US010393877B2

(12) **United States Patent**
Hall et al.

(10) **Patent No.: US 10,393,877 B2**
(45) **Date of Patent: Aug. 27, 2019**

(54) **MULTIPLE PIXEL SCANNING LIDAR**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 71 days.

(21) Appl. No.: **15/610,975**

(22) Filed: **Jun. 1, 2017**

(65) **Prior Publication Data**

US 2017/0350983 A1 Dec. 7, 2017

Related U.S. Application Data

(60) Provisional application No. 62/344,259, filed on Jun. 1, 2016.

(51) **Int. Cl.**

G01C 3/08	(2006.01)
G01S 17/89	(2006.01)
G01C 1/06	(2006.01)
G01S 7/481	(2006.01)
G01S 7/487	(2006.01)
G01S 17/87	(2006.01)
G01S 17/10	(2006.01)

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

CPC ***G01S 17/89*** (2013.01); ***G01C 1/06*** (2013.01); ***G01C 3/08*** (2013.01); ***G01S 7/487*** (2013.01); ***G01S 7/4815*** (2013.01); ***G01S 7/4817*** (2013.01); ***G01S 17/10*** (2013.01); ***G01S 17/87*** (2013.01)

(58) **Field of Classification Search**

CPC G01S 17/89; G01S 7/4815; G01S 7/4817; G01S 7/487; G01S 17/10; G01S 17/87; G01C 1/06; G01C 3/08

See application file for complete search history.

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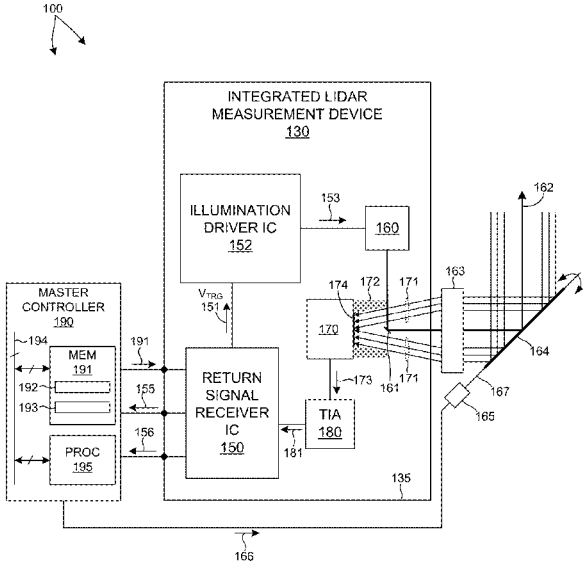
(57) **ABSTRACT**

Methods and systems for performing three dimensional LIDAR measurements with multiple illumination beams scanned over a three dimensional environment are described herein. In one aspect, illumination light from each LIDAR measurement channel is emitted to the surrounding environment in a different direction by a beam scanning device. The beam scanning device also directs each amount of return measurement light onto a corresponding photodetector. In some embodiments, a beam scanning device includes a scanning mirror rotated in an oscillatory manner about an axis of rotation by an actuator in accordance with command signals generated by a master controller. In some embodiments, the light source and photodetector associated with each LIDAR measurement channel are moved in two dimensions relative to beam shaping optics employed to collimate light emitted from the light source. The relative motion causes the illumination beams to sweep over a range of the three dimensional environment under measurement.

20 Claims, 10 Drawing Sheets



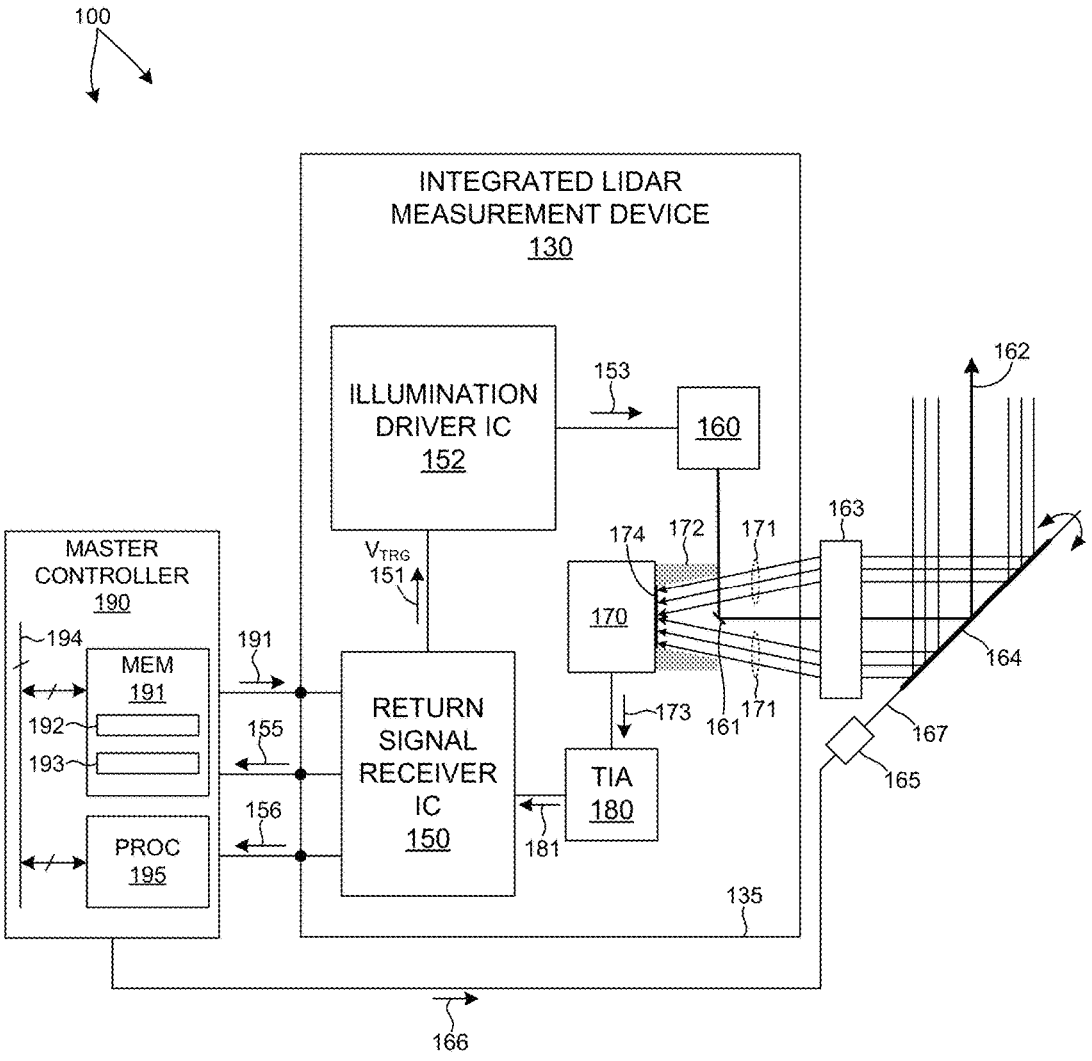

100
INTEGRATED LIDAR MEASUREMENT DEVICE 130
ILLUMINATION DRIVER IC 152
153
160
162
163
174
172
171
170
V_{TRG} 151
MASTER CONTROLLER 190
194
MEM 191
191
192
193
155
156
PROC 195
RETURN SIGNAL RECEIVER IC 150
TIA 180
181
173
161
171
164
167
165
135
166

FIG. 1

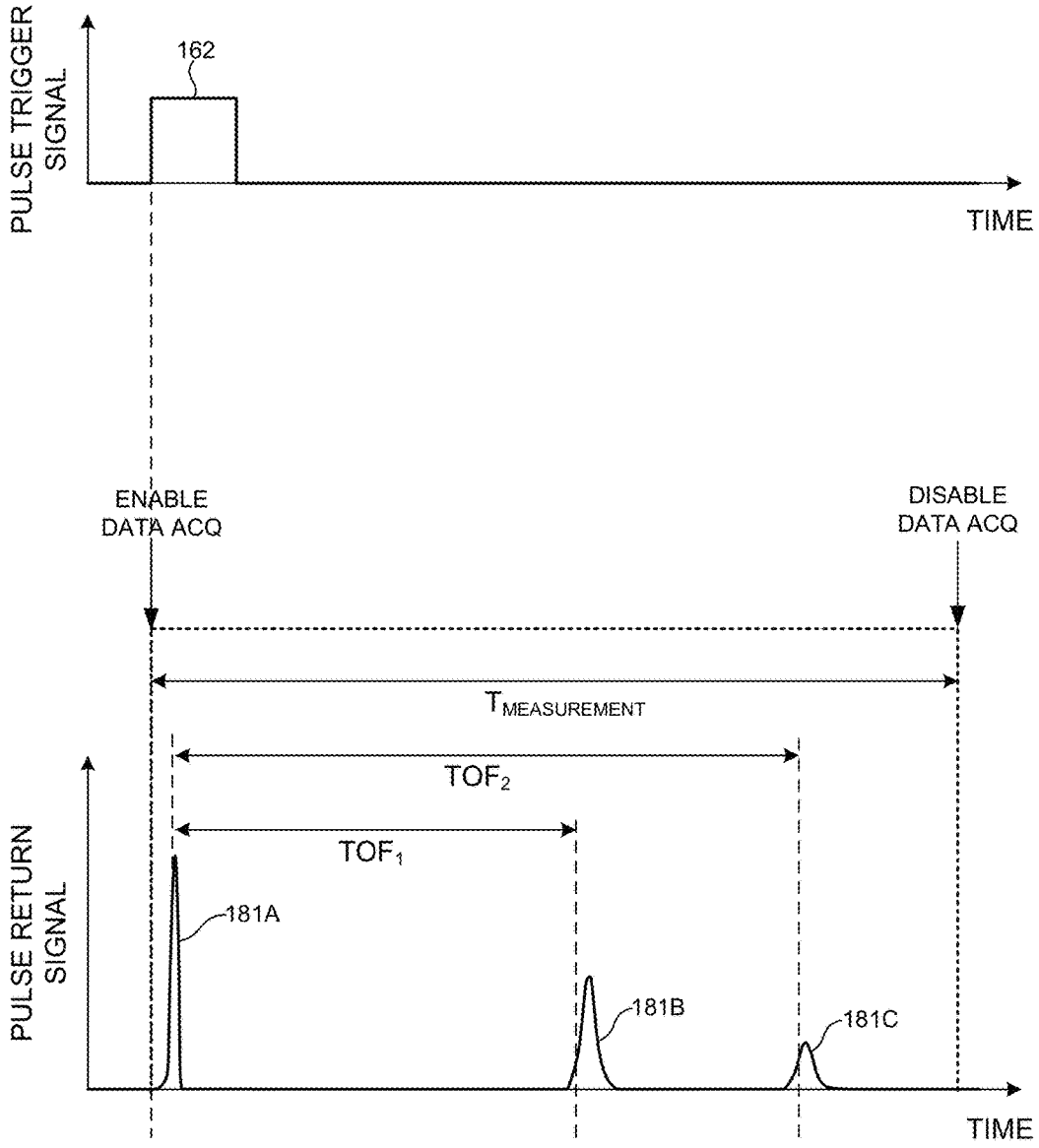

PULSE TRIGGER SIGNAL
162
TIME
ENABLE DATA ACQ
DISABLE DATA ACQ
$T_{MEASUREMENT}$
TOF_2
TOF_1
PULSE RETURN SIGNAL
181A
181B
181C
TIME

FIG. 2

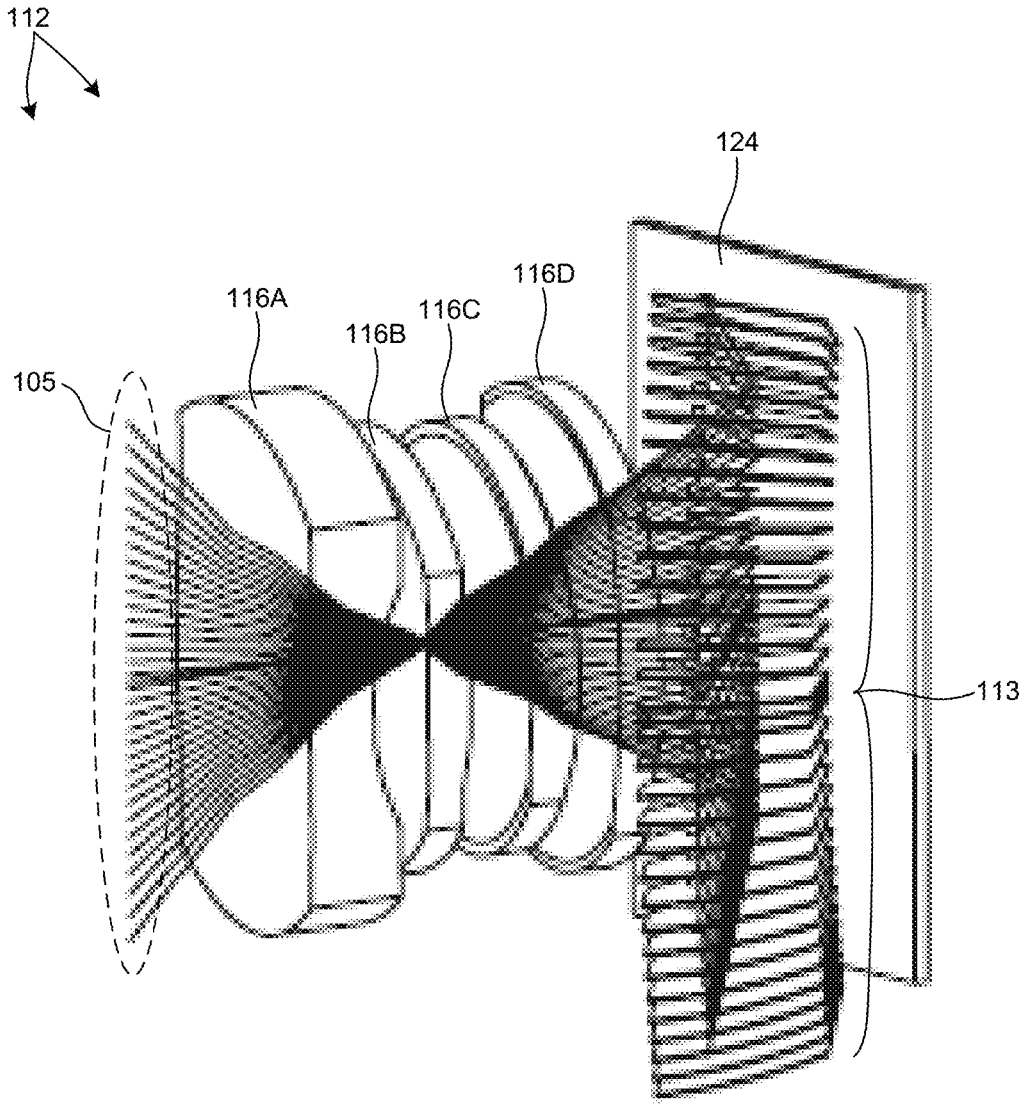


FIG. 3

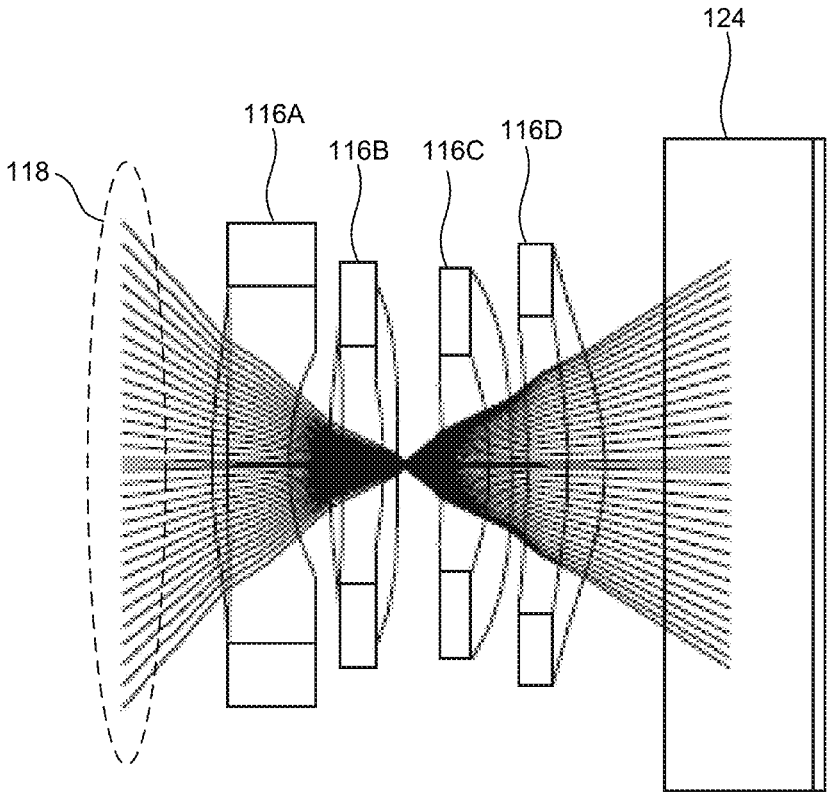


FIG. 4

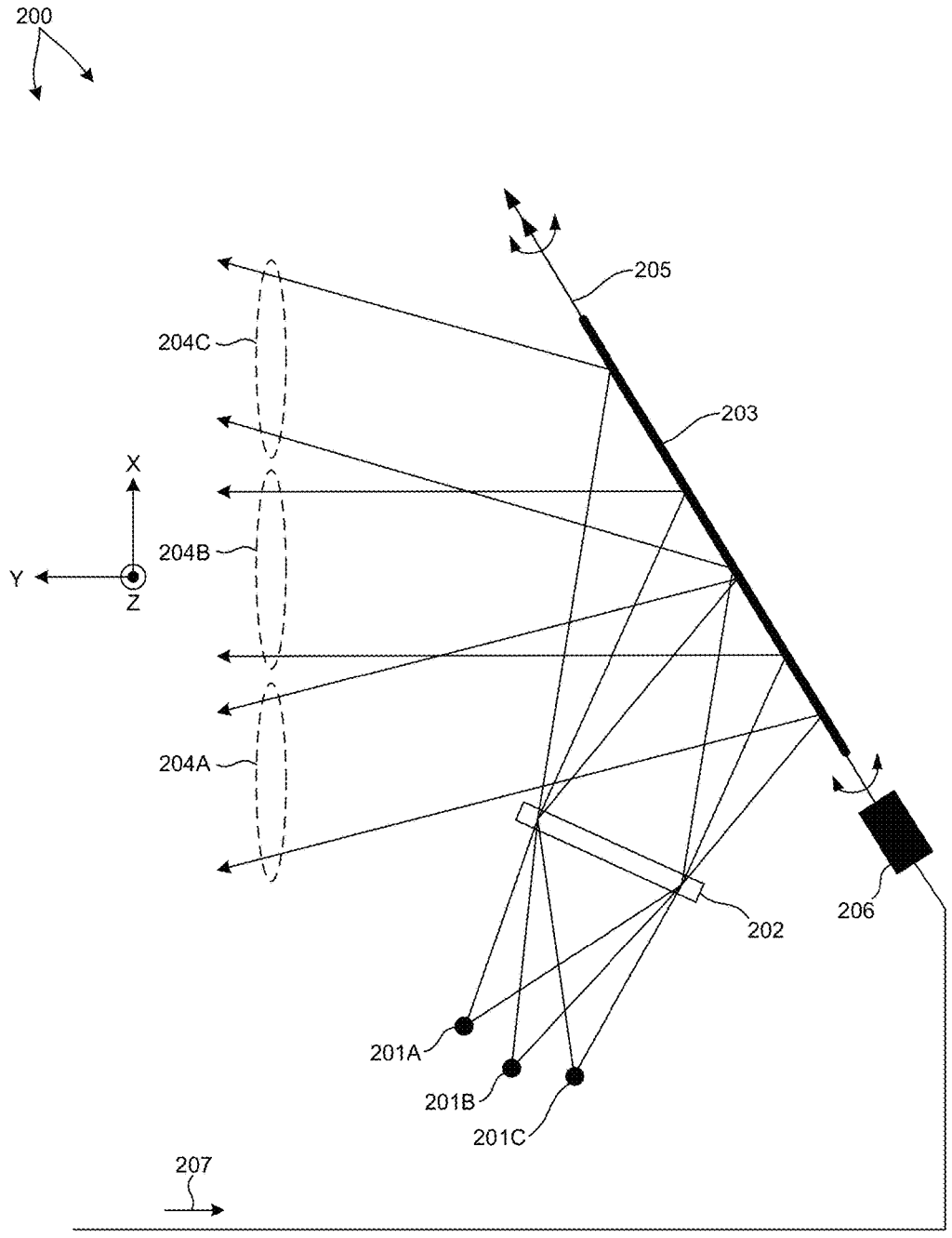


FIG. 5

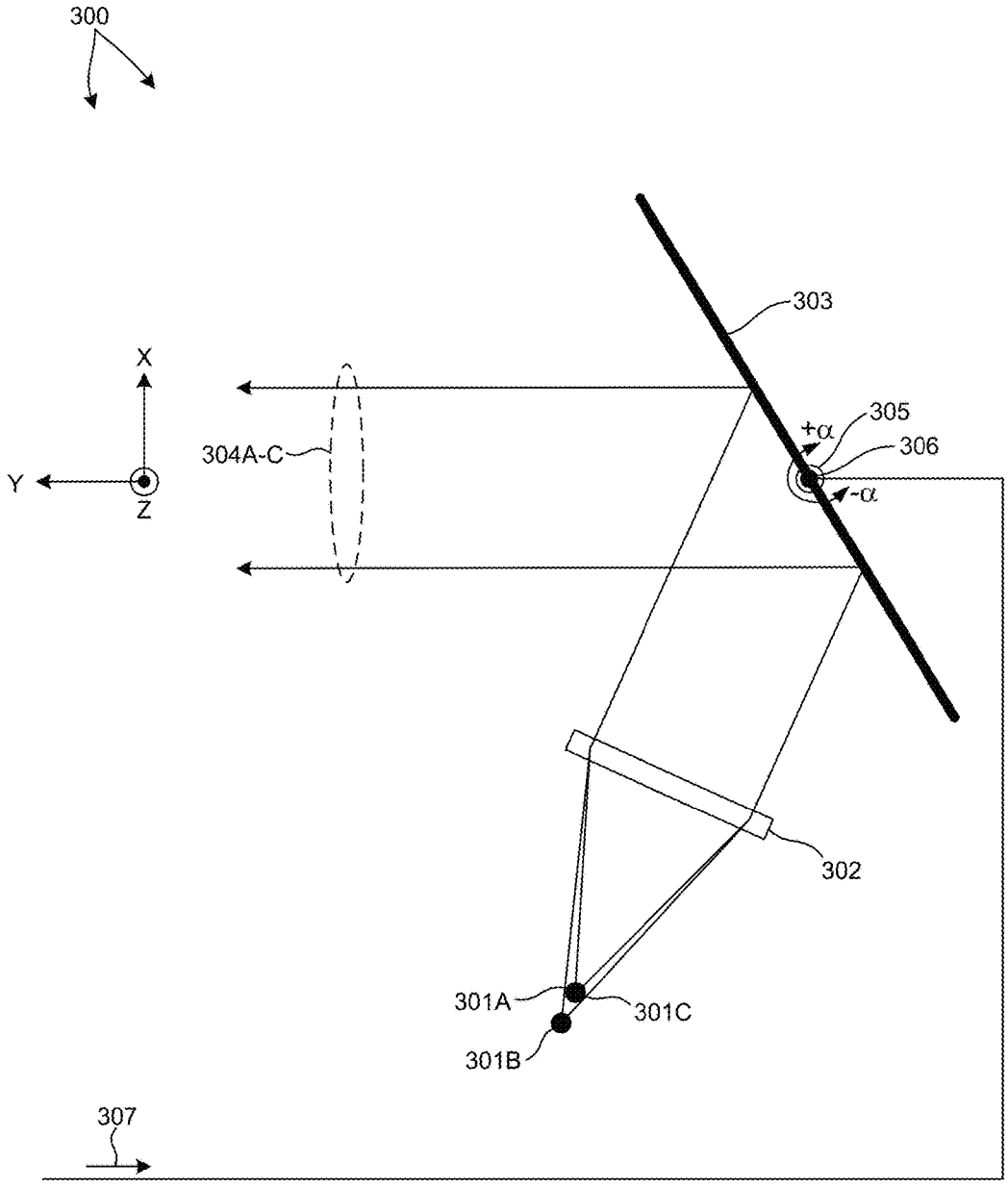


FIG. 6

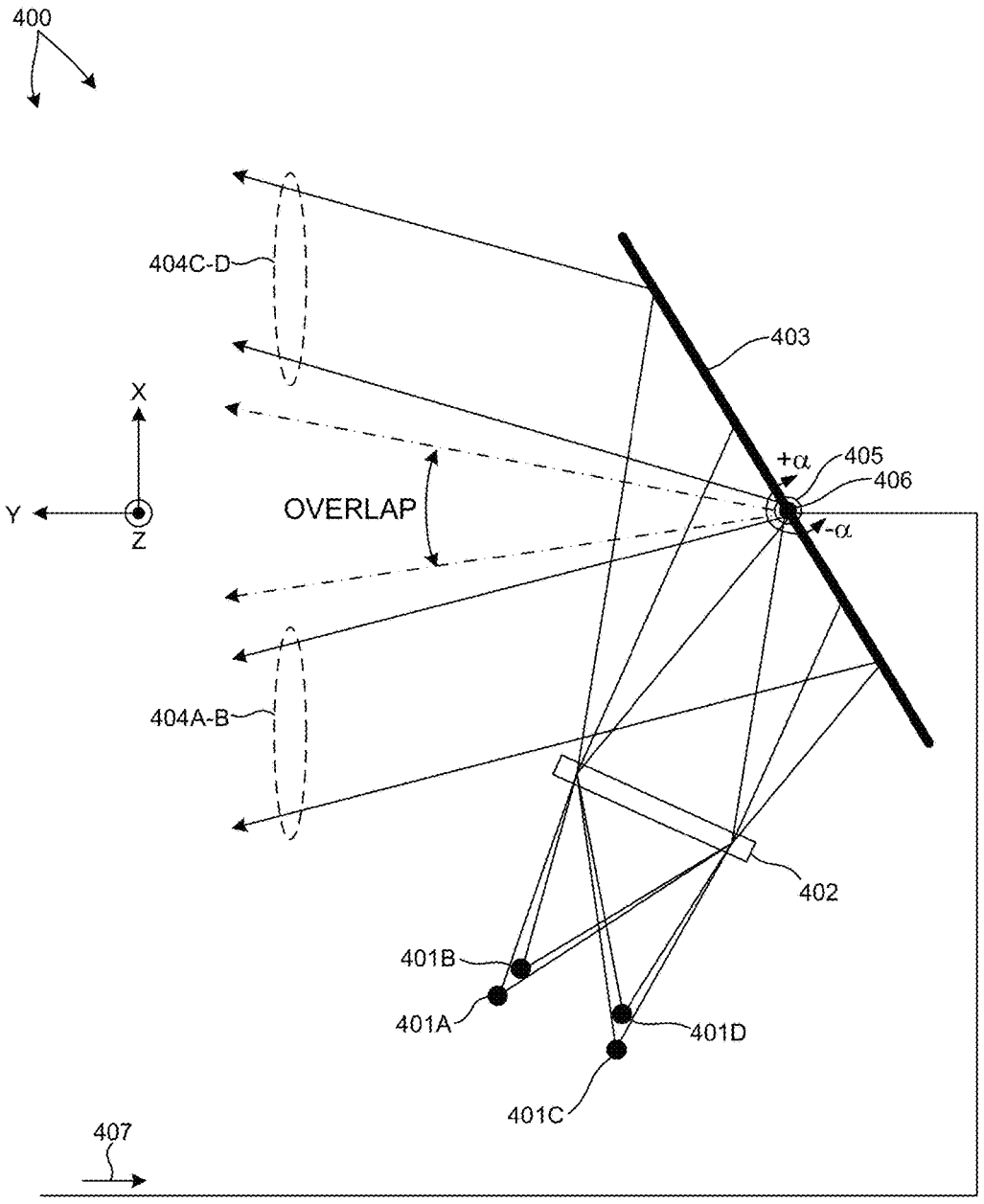

400
404C-D
403
X
Y
Z
OVERLAP
+α
405
406
-α
404A-B
402
401B
401A
401D
401C
407

FIG. 7

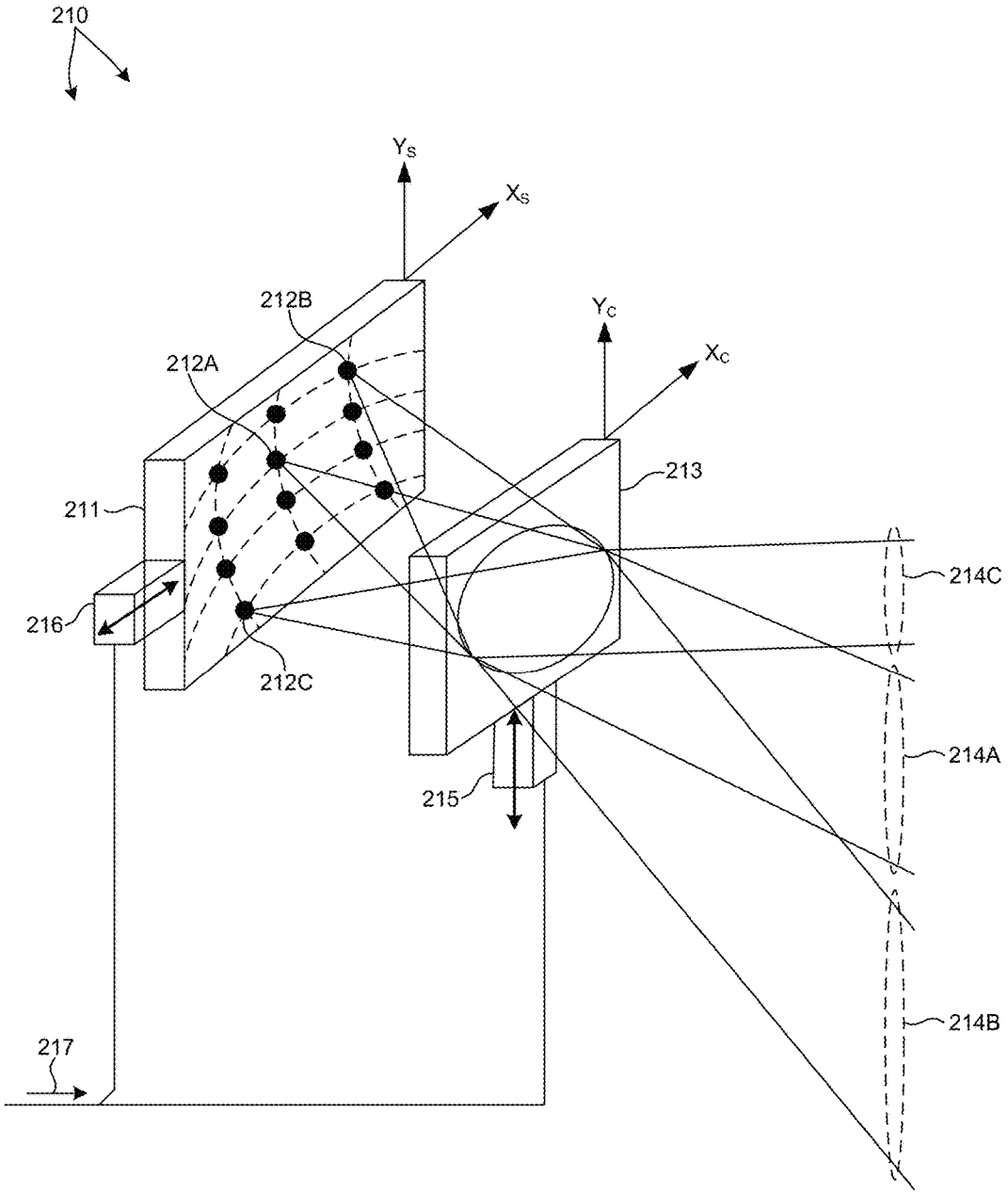

210
Y_S
X_S
212B
Y_C
212A
X_C
213
211
214C
216
212C
214A
215
214B
217

FIG. 8

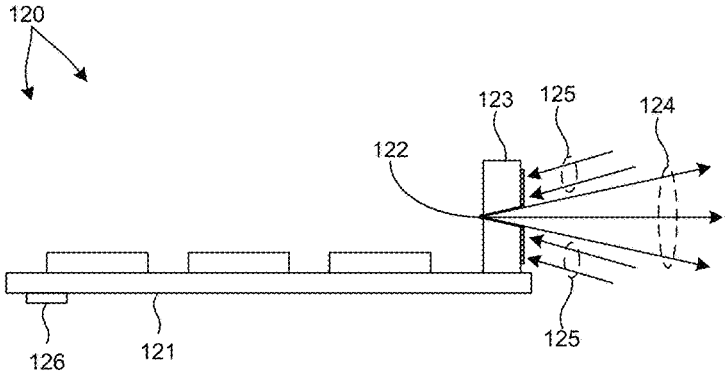

120
123
125
124
122
126
121
125

FIG. 9

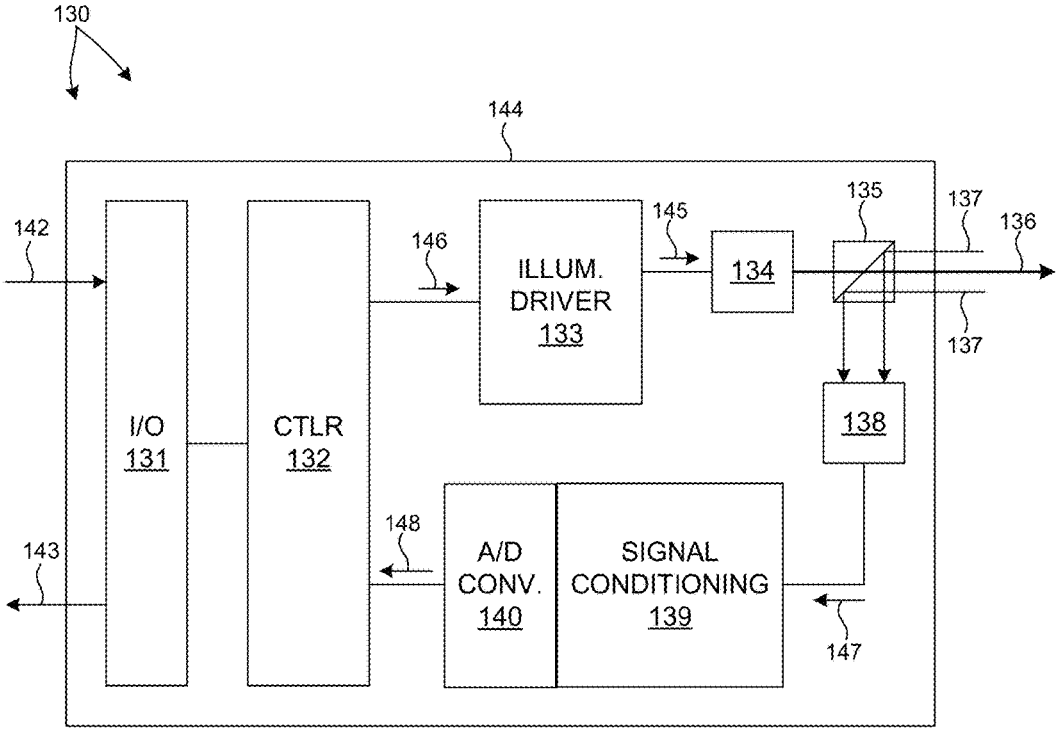

130
144
142
I/O
131
CTLR
132
146
ILLUM.
DRIVER
133
145
134
135
137
136
137
138
148
143
A/D
CONV.
140
SIGNAL
CONDITIONING
139
147

FIG. 10

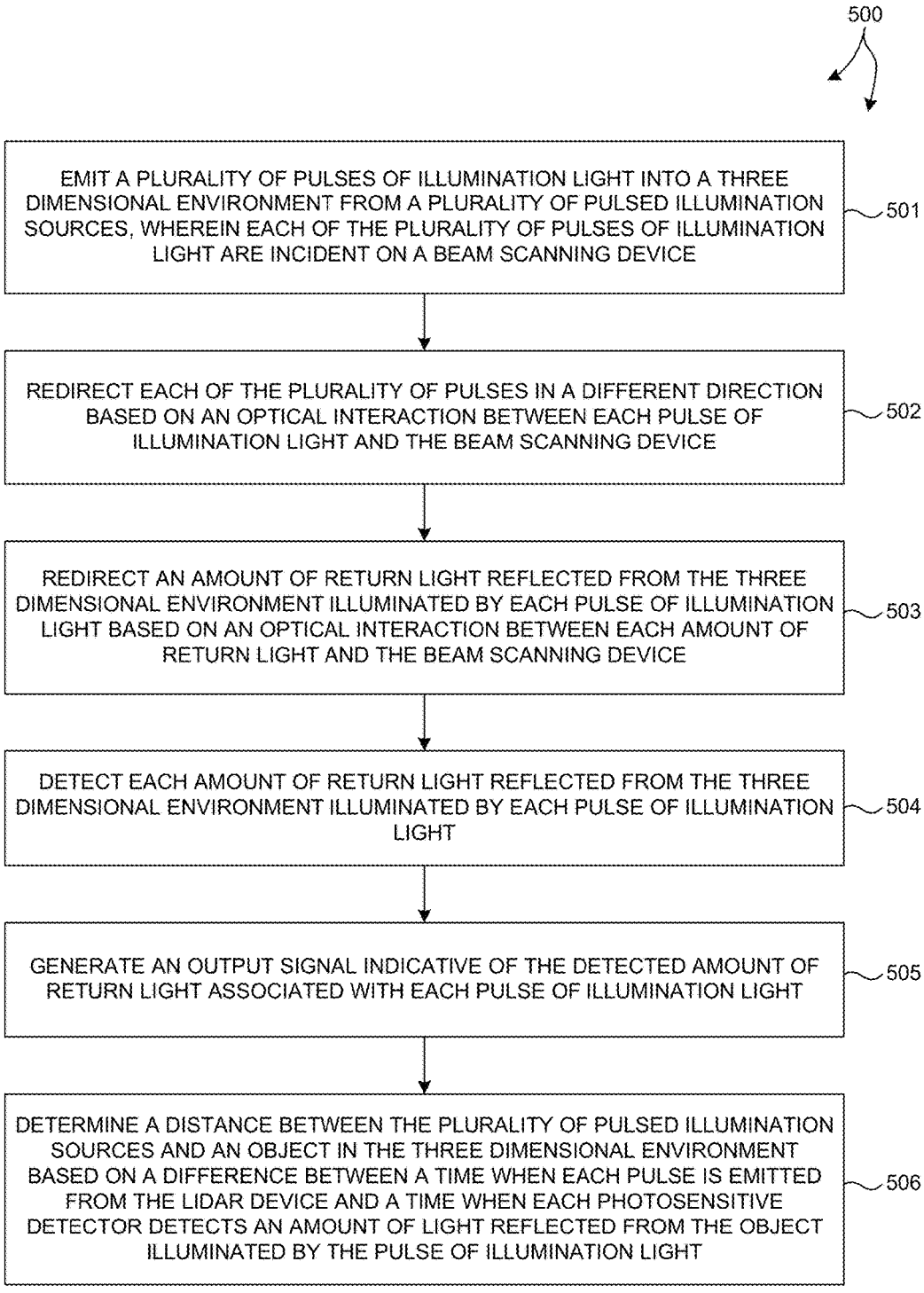

500
EMIT A PLURALITY OF PULSES OF ILLUMINATION LIGHT INTO A THREE DIMENSIONAL ENVIRONMENT FROM A PLURALITY OF PULSED ILLUMINATION SOURCES, WHEREIN EACH OF THE PLURALITY OF PULSES OF ILLUMINATION LIGHT ARE INCIDENT ON A BEAM SCANNING DEVICE
501
REDIRECT EACH OF THE PLURALITY OF PULSES IN A DIFFERENT DIRECTION BASED ON AN OPTICAL INTERACTION BETWEEN EACH PULSE OF ILLUMINATION LIGHT AND THE BEAM SCANNING DEVICE
502
REDIRECT AN AMOUNT OF RETURN LIGHT REFLECTED FROM THE THREE DIMENSIONAL ENVIRONMENT ILLUMINATED BY EACH PULSE OF ILLUMINATION LIGHT BASED ON AN OPTICAL INTERACTION BETWEEN EACH AMOUNT OF RETURN LIGHT AND THE BEAM SCANNING DEVICE
503
DETECT EACH AMOUNT OF RETURN LIGHT REFLECTED FROM THE THREE DIMENSIONAL ENVIRONMENT ILLUMINATED BY EACH PULSE OF ILLUMINATION LIGHT
504
GENERATE AN OUTPUT SIGNAL INDICATIVE OF THE DETECTED AMOUNT OF RETURN LIGHT ASSOCIATED WITH EACH PULSE OF ILLUMINATION LIGHT
505
DETERMINE A DISTANCE BETWEEN THE PLURALITY OF PULSED ILLUMINATION SOURCES AND AN OBJECT IN THE THREE DIMENSIONAL ENVIRONMENT BASED ON A DIFFERENCE BETWEEN A TIME WHEN EACH PULSE IS EMITTED FROM THE LIDAR DEVICE AND A TIME WHEN EACH PHOTOSENSITIVE DETECTOR DETECTS AN AMOUNT OF LIGHT REFLECTED FROM THE OBJECT ILLUMINATED BY THE PULSE OF ILLUMINATION LIGHT
506

FIG. 11

MULTIPLE PIXEL SCANNING LIDAR

CROSS REFERENCE TO RELATED APPLICATION

The present application for patent claims priority under 35 U.S.C. § 119 from U.S. provisional patent application Ser. No. 62/344,259, entitled "Multiple Pixel Scanning LIDAR," filed Jun. 1, 2016, the subject matter of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

The described embodiments relate to LIDAR based 3-D point cloud measuring systems.

BACKGROUND INFORMATION

LIDAR systems employ pulses of light to measure distance to an object based on the time of flight (TOF) of each pulse of light. A pulse of light emitted from a light source of a LIDAR system interacts with a distal object. A portion of the light reflects from the object and returns to a detector of the LIDAR system. Based on the time elapsed between emission of the pulse of light and detection of the returned pulse of light, a distance is estimated. In some examples, pulses of light are generated by a laser emitter. The light pulses are focused through a lens or lens assembly. The time it takes for a pulse of laser light to return to a detector mounted near the emitter is measured. A distance is derived from the time measurement with high accuracy.

Some LIDAR systems employ a single laser emitter/detector combination combined with a rotating mirror to effectively scan across a plane. Distance measurements performed by such a system are effectively two dimensional (i.e., planar), and the captured distance points are rendered as a 2-D (i.e. single plane) point cloud. In some examples, rotating mirrors are rotated at very fast speeds (e.g., thousands of revolutions per minute).

In many operational scenarios, a 3-D point cloud is required. A number of schemes have been employed to interrogate the surrounding environment in three dimensions. In some examples, a 2-D instrument is actuated up and down and/or back and forth, often on a gimbal. This is commonly known within the art as "winking" or "nodding" the sensor. Thus, a single beam LIDAR unit can be employed to capture an entire 3-D array of distance points, albeit one point at a time. In a related example, a prism is employed to "divide" the laser pulse into multiple layers, each having a slightly different vertical angle. This simulates the nodding effect described above, but without actuation of the sensor itself.

In all the above examples, the light path of a single laser emitter/detector combination is somehow altered to achieve a broader field of view than a single sensor. The number of pixels such devices can generate per unit time is inherently limited due limitations on the pulse repetition rate of a single laser. Any alteration of the beam path, whether it is by mirror, prism, or actuation of the device that achieves a larger coverage area comes at a cost of decreased point cloud density.

As noted above, 3-D point cloud systems exist in several configurations. However, in many applications it is necessary to see over a broad field of view. For example, in an autonomous vehicle application, the vertical field of view should extend down as close as possible to see the ground in front of the vehicle. In addition, the vertical field of view should extend above the horizon, in the event the car enters a dip in the road. In addition, it is necessary to have a minimum of delay between the actions happening in the real world and the imaging of those actions. In some examples, it is desirable to provide a complete image update at least five times per second. To address these requirements, a 3-D LIDAR system has been developed that includes an array of multiple laser emitters and detectors. This system is described in U.S. Pat. No. 7,969,558 issued on Jun. 28, 2011, the subject matter of which is incorporated herein by reference in its entirety.

In many applications, a sequence of pulses is emitted. The direction of each pulse is sequentially varied in rapid succession. In these examples, a distance measurement associated with each individual pulse can be considered a pixel, and a collection of pixels emitted and captured in rapid succession (i.e., "point cloud") can be rendered as an image or analyzed for other reasons (e.g., detecting obstacles). In some examples, viewing software is employed to render the resulting point clouds as images that appear three dimensional to a user. Different schemes can be used to depict the distance measurements as 3-D images that appear as if they were captured by a live action camera.

Improvements in the opto-mechanical design of LIDAR systems are desired, while maintaining high levels of imaging resolution and range.

SUMMARY

Methods and systems for performing three dimensional LIDAR measurements with multiple illumination beams scanned over a three dimensional environment are described herein.

In one aspect, illumination light is directed toward a particular location in the surrounding environment by one or more beam shaping optical elements and a beam scanning device. In a further aspect, the return measurement light is directed and focused onto a photodetector by the beam scanning device and the one or more beam shaping optical elements. The beam scanning device is employed in the optical path between the beam shaping optics and the environment under measurement. The beam scanning device effectively expands the field of view and increases the sampling density within the field of view of the 3-D LIDAR system.

In some embodiments, a 3-D LIDAR system includes a an array of light sources aligned in a plane. Each light source is associated with a different LIDAR measurement channel. The 3-D LIDAR system also includes a beam scanning device including a scanning mirror rotated in an oscillatory manner about an axis of rotation by an actuator in accordance with command signals generated by a master controller. Each beam reflects from the surface of the scanning mirror in a different direction. In this manner, the objects in the environment are interrogated by different beams of illumination light at different locations. The scanning mirror causes the illumination beams to sweep over a range of the three dimensional environment under measurement.

In some other embodiments, the array of light sources is two dimensional, and the two-dimensional field of measurement beams is swept over a range of the three dimensional environment under measurement.

In another aspect, the light source and detector of each LIDAR measurement channel are moved in two dimensions relative to beam shaping optics employed to collimate light emitted from the light source. The two dimensional motion is aligned with the optical plane of the beam shaping optic

and effectively expands the field of view and increases the sampling density within the field of view of the 3-D LIDAR system.

The foregoing is a summary and thus contains, by necessity, simplifications, generalizations and omissions of detail; consequently, those skilled in the art will appreciate that the summary is illustrative only and is not limiting in any way. Other aspects, inventive features, and advantages of the devices and/or processes described herein will become apparent in the non-limiting detailed description set forth herein.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified diagram illustrative of one embodiment of a 3-D LIDAR system **100** in at least one novel aspect.

FIG. **2** depicts an illustration of the timing of emission of a pulsed measurement beam and capture of the returning measurement pulse.

FIG. **3** depicts a view of light emission/collection engine **112** of 3-D LIDAR system **100**.

FIG. **4** depicts a view of collection optics **116** of 3-D LIDAR system **100** in greater detail.

FIG. **5** depicts an embodiment **200** of a 3-D LIDAR system employing a beam scanning device.

FIG. **6** depicts an embodiment **300** of a 3-D LIDAR system employing a beam scanning device.

FIG. **7** depicts an embodiment **400** of a 3-D LIDAR system employing a beam scanning device.

FIG. **8** depicts an embodiment **210** of a 3-D LIDAR system employing a two dimensional array of light sources **211**.

FIG. **9** depicts an integrated LIDAR measurement device **120** in one embodiment.

FIG. **10** depicts a schematic view of an integrated LIDAR measurement device **130**.

FIG. **11** depicts a flowchart illustrative of a method **500** of performing multiple LIDAR measurements based on scanning measurement beams in at least one novel aspect.

DETAILED DESCRIPTION

Reference will now be made in detail to background examples and some embodiments of the invention, examples of which are illustrated in the accompanying drawings.

FIG. **1** depicts an LIDAR measurement system **100** in one embodiment. LIDAR measurement system **100** includes a master controller **190** and one or more integrated LIDAR measurement devices **130**. An integrated LIDAR measurement device **130** includes a return signal receiver integrated circuit (IC), an illumination driver integrated circuit (IC) **152**, an illumination source **160**, a photodetector **170**, and a trans-impedance amplifier (TIA) **180**. Each of these elements is mounted to a common substrate **135** (e.g., printed circuit board) that provides mechanical support and electrical connectivity among the elements.

Illumination source **160** emits a measurement pulse of illumination light **162** in response to a pulse of electrical current **153**. In some embodiments, the illumination source **160** is laser based (e.g., laser diode). In some embodiments, the illumination source is based on one or more light emitting diodes. In general, any suitable pulsed illumination source may be contemplated. Illumination light **162** exits LIDAR measurement device **100** and reflects from an object in the surrounding three dimensional environment under measurement. A portion of the reflected light is collected as return measurement light **171** associated with the measurement pulse **162**. As depicted in FIG. **1**, illumination light **162** emitted from integrated LIDAR measurement device **130** and corresponding return measurement light **171** directed toward integrated LIDAR measurement device share a common optical path.

In one aspect, the illumination light **162** is focused and projected toward a particular location in the surrounding environment by one or more beam shaping optical elements **163** and a beam scanning device **164** of LIDAR measurement system **100**. In a further aspect, the return measurement light **171** is directed and focused onto photodetector **170** by beam scanning device **164** and the one or more beam shaping optical elements **163** of LIDAR measurement system **100**. The beam scanning device is employed in the optical path between the beam shaping optics and the environment under measurement. The beam scanning device effectively expands the field of view and increases the sampling density within the field of view of the 3-D LIDAR system.

In the embodiment depicted in FIG. **1**, beam scanning device **164** is a moveable mirror element that is rotated about an axis of rotation **167** by rotary actuator **165**. Command signals **166** generated by master controller **190** are communicated from master controller **190** to rotary actuator **165**. In response, rotary actuator **165** scans moveable mirror element **164** in accordance with a desired motion profile.

Integrated LIDAR measurement device **130** includes a photodetector **170** having an active sensor area **174**. As depicted in FIG. **1**, illumination source **160** is located outside the field of view of the active area **174** of the photodetector. As depicted in FIG. **1**, an overmold lens **172** is mounted over the photodetector **170**. The overmold lens **172** includes a conical cavity that corresponds with the ray acceptance cone of return light **171**. Illumination light **162** from illumination source **160** is injected into the detector reception cone by a fiber waveguide. An optical coupler optically couples illumination source **160** with the fiber waveguide. At the end of the fiber waveguide, a mirror element **161** is oriented at a 45 degree angle with respect to the waveguide to inject the illumination light **162** into the cone of return light **171**. In one embodiment, the end faces of fiber waveguide are cut at a 45 degree angle and the end faces are coated with a highly reflective dielectric coating to provide a mirror surface. In some embodiments, the waveguide includes a rectangular shaped glass core and a polymer cladding of lower index of refraction. In some embodiments, the entire optical assembly is encapsulated with a material having an index of refraction that closely matches the index of refraction of the polymer cladding. In this manner, the waveguide injects the illumination light **162** into the acceptance cone of return light **171** with minimal occlusion.

The placement of the waveguide within the acceptance cone of the return light **171** projected onto the active sensing area **174** of detector **170** is selected to ensure that the illumination spot and the detector field of view have maximum overlap in the far field.

As depicted in FIG. **1**, return light **171** reflected from the surrounding environment is detected by photodetector **170**. In some embodiments, photodetector **170** is an avalanche photodiode. Photodetector **170** generates an output signal **173** that is amplified by an analog trans-impedance amplifier (TIA) **180**. However, in general, the amplification of output signal **173** may include multiple, amplifier stages. In this sense, an analog trans-impedance amplifier is provided by way of non-limiting example, as many other analog signal

amplification schemes may be contemplated within the scope of this patent document. Although TIA **180** is depicted in FIG. **1** as a discrete device separate from the receiver IC **150**, in general, TIA **180** may be integrated with receiver IC **150**. In some embodiments, it is preferable to integrate TIA **180** with receiver IC **150** to save space and reduce signal contamination.

The amplified signal **181** is communicated to return signal receiver IC **150**. Receiver IC **150** includes timing circuitry and a time-to-digital converter that estimates the time of flight of the measurement pulse from illumination source **160**, to a reflective object in the three dimensional environment, and back to the photodetector **170**. A signal **155** indicative of the estimated time of flight is communicated to master controller **190** for further processing and communication to a user of the LIDAR measurement system **100**. In addition, return signal receiver IC **150** is configured to digitize segments of the return signal **181** that include peak values (i.e., return pulses), and communicate signals **156** indicative of the digitized segments to master controller **190**. In some embodiments, master controller **190** processes these signal segments to identify properties of the detected object. In some embodiments, master controller **190** communicates signals **156** to a user of the LIDAR measurement system **100** for further processing.

Master controller **190** is configured to generate a pulse command signal **191** that is communicated to receiver IC **150** of integrated LIDAR measurement device **130**. Pulse command signal **191** is a digital signal generated by master controller **190**. Thus, the timing of pulse command signal **191** is determined by a clock associated with master controller **190**. In some embodiments, the pulse command signal **191** is directly used to trigger pulse generation by illumination driver IC **152** and data acquisition by receiver IC **150**. However, illumination driver IC **152** and receiver IC **150** do not share the same clock as master controller **190**. For this reason, precise estimation of time of flight becomes much more computationally tedious when the pulse command signal **191** is directly used to trigger pulse generation and data acquisition.

In general, a LIDAR measurement system includes a number of different integrated LIDAR measurement devices **130** each emitting a pulsed beam of illumination light from the LIDAR device into the surrounding environment and measuring return light reflected from objects in the surrounding environment.

In these embodiments, master controller **190** communicates a pulse command signal **191** to each different integrated LIDAR measurement device. In this manner, master controller **190** coordinates the timing of LIDAR measurements performed by any number of integrated LIDAR measurement devices. In a further aspect, beam shaping optical elements **163** and beam scanning device **164** are in the optical path of the illumination pulses and return measurement pulses associated with each of the integrated LIDAR measurement devices. In this manner, beam scanning device **164** directs each illumination pulse and return measurement pulse of LIDAR measurement system **100**.

In the depicted embodiment, receiver IC **150** receives pulse command signal **191** and generates a pulse trigger signal, V_{TRG} **151**, in response to the pulse command signal **191**. Pulse trigger signal **151** is communicated to illumination driver IC **152** and directly triggers illumination driver IC **152** to electrically couple illumination source **160** to power supply **133** and generate a pulse of illumination light **162**. In addition, pulse trigger signal **151** directly triggers data acquisition of return signal **181** and associated time of flight calculation. In this manner, pulse trigger signal **151** generated based on the internal clock of receiver IC **150** is employed to trigger both pulse generation and return pulse data acquisition. This ensures precise synchronization of pulse generation and return pulse acquisition which enables precise time of flight calculations by time-to-digital conversion.

FIG. **2** depicts an illustration of the timing associated with the emission of a measurement pulse from an integrated LIDAR measurement device **130** and capture of the returning measurement pulse. As depicted in FIG. **2**, a measurement is initiated by the rising edge of pulse trigger signal **162** generated by receiver IC **150**. As depicted in FIGS. **1** and **2**, an amplified, return signal **181** is received by receiver IC **150**. As described hereinbefore, a measurement window (i.e., a period of time over which collected return signal data is associated with a particular measurement pulse) is initiated by enabling data acquisition at the rising edge of pulse trigger signal **162**. Receiver IC **150** controls the duration of the measurement window, $T_{measurement}$, to correspond with the window of time when a return signal is expected in response to the emission of a measurement pulse sequence. In some examples, the measurement window is enabled at the rising edge of pulse trigger signal **162** and is disabled at a time corresponding to the time of flight of light over a distance that is approximately twice the range of the LIDAR system. In this manner, the measurement window is open to collect return light from objects adjacent to the LIDAR system (i.e., negligible time of flight) to objects that are located at the maximum range of the LIDAR system. In this manner, all other light that cannot possibly contribute to useful return signal is rejected.

As depicted in FIG. **2**, return signal **181** includes three return measurement pulses that correspond with the emitted measurement pulse. In general, signal detection is performed on all detected measurement pulses. Further signal analysis may be performed to identify the closest valid signal **181**B (i.e., first valid instance of the return measurement pulse), the strongest signal, and the furthest valid signal **181**C (i.e., last valid instance of the return measurement pulse in the measurement window). Any of these instances may be reported as potentially valid distance measurements by the LIDAR system.

Internal system delays associated with emission of light from the LIDAR system (e.g., signal communication delays and latency associated with the switching elements, energy storage elements, and pulsed light emitting device) and delays associated with collecting light and generating signals indicative of the collected light (e.g., amplifier latency, analog-digital conversion delay, etc.) contribute to errors in the estimation of the time of flight of a measurement pulse of light. Thus, measurement of time of flight based on the elapsed time between the rising edge of the pulse trigger signal **162** and each valid return pulse (i.e., **181**B and **181**C) introduces undesireable measurement error. In some embodiments, a calibrated, pre-determined delay time is employed to compensate for the electronic delays to arrive at a corrected estimate of the actual optical time of flight. However, the accuracy of a static correction to dynamically changing electronic delays is limited. Although, frequent re-calibrations may be employed, this comes at a cost of computational complexity and may interfere with system up-time.

In another aspect, receiver IC **150** measures time of flight based on the time elapsed between the detection of a detected pulse **181**A due to internal cross-talk between the illumination source **160** and photodetector **170** and a valid

return pulse (e.g., **181**B and **181**C). In this manner, systematic delays are eliminated from the estimation of time of flight. Pulse **181**A is generated by internal cross-talk with effectively no distance of light propagation. Thus, the delay in time from the rising edge of the pulse trigger signal and the instance of detection of pulse **181**A captures all of the systematic delays associated with illumination and signal detection. By measuring the time of flight of valid return pulses (e.g., return pulses **181**B and **181**C) with reference to detected pulse **181**A, all of the systematic delays associated with illumination and signal detection due to internal cross-talk are eliminated. As depicted in FIG. **2**, receiver IC **150** estimates the time of flight, TOF_1, associated with return pulse **181**B and the time of flight, TOF_2, associated with return pulse **181**C with reference to return pulse **181**A.

In some embodiments, the signal analysis is performed by receiver IC **150**, entirely. In these embodiments, signals **155** communicated from integrated LIDAR measurement device **130** include an indication of the time of flight determined by receiver IC **150**. In some embodiments, signals **156** include digitized segments of return signal **181** generated by receiver IC **150**. These raw measurement signal segments are processed further by one or more processors located on board the 3-D LIDAR system, or external to the 3-D LIDAR system to arrive at another estimate of distance, an estimate of one of more physical properties of the detected object, or a combination thereof.

FIG. **3** depicts a light emission/collection engine **112** in one embodiment. Light emission/collection engine **112** includes an array of integrated LIDAR measurement devices **113**. Each integrated LIDAR measurement device includes a light emitting element, a light detecting element, and associated control and signal conditioning electronics integrated onto a common substrate (e.g., electrical board).

Light emitted from each integrated LIDAR measurement device passes through beam shaping optical elements **116** that collimate the emitted light to generate a beam of illumination light projected from the 3-D LIDAR system into the environment. In this manner, an array of beams of light **105**, each emitted from a different LIDAR measurement device are emitted from 3-D LIDAR system **100** as depicted in FIG. **3**. In general, any number of LIDAR measurement devices can be arranged to simultaneously emit any number of light beams from 3-D LIDAR system **100**. Light reflected from an object in the environment due to its illumination by a particular LIDAR measurement device is collected by beam shaping optical elements **116**. The collected light passes through beam shaping optical elements **116** where it is focused onto the detecting element of the same, particular LIDAR measurement device. In this manner, collected light associated with the illumination of different portions of the environment by illumination generated by different LIDAR measurement devices is separately focused onto the detector of each corresponding LIDAR measurement device.

FIG. **4** depicts a view of beam shaping optical elements **116** in greater detail. As depicted in FIG. **4**, beam shaping optical elements **116** include four lens elements **116**A-D arranged to focus collected light **118** onto each detector of the array of integrated LIDAR measurement devices **113**. In the embodiment depicted in FIG. **4**, light passing through optics **116** is reflected from mirror **124** and is directed onto each detector of the array of integrated LIDAR measurement devices. In some embodiments, one or more of the beam shaping optical elements **116** is constructed from one or more materials that absorb light outside of a predetermined wavelength range. The predetermined wavelength range includes the wavelengths of light emitted by the array of integrated LIDAR measurement devices **113**. In one example, one or more of the lens elements are constructed from a plastic material that includes a colorant additive to absorb light having wavelengths less than infrared light generated by each of the array of integrated LIDAR measurement devices **113**. In one example, the colorant is Epolight 7276A available from Aako BV (The Netherlands). In general, any number of different colorants can be added to any of the plastic lens elements of optics **116** to filter out undesired spectra.

FIG. **5** depicts an embodiment **200** of a 3-D LIDAR system employing a beam scanning device. Embodiment **200** includes a one-dimensional array of light sources **201**A-C (i.e., an array of light sources aligned in a single plane such as the xy plane depicted in FIG. **5**). Each light source is associated with a different LIDAR measurement channel. Light emitted from each light source **201**A-C is divergent. These divergent beams pass through beam shaping optics **202** (e.g., collimating optics) where the emitted light is approximately collimated. The term "approximately" collimated is employed to note that in practice, perfect collimation of light beams is rarely achieved. Thus, typically, the resulting beams remain slightly divergent or convergent after passing through beam shaping optics **202**. After passing through beam shaping optics **202**, each beam reflects from the surface of scanning mirror **203**. Scanning mirror **203** is rotated in an oscillatory manner about axis **205** by actuator **206** in accordance with command signals **207** received from a controller (e.g., master controller **190**). As depicted in FIG. **5**, the reflected beams **204**A-C are associated with light sources **201**A-C, respectively. Scanning mirror **203** is oriented such that reflected beams **204**A-C do not intersect with collimating optics **202**, light sources **201**A-C, or any other elements of the illumination and detection systems of the 3-D LIDAR system. Furthermore, reflected beams **204**A-C maintain their separate trajectories in the x-direction. In this manner, the objects in the environment are interrogated by different beams of illumination light at different locations in the x-direction. In some embodiments, the reflected beams fan out over a range of angles that is less than 40 degrees measured in the x-y plane.

Scanning mirror **203** causes beams **204**A-C to sweep in the z-direction (in and out of the drawing depicted in FIG. **5**). In some embodiments, the reflected beams scan over a range of angles that is less than 120 degrees measured in the y-z plane.

FIG. **6** depicts another embodiment **300** of a 3-D LIDAR system employing a beam scanning device. Embodiment **300** includes a one-dimensional array of light sources **301**A-C, each associated with a different LIDAR measurement channel. Light sources **301**A-C are located in a one dimensional array (i.e., located on a plane parallel to the z-direction; in and out of the drawing depicted in FIG. **6**). Light emitted from each light source **301**A-C is divergent. These divergent beams pass through beam shaping optics **302** where they are approximately collimated. After passing through beam shaping optics **302**, each beam reflects from the surface of scanning mirror **303**. The reflected beams **304**A-C fan out in the y-z plane (i.e., in and out of the drawing depicted in FIG. **6**). Scanning mirror **303** rotates in an oscillatory manner (e.g., within a range of angles between $+\alpha$ and $-\alpha$) about an axis **305** aligned with the surface of scanning mirror **303** and oriented in the z-direction as depicted in FIG. **6**. Scanning mirror **203** is rotated in an oscillatory manner about axis **305** by actuator **306** in accordance with command signals **307** received from a controller

(e.g., master controller **190**). As depicted in FIG. **6**, the reflected beams **304**A-C are associated with light source **301**A-C. Scanning mirror **303** is oriented such that reflected beams **304**A-C do not intersect with collimating optics **302**, light sources **301**A-C, or any other elements of the illumination and detection systems of the 3-D LIDAR system. Furthermore, reflected beams **304**A-C maintain their separate trajectories in the z-direction. In this manner, the objects in the environment are interrogated by different beams of illumination light at different locations in the z-direction. In some embodiments, the reflected beams fan out over a range of angles that is less than 40 degrees measured in the y-z plane.

Scanning mirror **303** causes beams **304**A-C to sweep in the x-direction. In some embodiments, the reflected beams scan over a range of angles that is less than 120 degrees measured in the x-y plane.

In the embodiment depicted in FIG. **5**, each light source of the array of light sources **201**A-C is located in a plane. Similarly, in the embodiment depicted in FIG. **6**, each light source of the array of light sources **301**A-C is located in a plane. This is often referred to as a one-dimensional array of light sources. In the embodiment depicted in FIG. **5**, axis **205** of scanning mirror **203** lies in the plane (e.g., the x-y plane) including light sources **201**A-C. Similarly, in the embodiment depicted in FIG. **6**, axis **305** of scanning mirror **303** lies in the plane including light sources **301**A-C. However, in general, the array of light sources may be two dimensional.

FIG. **7** depicts another embodiment **400** of a 3-D LIDAR system. Embodiment **400** includes a two-dimensional array of light sources **401**A-D, each associated with a different LIDAR measurement channel. Light sources **401**A-B are located in a plane (i.e., located on a plane parallel to the z-direction and light sources **401**C-D are located in another plane parallel to the z-direction. In addition, light sources **401**A and **401**C are located in a plane parallel to the xy plane and light sources **401**B and **401**D are located in another plane parallel to the xy plane. Light emitted from each light source **401**A-D is divergent. These divergent beams pass through beam shaping optics **402** where they are approximately collimated. After passing through beam shaping optics **402**, each beam reflects from the surface of scanning mirror **403**. The reflected beams **404**A-B and reflected beams **404**C-D fan out in the y-z plane (i.e., in and out of the drawing depicted in FIG. **7**). Scanning mirror **403** rotates in an oscillatory manner (e.g., within a range of angles between $+\alpha$ and $-\alpha$) about an axis **405** aligned with the surface of scanning mirror **403** and oriented in the z-direction as depicted in FIG. **7**. Scanning mirror **403** is rotated in an oscillatory manner about axis **405** by actuator **406** in accordance with command signals **407** received from a controller (e.g., master controller **190**). As depicted in FIG. **7**, the reflected beams **404**A-D are associated with light source **401**A-D. Scanning mirror **403** is oriented such that reflected beams **404**A-D do not intersect with collimating optics **402**, light sources **401**A-C, or any other elements of the illumination and detection systems of the 3-D LIDAR system. Furthermore, reflected beams **404**A-D maintain their separate trajectories in the z-direction and the x-direction. In this manner, the objects in the environment are interrogated by different beams of illumination light at different locations in the z-direction. In some embodiments, the reflected beams fan out over a range of angles that is less than 40 degrees measured in the y-z plane.

Scanning mirror **403** causes beams **404**A-D to sweep in the x-direction. In some embodiments, the reflected beams scan over a range of angles that is less than 120 degrees measured in the x-y plane. In a further aspect, the range of scanning angles is configured such that a portion of the environment interrogated by reflected beams **404**A and **404**B is also interrogated by reflected beams **404**C and **404**D, respectively. This is depicted by the angular "overlap" range depicted in FIG. **7**. In this manner, the spatial sampling resolution in this portion of the environment is effectively increased because this portion of the environment is being sampled by two different beams at different times.

In another further aspect, the scanning angle approximately tracks a sinusoidal function. As such, the dwell time near the middle of the scan is significantly less than the dwell time near the end of the scan. In this manner, the spatial sampling resolution of the 3D LIDAR system is higher at the ends of the scan.

In the embodiment **400** depicted in FIG. **7**, four light sources are arranged in a 2×2 array. However, in general, any number of light sources may be arranged in any suitable manner. In one example, the 2×2 array is tilted with respect to the scanning mirror such that the measurement beams are interlaced in the overlap region.

In another aspect, the light source and detector of each LIDAR measurement channel is moved in two dimensions relative to the beam shaping optics employed to collimate light emitted from the light source. The two dimensional motion is aligned with the optical plane of the beam shaping optic and effectively expands the field of view and increases the sampling density within the field of view of the 3-D LIDAR system.

FIG. **8** depicts an embodiment **210** of a 3-D LIDAR system employing a two dimensional array of light sources **211**, including light sources **212**A-C. Light sources **212**A-C are each associated with a different LIDAR measurement channel. Light emitted from each light source **212**A-C is divergent. These divergent beams pass through beam shaping optics **213** where they are approximately collimated. Collimated beams **214**A-C, are each associated with light sources **212**A-C, respectively. The collimated beams **214**A-C pass on the 3-D environment to be measured. The term "approximately" collimated is employed to note that in practice, perfect collimation of light beams is rarely achieved. Thus, typically, the resulting beams remain slightly divergent or convergent after passing through beam shaping optics **213**.

In the depicted embodiment, the two dimensional array of light sources **211** is moved in one direction (e.g., the X_s direction) by actuator **216**, and the beam shaping optics **213** are moved in an orthogonal direction (e.g., the Y_c direction) by actuator **215**. The relative motion in orthogonal directions between the two dimensional array of light sources **211** and the beam shaping optics **213** effectively scans the collimated beams **214**A-C over the 3-D environment to be measured. This effectively expands the field of view and increases the sampling density within the field of view of the 3-D LIDAR system. The two dimensional array of light sources **211** is translated in an oscillatory manner parallel to the X_s by actuator **216** and the beam shaping optic **213** is translated in an oscillatory manner parallel to the Y_c axis in accordance with command signals **217** received from a controller (e.g., master controller **190**).

In the embodiment depicted in FIG. **8**, the X_c-Y_c plane is parallel to the X_s-Y_s plane. As depicted in FIG. **8**, the source and detector of each LIDAR measurement channel is moved in two dimensions relative to the beam shaping optics employed to collimate light emitted from the light source. The motion of both the two dimensional array of light

sources **211** and the beam shaping optics **213** is aligned with the optical plane of the collimating optic (i.e., X_c-Y_c plane). In general, the same effect may be achieved by moving the array of light sources **211** in both the X_s and Y_s directions, while keeping collimating optics **213** stationary. Similarly, the same effect may be achieved by moving the beam shaping optics **213** in both the X_c and Y_c directions, while keeping the array of light sources **211** stationary.

In general, the rotations of scanning mirrors **203**, **303**, **403**, and the displacements of the array of light sources **211**, beam shaping optics **213**, may be realized by any suitable drive system. In one example, flexture mechanisms harmonically driven by electrostatic actuators may be employed to exploit resonant behavior. In another example, an eccentric, rotary mechanism may be employed to transform a rotary motion generated by an rotational actuator into a two-dimensional planar motion. In general, the motion may be generated by any suitable actuator system (e.g., an electromagnetic actuator, a piezo actuator, etc.). In general, the motion may be sinusoidal, pseudorandom, or track any other suitable function.

FIG. **9** depicts an integrated LIDAR measurement device **120** in another embodiment. Integrated LIDAR measurement device **120** includes a pulsed light emitting device **122**, a light detecting element **123**, associated control and signal conditioning electronics integrated onto a common substrate **121** (e.g., electrical board), and connector **126**. Pulsed emitting device **122** generates pulses of illumination light **124** and detector **123** detects collected light **125**. Integrated LIDAR measurement device **120** generates digital signals indicative of the distance between the 3-D LIDAR system and an object in the surrounding environment based on a time of flight of light emitted from the integrated LIDAR measurement device **120** and detected by the integrated LIDAR measurement device **120**. Integrated LIDAR measurement device **120** is electrically coupled to the 3-D LIDAR system via connector **126**. Integrated LIDAR measurement device **120** receives control signals from the 3-D LIDAR system and communicates measurement results to the 3-D LIDAR system over connector **126**.

FIG. **10** depicts a schematic view of an integrated LIDAR measurement device **130** in another embodiment. Integrated LIDAR measurement device **130** includes a pulsed light emitting device **134**, a light detecting element **138**, a beam splitter **135** (e.g., polarizing beam splitter, regular beam splitter, etc.), an illumination driver **133**, signal conditioning electronics **139**, analog to digital (A/D) conversion electronics **140**, controller **132**, and digital input/output (I/O) electronics **131** integrated onto a common substrate **144**.

As depicted in FIG. **10**, a measurement begins with a pulse firing signal **146** generated by controller **132**. In some examples, a pulse index signal is determined by controller **132** that is shifted from the pulse firing signal **146** by a time delay, T_D. The time delay includes the known delays associated with emitting light from the LIDAR system (e.g., signal communication delays and latency associated with the switching elements, energy storage elements, and pulsed light emitting device) and known delays associated with collecting light and generating signals indicative of the collected light (e.g., amplifier latency, analog-digital conversion delay, etc.).

Illumination driver **133** generates a pulse electrical current signal **145** in response to pulse firing signal **146**. Pulsed light emitting device **134** generates pulsed light emission **136** in response to pulsed electrical current signal **145**. The illumination light **136** is focused and projected onto a particular location in the surrounding environment by one or more optical elements of the LIDAR system (not shown).

In some embodiments, the pulsed light emitting device is laser based (e.g., laser diode). In some embodiments, the pulsed illumination sources are based on one or more light emitting diodes. In general, any suitable pulsed illumination source may be contemplated.

As depicted in FIG. **10**, return light **137** reflected from the surrounding environment is detected by light detector **138**. In some embodiments, light detector **138** is an avalanche photodiode. Light detector **138** generates an output signal **147** that is amplified by signal conditioning electronics **139**. In some embodiments, signal conditioning electronics **139** includes an analog trans-impedance amplifier. However, in general, the amplification of output signal **147** may include multiple, amplifier stages. In this sense, an analog trans-impedance amplifier is provided by way of non-limiting example, as many other analog signal amplification schemes may be contemplated within the scope of this patent document.

The amplified signal is communicated to A/D converter **140**. The digital signals are communicated to controller **132**. Controller **132** generates an enable/disable signal employed to control the timing of data acquisition by ADC **140** in concert with pulse firing signal **146**.

As depicted in FIG. **10**, the illumination light **136** emitted from integrated LIDAR measurement device **130** and the return light **137** directed toward integrated LIDAR measurement device share a common path. In the embodiment depicted in FIG. **10**, the return light **137** is separated from the illumination light **136** by a polarizing beam splitter (PBS) **135**. PBS **135** could also be a non-polarizing beam splitter, but this generally would result in an additional loss of light. In this embodiment, the light emitted from pulsed light emitting device **134** is polarized such that the illumination light passes through PBS **135**. However, return light **137** generally includes a mix of polarizations. Thus, PBS **135** directs a portion of the return light toward detector **138** and a portion of the return light toward pulsed light emitting device **134**. In some embodiments, it is desirable to include a quarter waveplate after PBS **135**. This is advantageous in situations when the polarization of the return light is not significantly changed by its interaction with the environment. Without the quarter waveplate, the majority of the return light would pass through PBS **135** and be directed toward the pulsed light emitting device **134**, which is undesireable. However, with the quarter waveplate, the majority of the return light will pass through PBS **135** and be directed toward detector **138**.

In general, a multiple pixel 3-D LIDAR system includes a plurality of LIDAR measurement channels. In some embodiments, a multiple pixel 3-D LIDAR system includes a plurality of integrated LIDAR measurement devices each emitting a pulsed beam of illumination light from the LIDAR device into the surrounding environment and measuring return light reflected from objects in the surrounding environment.

In some embodiments, digital I/O **131**, timing logic **132**, A/D conversion electronics **140**, and signal conditioning electronics **139** are integrated onto a single, silicon-based microelectronic chip. In another embodiment these same elements are integrated into a single gallium-nitride or silicon based circuit that also includes the illumination driver. In some embodiments, the A/D conversion electronics and controller **132** are combined as a time-to-digital converter.

In some embodiments, the time of flight signal analysis is performed by controller **132**, entirely. In these embodiments, signals **143** communicated from integrated LIDAR measurement device **130** include an indication of the distances determined by controller **132**. In some embodiments, signals **143** include the digital signals **148** generated by A/D converter **140**. These raw measurement signals are processed further by one or more processors located on board the 3-D LIDAR system, or external to the 3-D LIDAR system to arrive at a measurement of distance. In some embodiments, controller **132** performs preliminary signal processing steps on signals **148** and signals **143** include processed data that is further processed by one or more processors located on board the 3-D LIDAR system, or external to the 3-D LIDAR system to arrive at a measurement of distance.

In some embodiments a 3-D LIDAR system includes multiple integrated LIDAR measurement devices. In some embodiments, a delay time is set between the firing of each integrated LIDAR measurement device. Signal **142** includes an indication of the delay time associated with the firing of integrated LIDAR measurement device **130**. In some examples, the delay time is greater than the time of flight of the measurement pulse sequence to and from an object located at the maximum range of the LIDAR device. In this manner, there is no cross-talk among any of the integrated LIDAR measurement devices. In some other examples, a measurement pulse is emitted from one integrated LIDAR measurement device before a measurement pulse emitted from another integrated LIDAR measurement device has had time to return to the LIDAR device. In these embodiments, care is taken to ensure that there is sufficient spatial separation between the areas of the surrounding environment interrogated by each beam to avoid cross-talk.

FIG. **11** illustrates a flowchart of a method **500** suitable for implementation by a LIDAR system as described herein. In some embodiments, LIDAR system **100** is operable in accordance with method **500** illustrated in FIG. **11**. However, in general, the execution of method **500** is not limited to the embodiments of LIDAR system **100** described with reference to FIG. **1**. These illustrations and corresponding explanation are provided by way of example as many other embodiments and operational examples may be contemplated.

In block **501**, a plurality of pulses of illumination light are emitted into a three dimensional environment from a plurality of pulsed illumination sources. Each of the plurality of pulses of illumination light are incident on a beam scanning device.

In block **502**, each of the plurality of pulses is redirected in a different direction based on an optical interaction between each pulse of illumination light and the beam scanning device.

In block **503**, an amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light is redirected based on an optical interaction between each amount of return light and the beam scanning device.

In block **504**, each amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light is detected (e.g., by a photosensitive detector).

In block **505**, an output signal indicative of the detected amount of return light associated with each pulse of illumination light is generated.

In block **506**, a distance between the plurality of pulsed illumination sources and an object in the three dimensional environment is determined based on a difference between a time when each pulse is emitted from the LIDAR device and a time when each photosensitive detector detects an amount of light reflected from the object illuminated by the pulse of illumination light.

Master controller **190** or any external computing system may include, but is not limited to, a personal computer system, mainframe computer system, workstation, image computer, parallel processor, or any other device known in the art. In general, the term "computing system" may be broadly defined to encompass any device having one or more processors, which execute instructions from a memory medium.

Program instructions **192** implementing methods such as those described herein may be transmitted over a transmission medium such as a wire, cable, or wireless transmission link. For example, as illustrated in FIG. **1**, program instructions **192** stored in memory **191** are transmitted to processor **195** over bus **194**. Program instructions **192** are stored in a computer readable medium (e.g., memory **191**). Exemplary computer-readable media include read-only memory, a random access memory, a magnetic or optical disk, or a magnetic tape.

In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a general purpose or special purpose computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code means in the form of instructions or data structures and that can be accessed by a general-purpose or special-purpose computer, or a general-purpose or special-purpose processor. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

Although certain specific embodiments are described above for instructional purposes, the teachings of this patent document have general applicability and are not limited to the specific embodiments described above. Accordingly, various modifications, adaptations, and combinations of various features of the described embodiments can be practiced without departing from the scope of the invention as set forth in the claims.

What is claimed is:

1. A light detection and ranging (LIDAR) device, comprising:

a plurality of pulsed illumination sources each emitting a pulse of illumination light from the LIDAR device in different directions into a three dimensional environment;

a plurality of photosensitive detectors each detecting an amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light and generating an output signal indicative of the detected amount of return light associated with each pulse of illumination light;

a beam scanning device disposed in an optical path between the plurality of pulsed illumination sources and the three dimensional environment under measurement and between the plurality of photosensitive detectors and the three dimensional environment under measurement, the beam scanning device configured to redirect each pulse of illumination light with respect to each of the plurality of pulse illumination sources and each of the plurality of photosensitive detectors in response to a command signal; and

a computing system configured to:

receive each output signal indicative of the detected amount of light; and

determine a distance between the LIDAR device and an object in the three dimensional environment based on a difference between a time when each pulse is emitted from the LIDAR device and a time when each photosensitive detector detects an amount of light reflected from the object illuminated by the pulse of illumination light.

2. The LIDAR device of claim 1, further comprising:

one or more beam shaping optical elements disposed in the optical path between the beam scanning device and the plurality of pulsed illumination sources and between the beam scanning device and the plurality of photosensitive elements.

3. The LIDAR device of claim 1, wherein the beam scanning device includes one or more beam shaping optical elements.

4. The LIDAR device of claim 1, wherein a first range of the three dimensional environment measured by a sequence of pulses of illumination light emitted by a first pulsed illumination source of the plurality of pulsed illumination sources light and scanned over the first range by the beam scanning device spatially overlaps a second range of the three dimensional environment measured by a sequence of pulses of illumination light emitted by a second pulsed illumination source of the plurality of pulsed illumination sources light and scanned over the second range by the beam scanning device.

5. The LIDAR device of claim 1, wherein the beam scanning device includes a mirror element rotated by an actuator about an axis of rotation.

6. The LIDAR device of claim 5, wherein the mirror element is rotated about that axis of rotation with an oscillatory angular velocity.

7. The LIDAR device of claim 6, wherein the oscillatory angular velocity tracks a sinusoidal profile.

8. The LIDAR device of claim 5, wherein the plurality of pulsed illumination sources are disposed in a plane parallel to the axis of rotation.

9. The LIDAR device of claim 5, wherein the plurality of pulsed illumination sources are disposed in a plane perpendicular to the axis of rotation.

10. The LIDAR device of claim 3, wherein the one or more beam shaping optical elements are translated in a first direction parallel to an optical plane of the one or more beam shaping optical elements.

11. The LIDAR device of claim 10, wherein the plurality of pulsed illumination sources are translated in a second direction parallel to the optical plane of the one or more beam shaping elements, wherein the first and second directions are different directions.

12. The LIDAR device of claim 1, wherein the command signal is generated by the computing system.

13. A light detection and ranging (LIDAR) device, comprising:

a plurality of pulsed illumination sources each emitting a pulse of illumination light from the LIDAR device in different directions into a three dimensional environment;

a plurality of photosensitive detectors each detecting an amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light and generating an output signal indicative of the detected amount of return light associated with each pulse of illumination light;

a beam scanning device disposed in an optical path between the plurality of pulsed illumination sources and the three dimensional environment under measurement and between the plurality of photosensitive detectors and the three dimensional environment under measurement, the beam scanning device configured to redirect each pulse of illumination light with respect to each of the plurality of pulse illumination sources and each of the plurality of photosensitive detectors in response to a command signal; and

a non-transient computer-readable medium comprising computer-readable instructions that when read by a computing system cause the computing system to:

receive each output signal indicative of the detected amount of light; and

determine a distance between the LIDAR device and an object in the three dimensional environment based on a difference between a time when each pulse is emitted from the LIDAR device and a time when each photosensitive detector detects an amount of light reflected from the object illuminated by the pulse of illumination light.

14. The LIDAR device of claim 13, further comprising:

one or more beam shaping optical elements disposed in the optical path between the beam scanning device and the plurality of pulsed illumination sources and between the beam scanning device and the plurality of photosensitive elements.

15. The LIDAR device of claim 13, wherein the beam scanning device includes one or more beam shaping optical elements.

16. The LIDAR device of claim 13, wherein a first range of the three dimensional environment measured by a sequence of pulses of illumination light emitted by a first pulsed illumination source of the plurality of pulsed illumination sources light and scanned over the first range by the beam scanning device spatially overlaps a second range of the three dimensional environment measured by a sequence of pulses of illumination light emitted by a second pulsed illumination source of the plurality of pulsed illumination sources light and scanned over the second range by the beam scanning device.

17. The LIDAR device of claim 13, wherein the beam scanning device includes a mirror element rotated by an actuator about an axis of rotation.

18. The LIDAR device of claim 15, wherein the one or more beam shaping optical elements are translated in a first direction parallel to an optical plane of the one or more beam shaping optical elements, and wherein the plurality of pulsed illumination sources are translated in a second direction parallel to the optical plane of the one or more beam shaping elements, wherein the first and second directions are different directions.

19. A method comprising:

emitting a plurality of pulses of illumination light into a three dimensional environment from a plurality of pulsed illumination sources, wherein each of the plurality of pulses of illumination light are incident on a beam scanning device;

redirecting each of the plurality of pulses in a different direction with respect to each of the plurality of pulse illumination sources in response to a command signal communicated to the beam scanning device based on an optical interaction between each pulse of illumination light and the beam scanning device;

redirecting an amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light based on an optical interaction between each amount of return light and the beam scanning device;

detecting each amount of return light reflected from the three dimensional environment illuminated by each pulse of illumination light;

generating an output signal indicative of the detected amount of return light associated with each pulse of illumination light; and

determining a distance between the plurality of pulsed illumination sources and an object in the three dimensional environment based on a difference between a time when each pulse is emitted from the LIDAR device and a time when each photosensitive detector detects an amount of light reflected from the object illuminated by the pulse of illumination light.

20. The method of claim 19, wherein the redirecting of each of the plurality of pulses and the redirecting of each amount of return light reflected from the three dimensional environment involves a mirror element rotated by an actuator about an axis of rotation.

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