor including a plurality of photosensitive pixel elements, the first motor configured to adjust a spacing between the first lens group and the magnifier lens group.

2. The device of claim 1, further comprising:

a three-dimensional (3D) measuring assembly configured to measure for the retroreflector a first distance, a first angle of rotation, and a second angle of rotation, the 3D measuring assembly including a second motor, a third motor, a first angle measuring device, a second angle measuring device, and a distance meter, the second motor and the third motor configured together to direct a third beam of light to a first direction, the first direction determined by the first angle of rotation about a first axis and the second angle of rotation about a second axis, the first angle of rotation produced by the second motor and the second angle of rotation produced by the third motor, the first angle measuring device configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation, the distance meter configured to measure the first distance from the coordinate measurement device to the retroreflector, the first distance based at least in part on a reflected portion of the third beam of light and on a speed of the third beam of light in air.

3. The device of claim 1, wherein the first lens group is an afocal group having an infinite effective focal length.

4. The device of claim 2, wherein the zoom-camera assembly rotates about the first axis.
5. The device of claim 4, wherein the zoom-camera assembly rotates about the second axis.
6. The device of claim 1, wherein the retroreflector is a spherically mounted retroreflector.
7. The device of claim 2, wherein the first beam of light has a first wavelength and the third beam of light has a second wavelength, the second wavelength being different from the first wavelength.
8. The device of claim 1, wherein the illuminator is selected from the group consisting of a laser, a light emitting diode, and a superluminescent diode.
9. The device of claim 1, further comprising a mirror in an optical path between the first lens group and the imaging sensor, the optical path being traveled by the received second beam of light.
10. The device of claim 9, wherein the mirror is moved by the first motor.
11. The device of claim 1, wherein a second distance between the illuminator and the first lens group is fixed with respect to the adjustment.
12. The device of claim 2, wherein a diameter of the first beam of light is greater than a diameter of the third beam of light.
13. The device of claim 2, wherein the third beam of light is coaxial with the first beam of light.

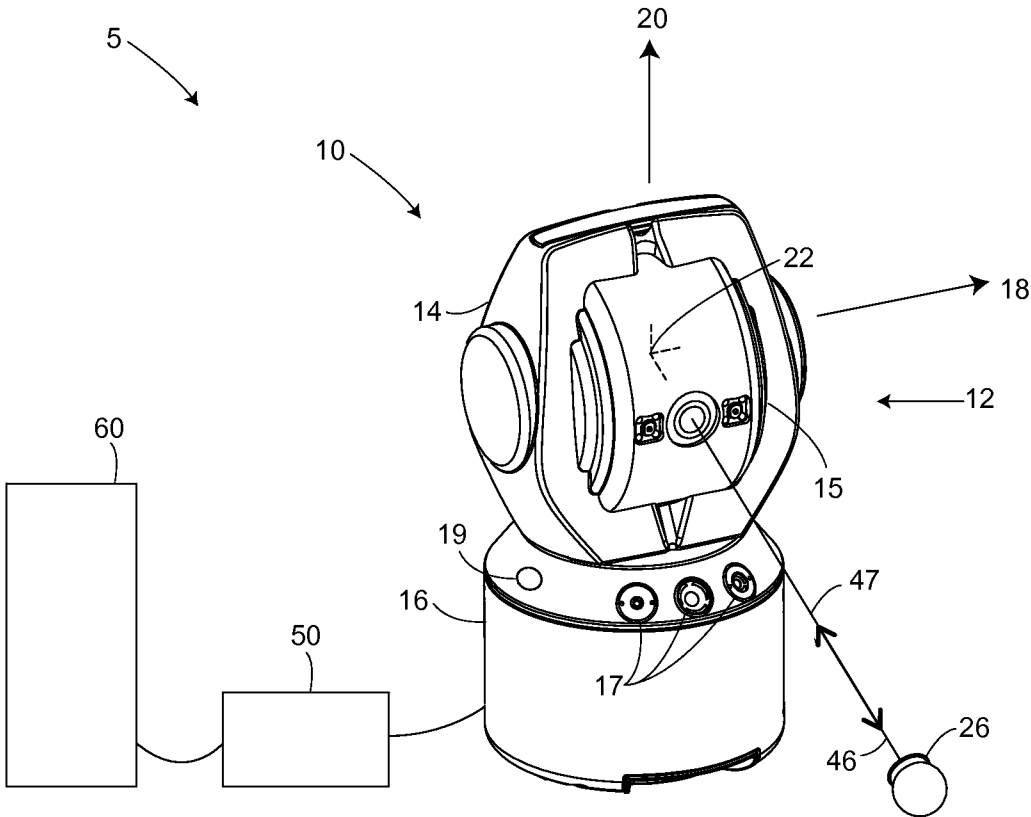


FIGURE 1

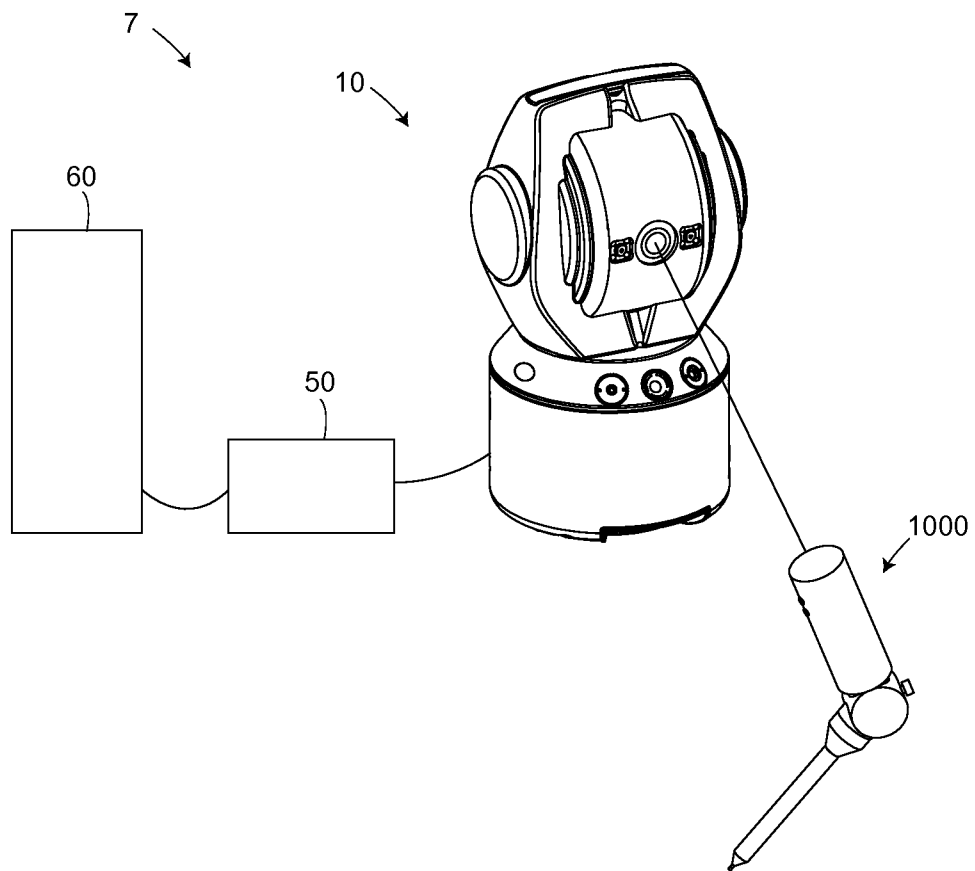


FIGURE 2

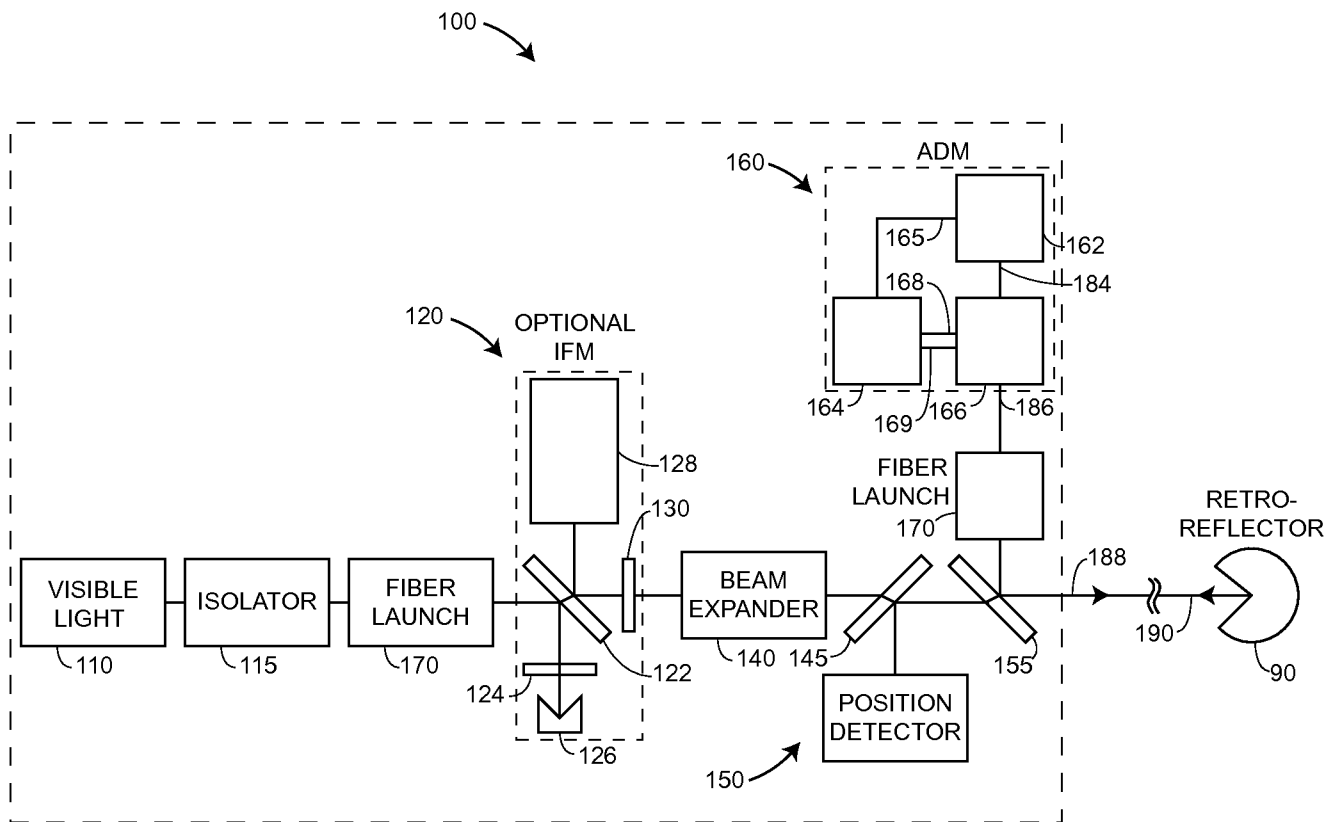
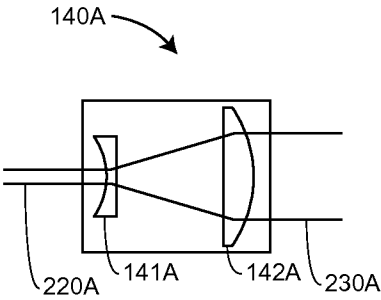
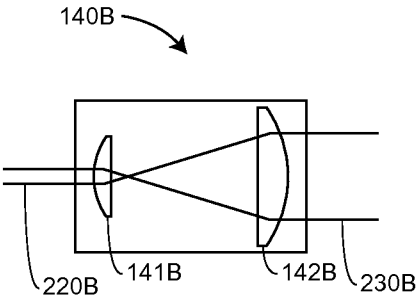


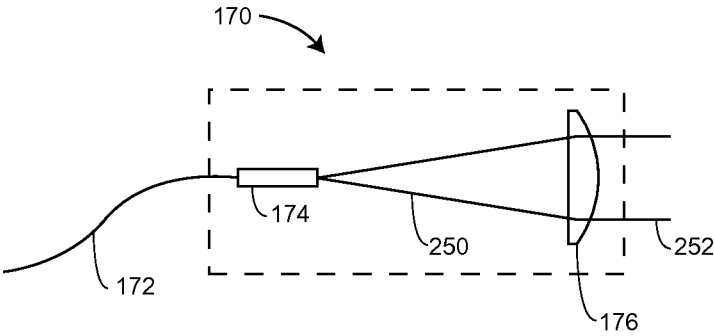
FIGURE 3



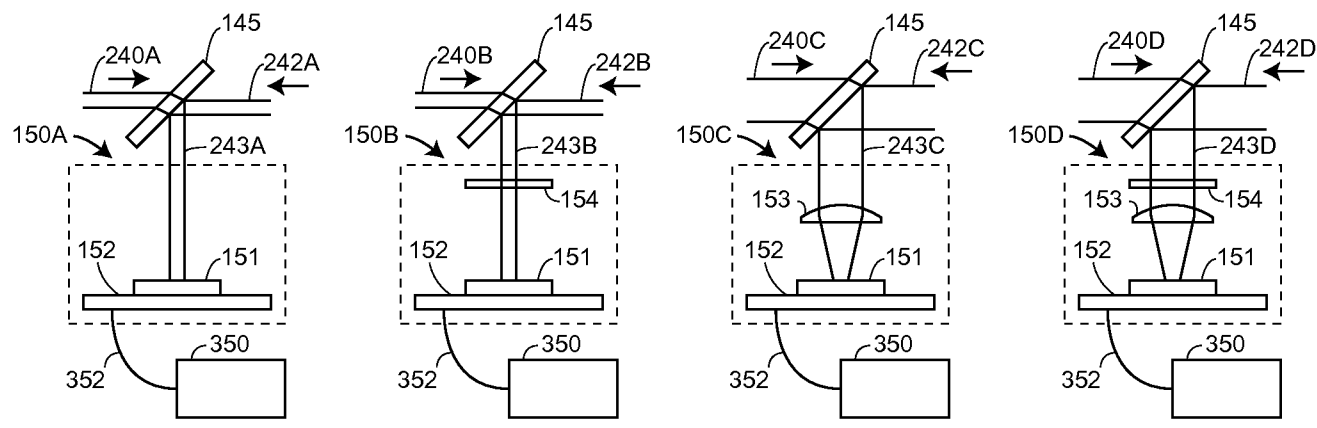
PRIOR ART
FIGURE 4A



PRIOR ART
FIGURE 4B



PRIOR ART
FIGURE 5



PRIOR ART
FIG. 6A

PRIOR ART
FIG. 6B

PRIOR ART
FIG. 6C

PRIOR ART
FIG. 6D

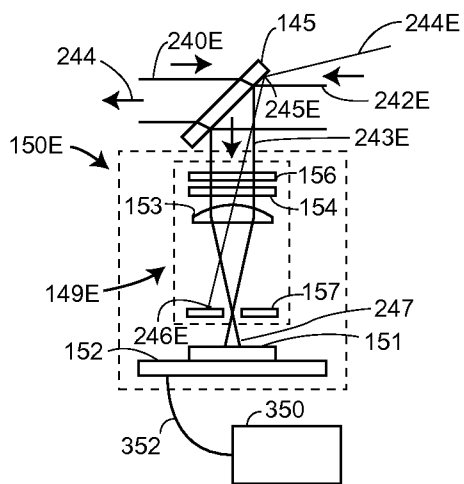


FIG. 6E

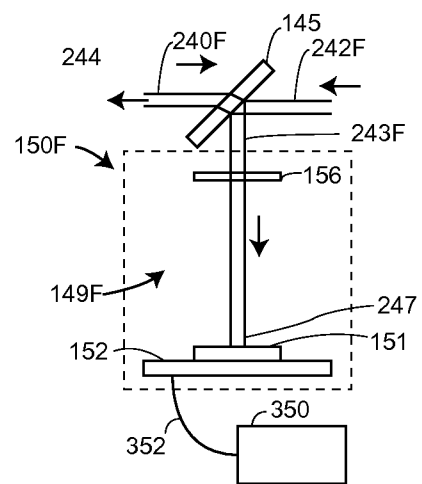
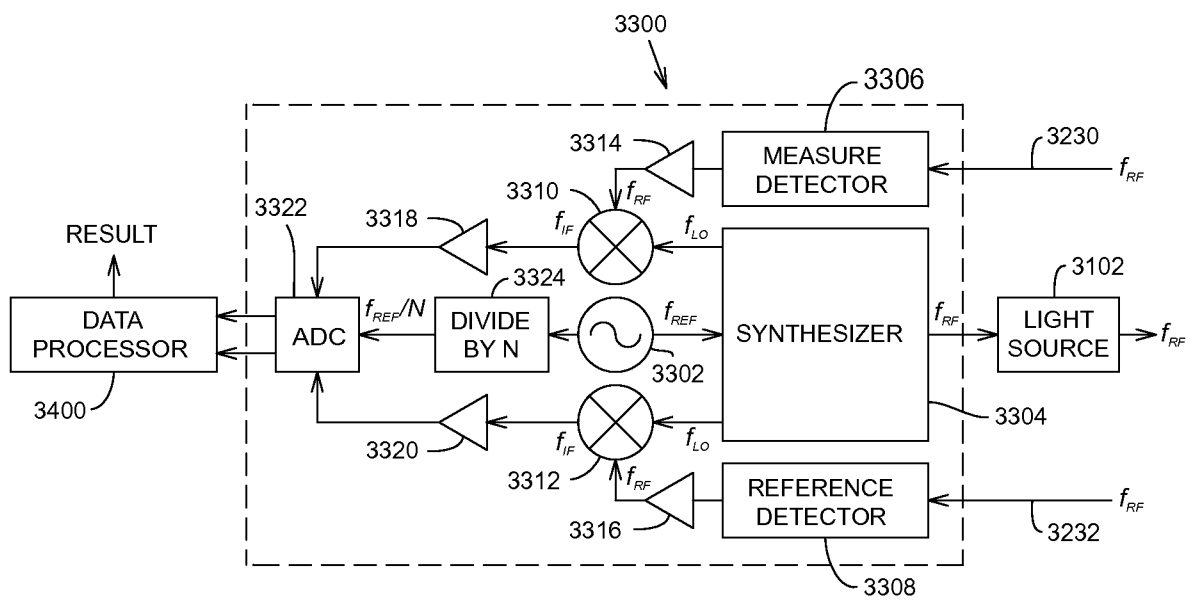
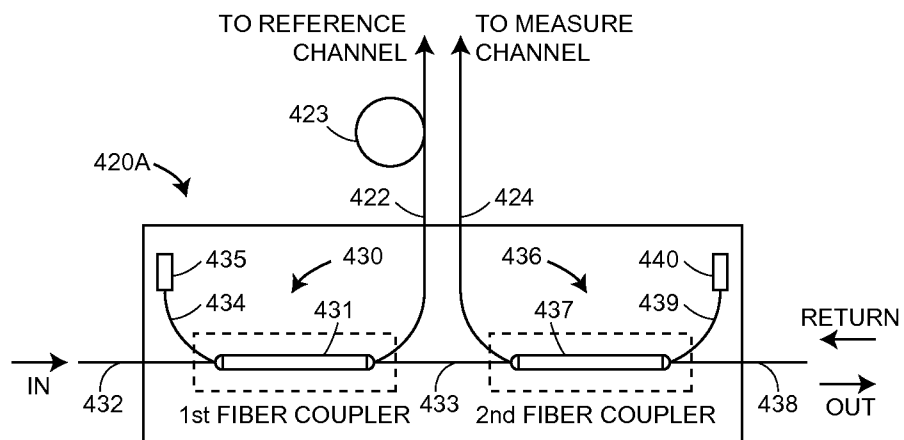
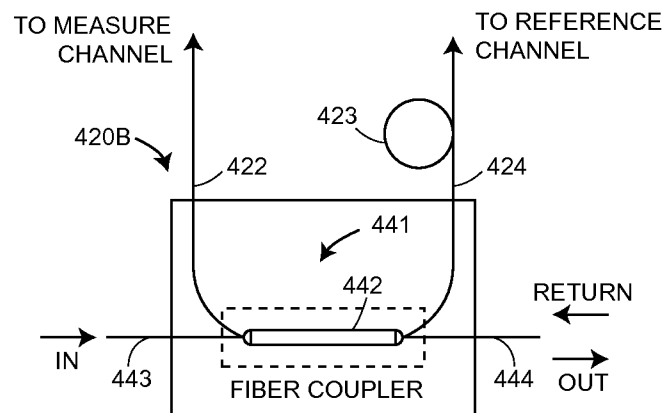


FIG. 6F



PRIOR ART
FIGURE 7

PRIOR ART
FIGURE 8APRIOR ART
FIGURE 8B

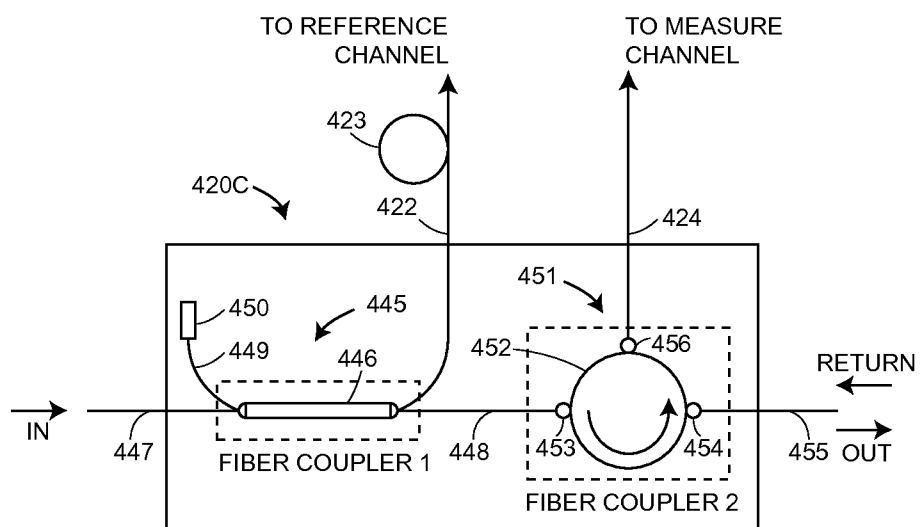
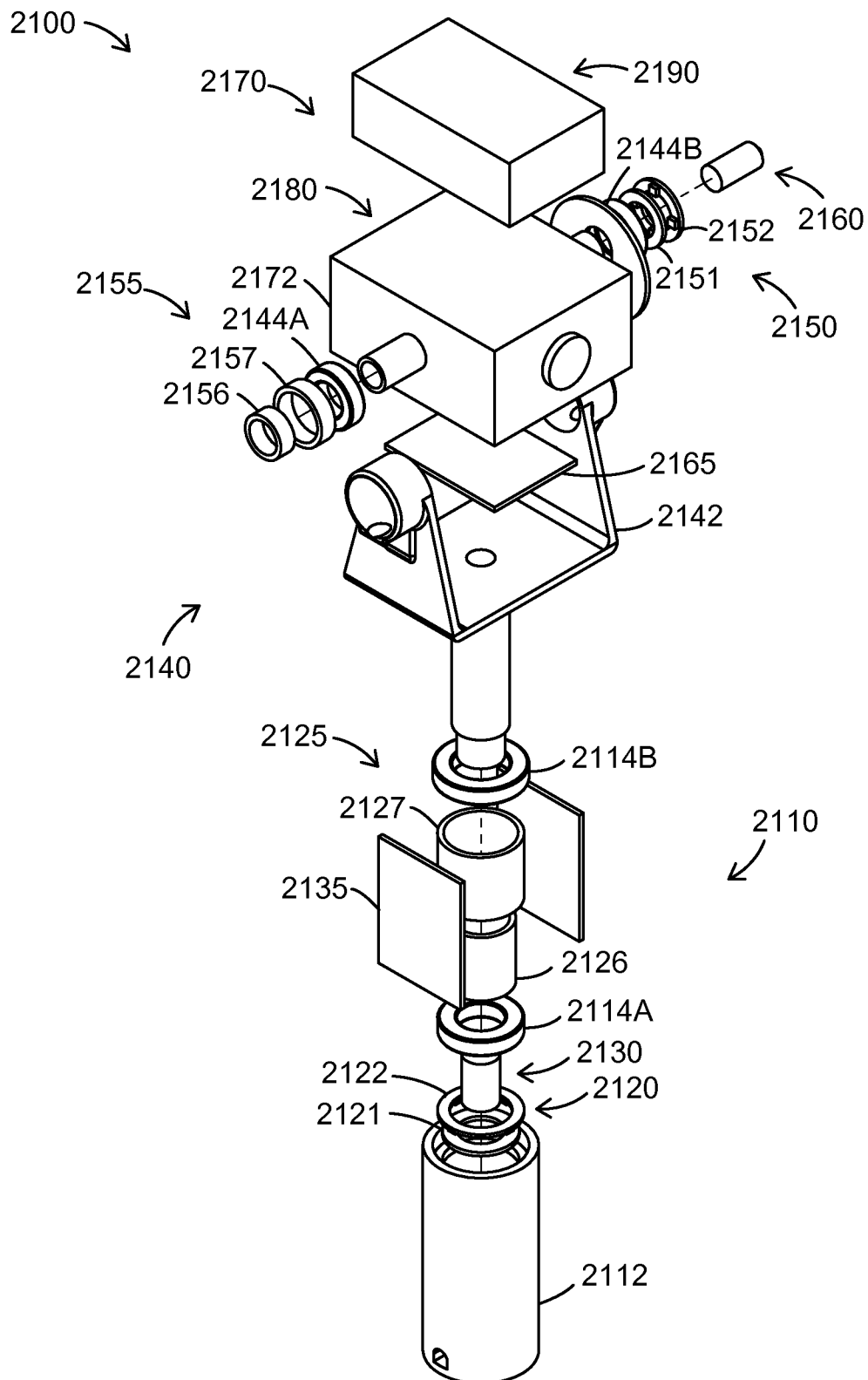
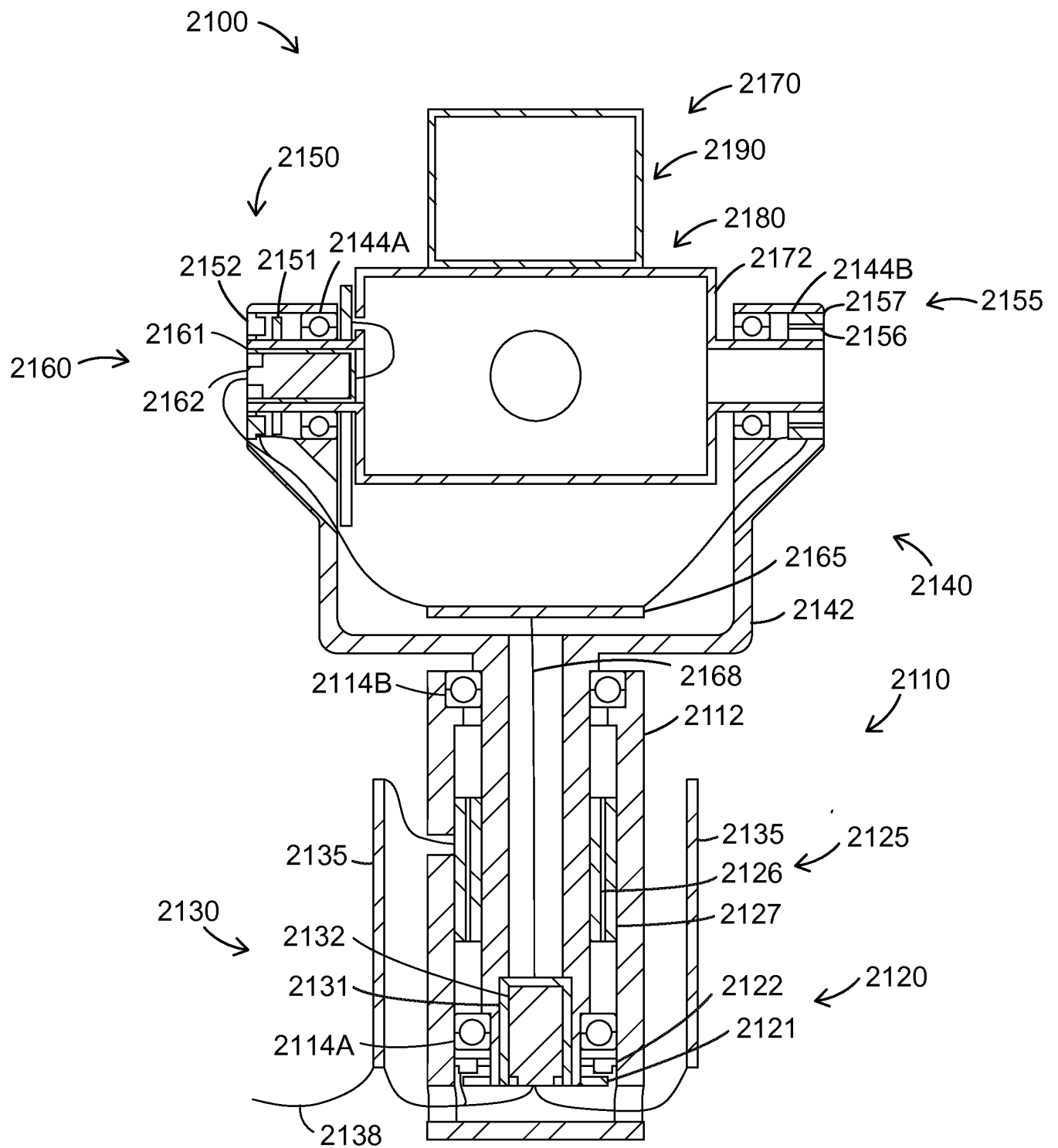


FIGURE 8C



PRIOR ART
FIGURE 9



PRIOR ART
FIGURE 10

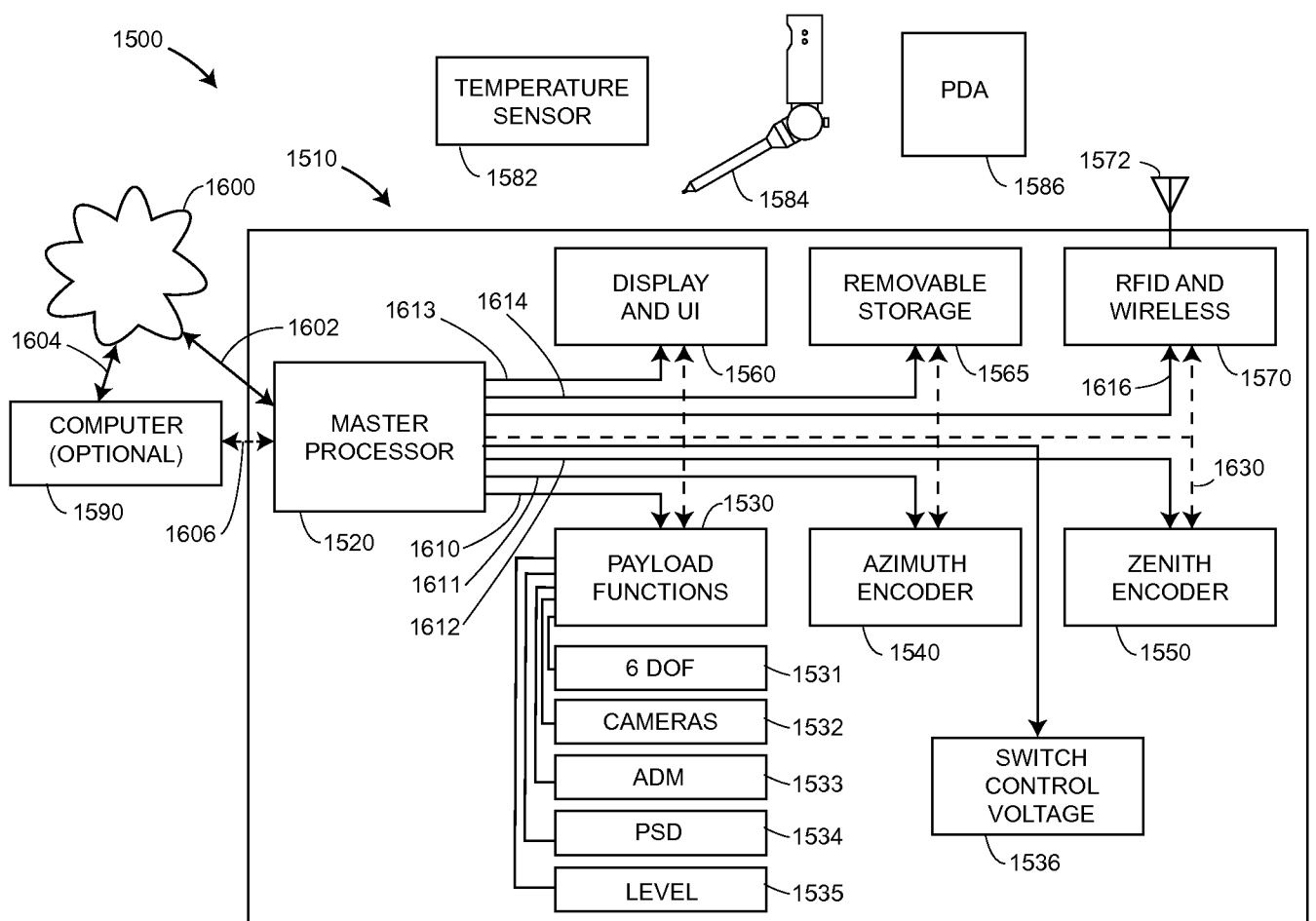


FIGURE 11

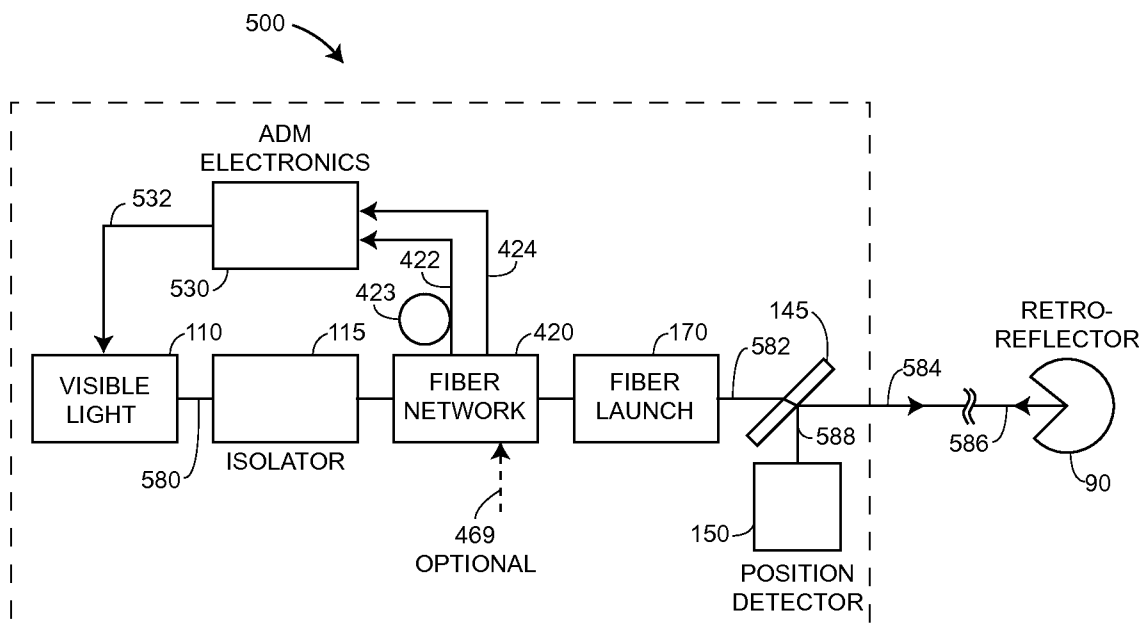


FIGURE 12A

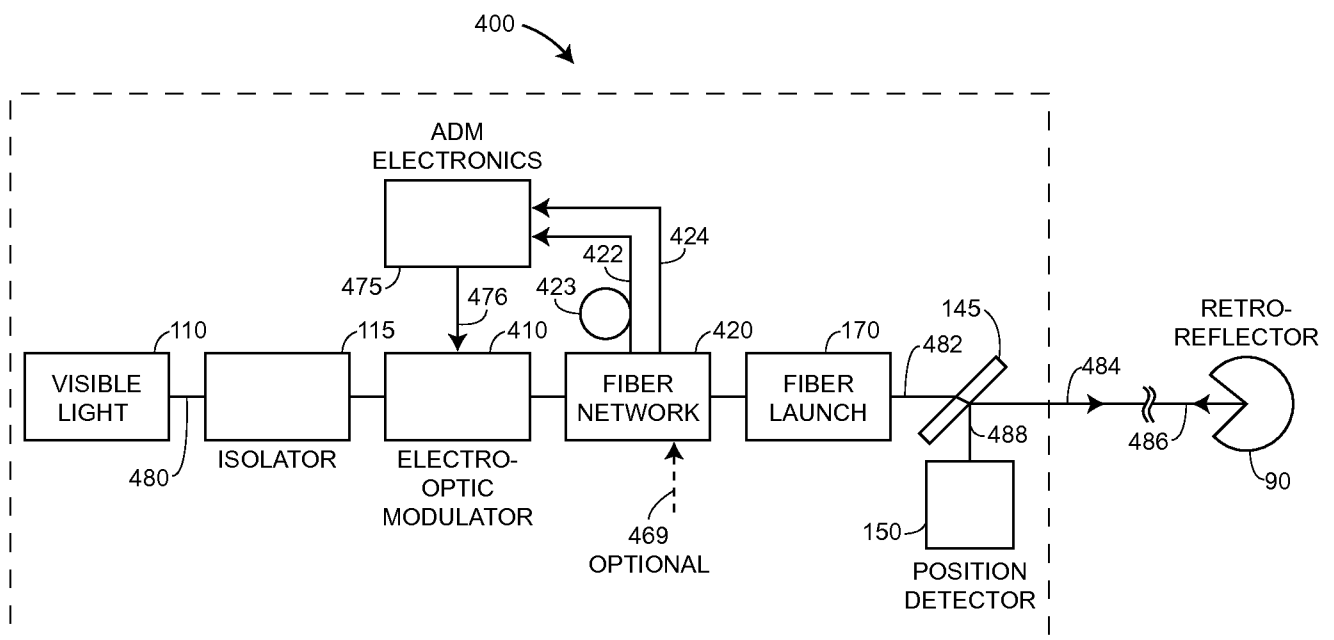


FIGURE 12B

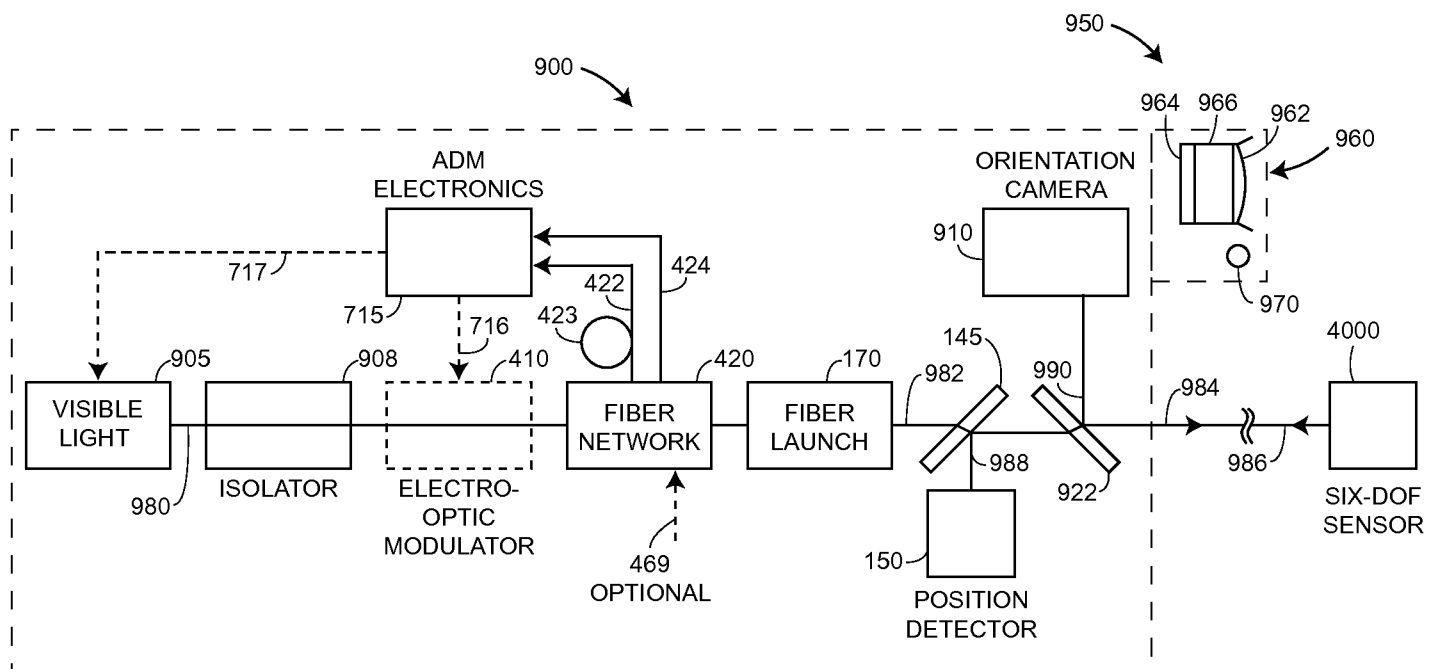
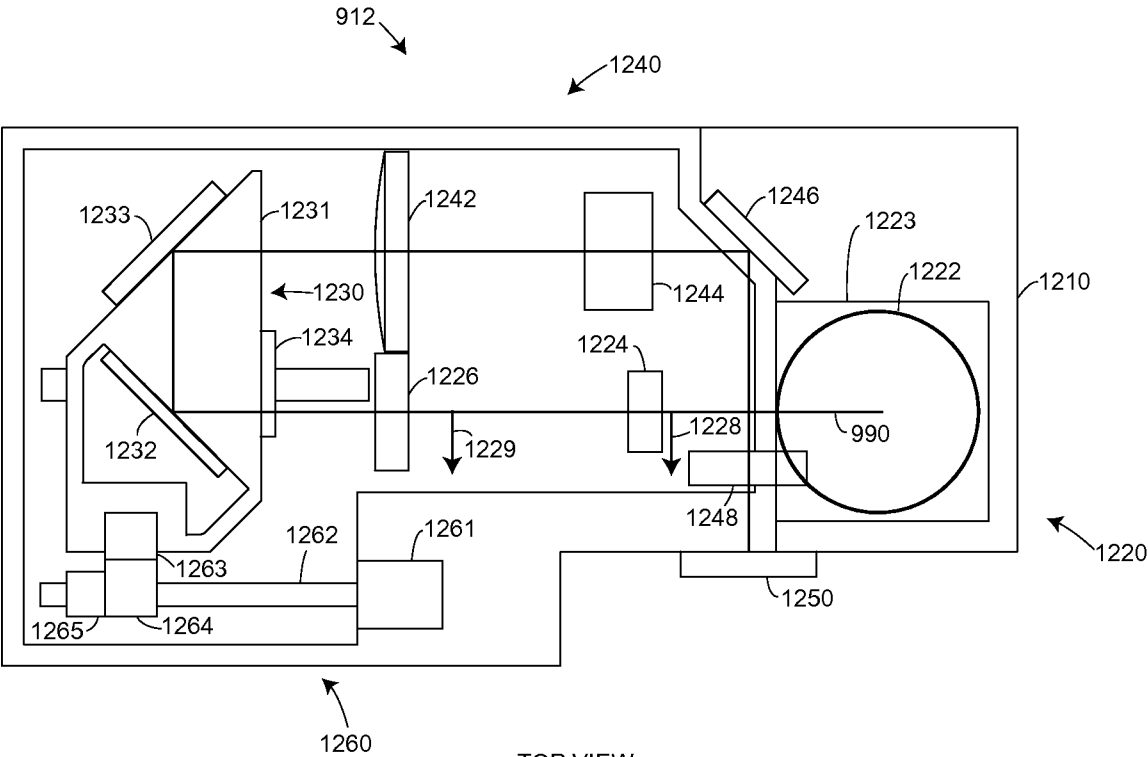


FIGURE 13



TOP VIEW

FIGURE 14

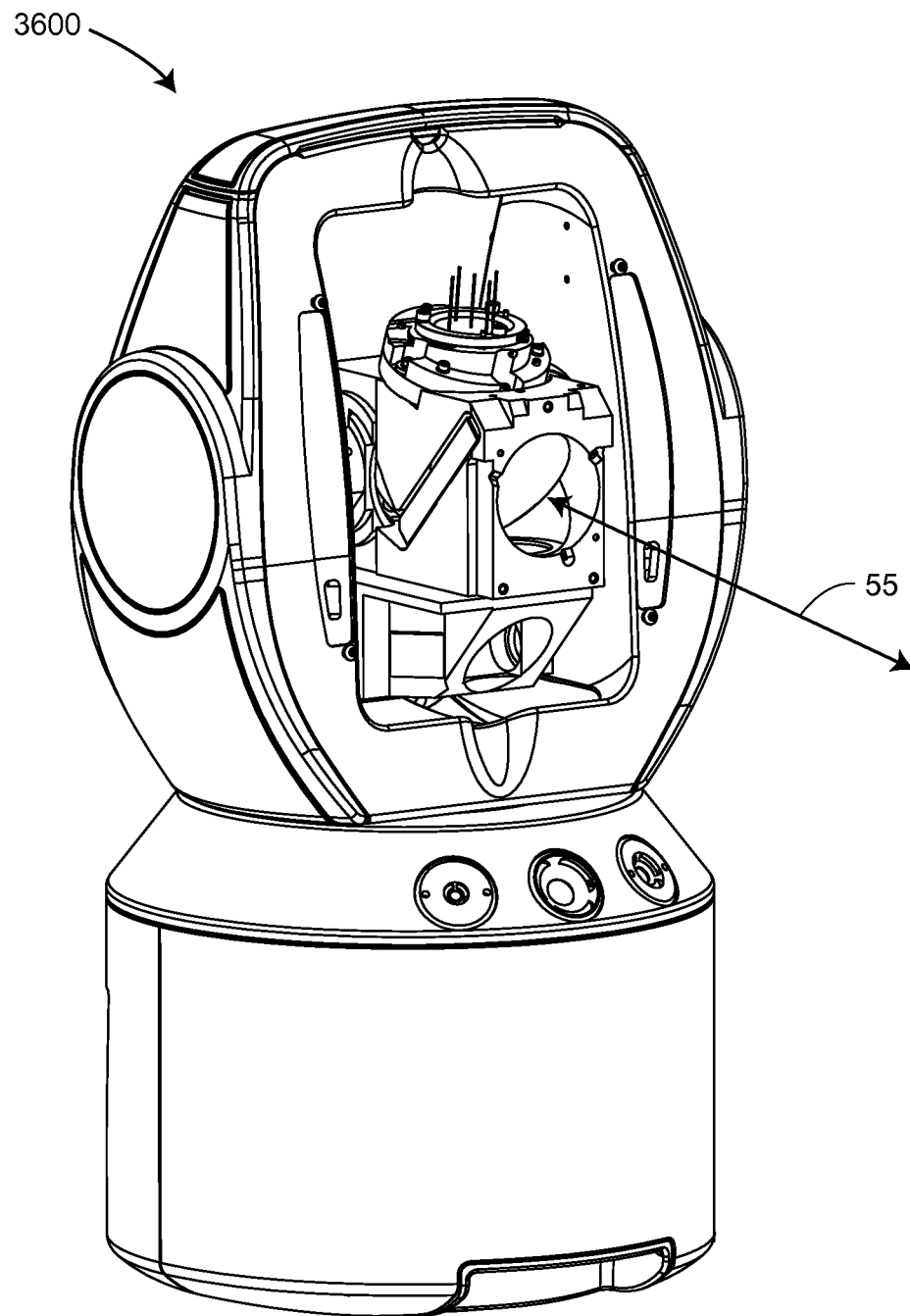


FIGURE 15

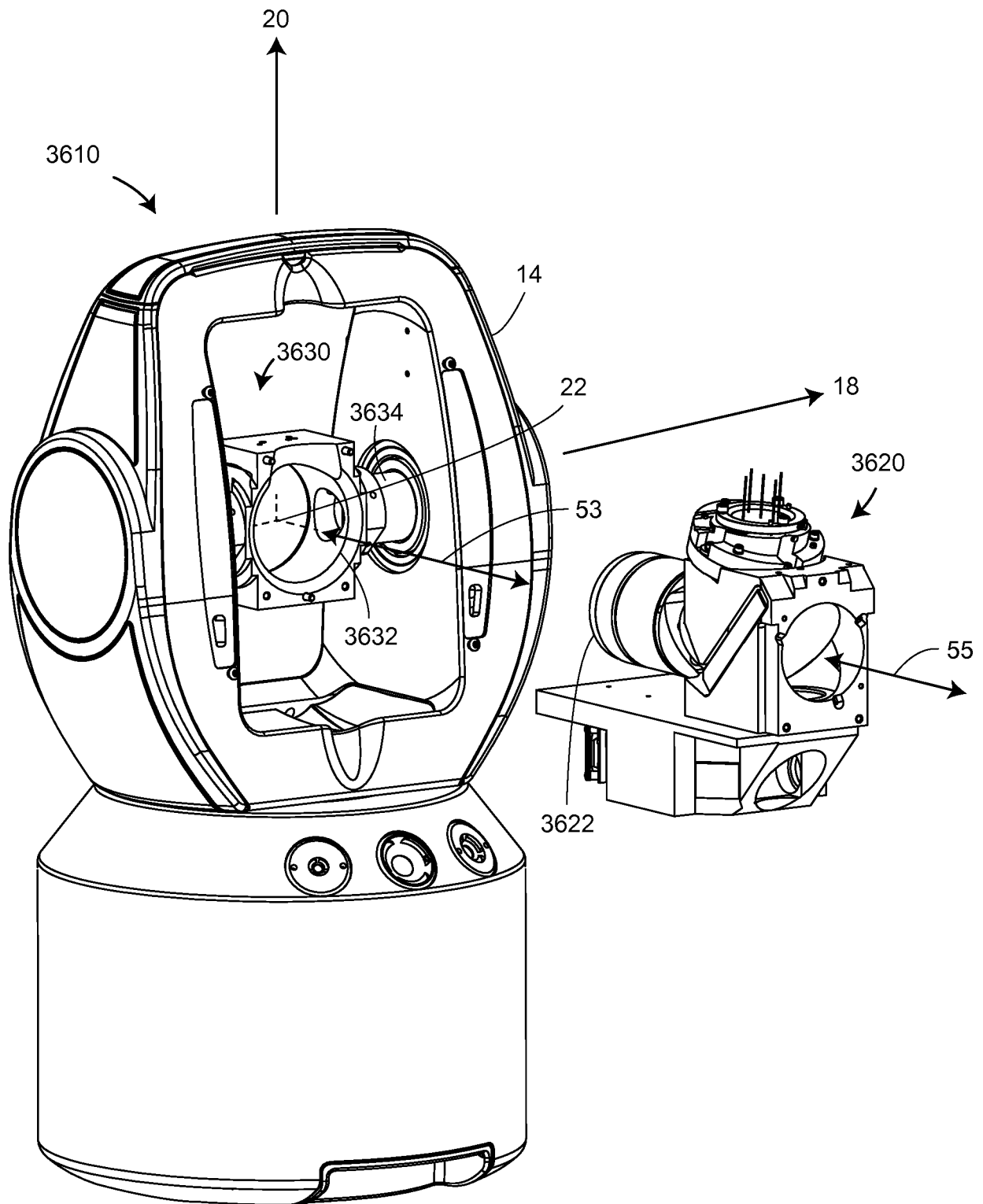


FIGURE 16

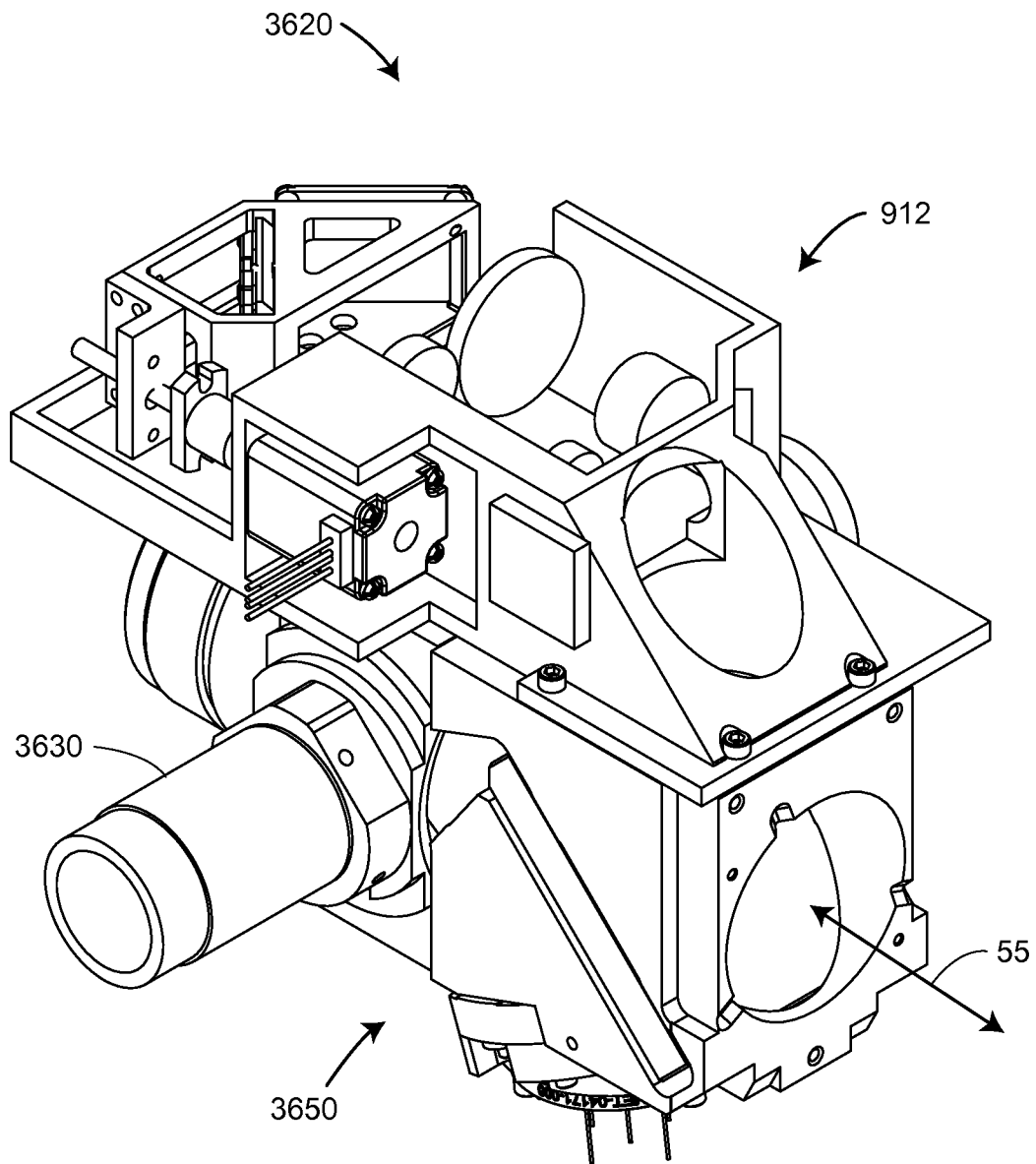
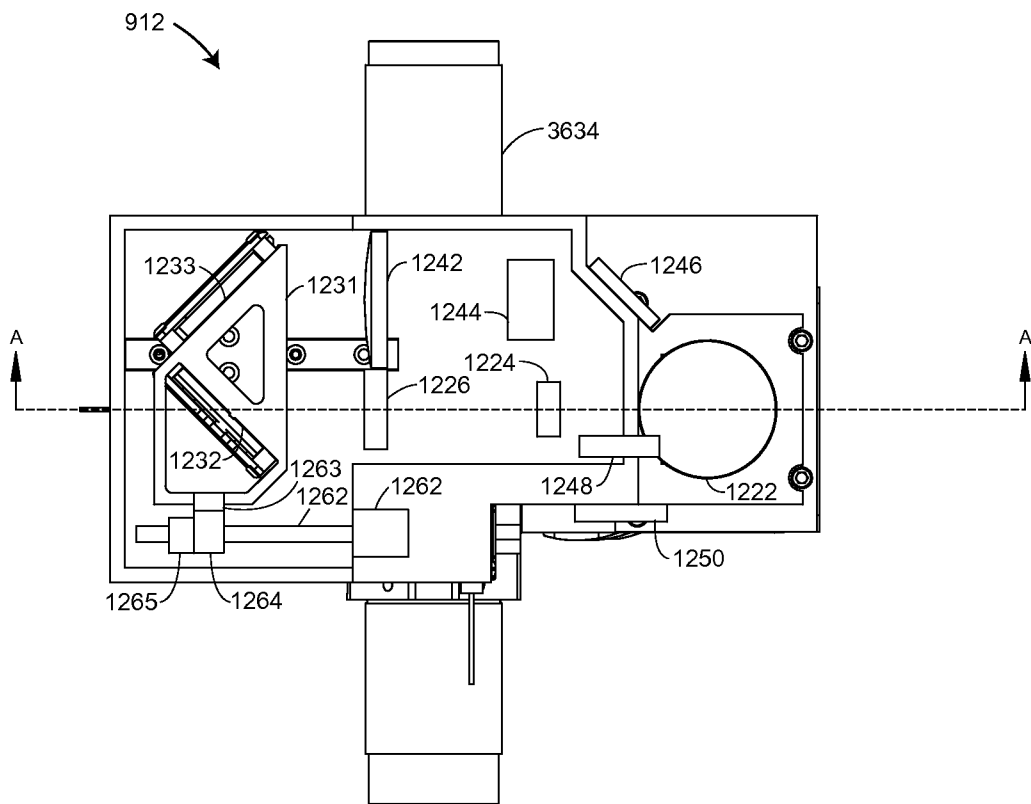
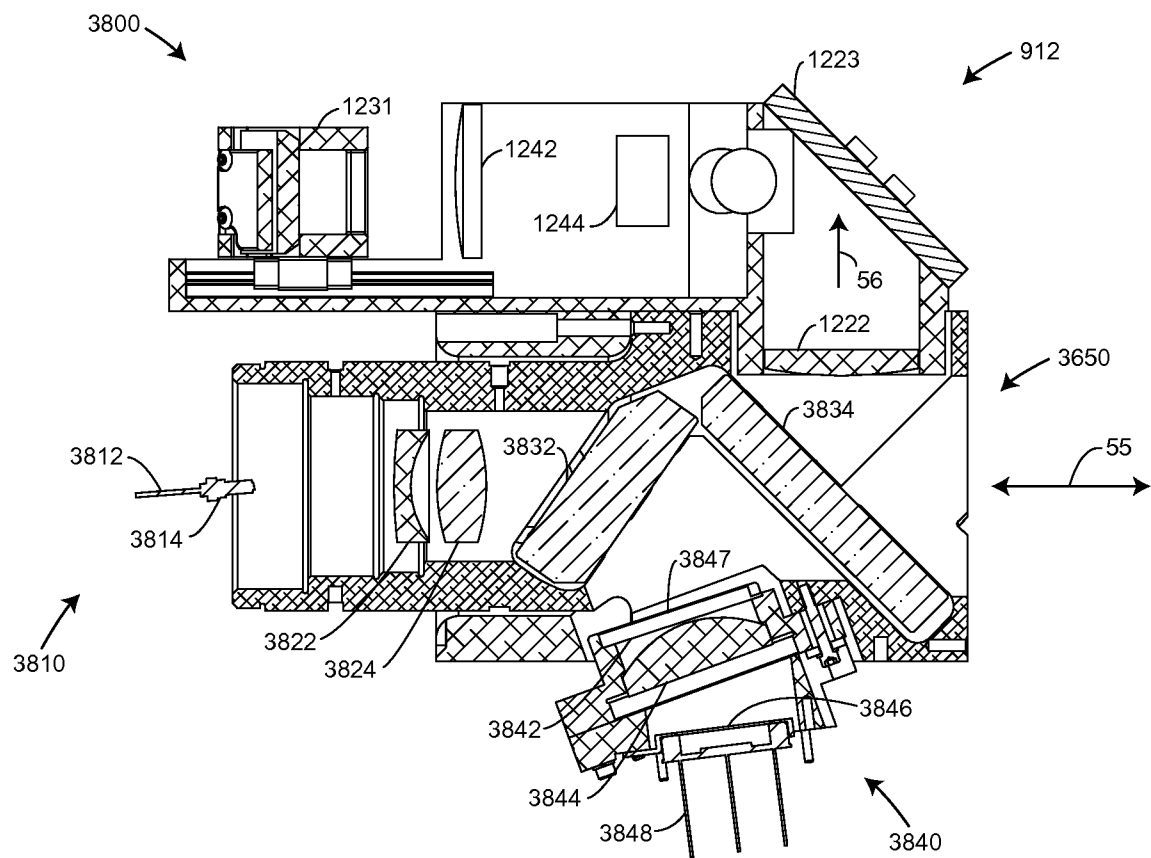


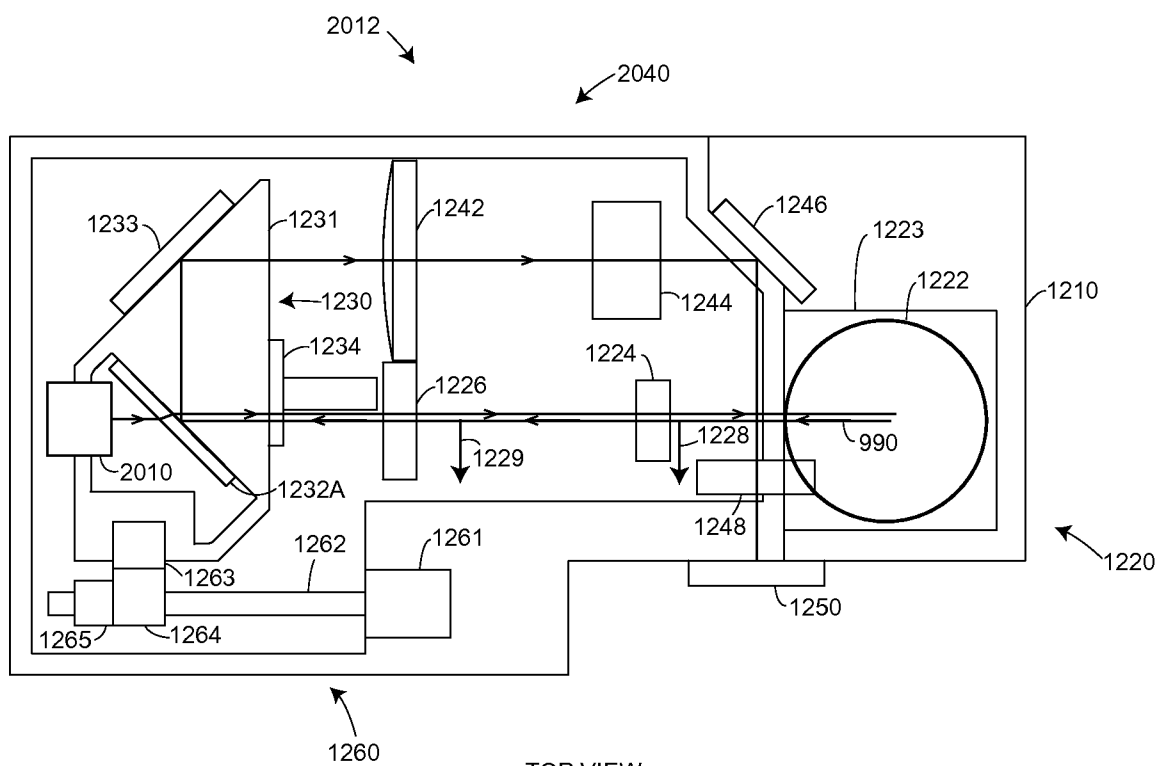
FIGURE 17



TOP VIEW
FIGURE 18



SECTION A-A
FIGURE 19



TOP VIEW

FIGURE 20

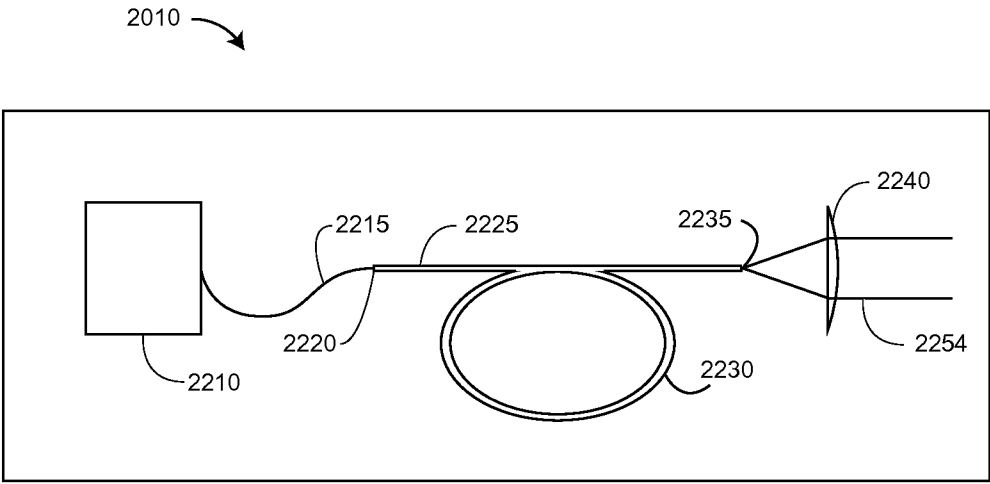


FIGURE 21

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/037063

A. CLASSIFICATION OF SUBJECT MATTER INV. G01S7/481 G01S17/02 G01S17/42 G01S17/66 G01B11/00 G02B7/04 ADD. According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G01S G01B G02B Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 800 758 B1 (BRIDGES ROBERT E [US] ET AL) 21 September 2010 (2010-09-21) abstract; figures 1-7 column 5, line 61 - column 6, line 23 column 6, line 59 - column 7, line 18 column 8, line 25 - line 68 column 12, line 27 - column 14, line 6 -----	1-13
A	US 2004/163266 A1 (KANEKO KENJI [JP]) 26 August 2004 (2004-08-26) abstract; figure 7 paragraphs [0058] - [0066] -----	1-13
A	US 2010/253931 A1 (MEIER DIETRICH [CH] ET AL) 7 October 2010 (2010-10-07) abstract; figures 1,4,6 paragraphs [0066] - [0068], [0075] - [0078] -----	1-13
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 28 September 2015		Date of mailing of the international search report 05/10/2015
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Roost, Joseph

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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