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(54) Title: USING TWO-DIMENSIONAL CAMERA IMAGES TO SPEED REGISTRATION OF THREE-DIMENSIONAL SCANS

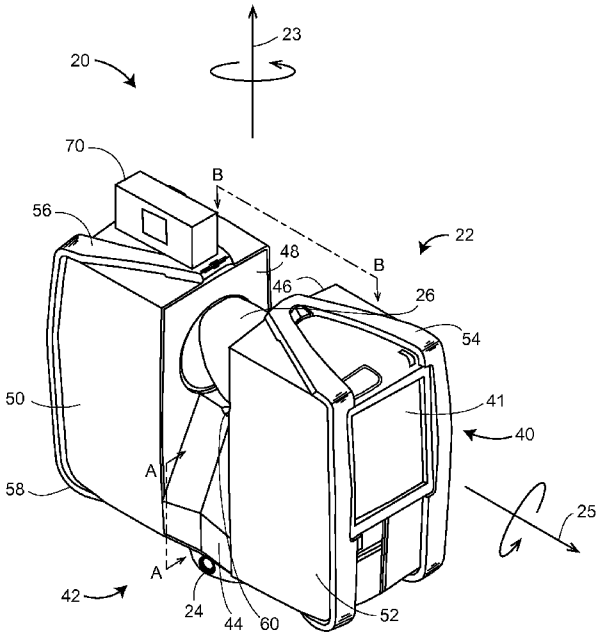


FIG. 1

(57) Abstract: A method for measuring and registering 3D coordinates has a 3D scanner measure a first collection of 3D coordinates of points from a first registration position and a second collection of 3D coordinates of points from a second registration position. In between these positions, the 3D scanner collects 2D camera images. A processor determines first and second translation values and a first rotation value based on the 2D camera images. The processor adjusts the second collection of points relative to the first collection of points based at least in part on the first and second translation values and the first rotation value. The processor identifies a correspondence among registration targets in the first and second collection of 3D coordinates, and uses this correspondence to further adjust the relative position and orientation of the first and second collection of 3D coordinates.

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USING TWO-DIMENSIONAL CAMERA IMAGES TO SPEED REGISTRATION OF THREE-DIMENSIONAL SCANS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of International Patent Application No. PCT/IB2013/003082, filed September 27, 2013, which claims the benefit of German Patent Application No. 10 2012 109 481.0, filed October 5, 2012 and of U.S. Patent Application No. 61/716,845, filed October 22, 2012, the contents of all of which are incorporated by reference herein.

BACKGROUND OF THE INVENTION

[0002] U.S. Patent No. 8,705,016 ('016) describes a laser scanner which, through use of a rotatable mirror, emits a light beam into its environment to generate a three-dimensional (3D) scan. The contents of this patent are incorporated herein by reference.

[0003] The subject matter disclosed herein relates to use of a 3D laser scanner time-of-flight (TOF) coordinate measurement device. A 3D laser scanner of this type steers a beam of light to a non-cooperative target such as a diffusely scattering surface of an object. A distance meter in the device measures a distance to the object, and angular encoders measure the angles of rotation of two axles in the device. The measured distance and two angles enable a processor in the device to determine the 3D coordinates of the target.

[0004] A TOF laser scanner is a scanner in which the distance to a target point is determined based on the speed of light in air between the scanner and a target point. Laser scanners are typically used for scanning closed or open spaces such as interior areas of buildings, industrial installations and tunnels. They may be used, for example, in industrial applications and accident reconstruction applications. A laser scanner optically scans and measures objects in a volume around the scanner through the acquisition of data points representing object surfaces within the volume. Such data points are obtained by transmitting a beam of light onto the objects and collecting the reflected or scattered light to determine the distance, two-angles (i.e., an azimuth and a zenith angle), and optionally a gray-scale value. This raw scan data is collected, stored and sent to a processor or processors to generate a 3D image representing the scanned area or object.

[0005] Generating an image requires at least three values for each data point. These three values may include the distance and two angles, or may be transformed values, such as the x, y, z coordinates. In an embodiment, an image is also based on a fourth gray-scale value, which is a value related to irradiance of scattered light returning to the scanner.

[0006] Most TOF scanners direct the beam of light within the measurement volume by steering the light with a beam steering mechanism. The beam steering mechanism includes a first motor that steers the beam of light about a first axis by a first angle that is measured by a first angular encoder (or other angle transducer). The beam steering mechanism also includes a second motor that steers the beam of light about a second axis by a second angle that is measured by a second angular encoder (or other angle transducer).

[0007] Many contemporary laser scanners include a camera mounted on the laser scanner for gathering camera digital images of the environment and for presenting the camera digital images to an operator of the laser scanner. By viewing the camera images, the operator of the scanner can determine the field of view of the measured volume and adjust settings on the laser scanner to measure over a larger or smaller region of space. In addition, the camera digital images may be transmitted to a processor to add color to the scanner image. To generate a color scanner image, at least three positional coordinates (such as x, y, z) and three color values (such as red, green, blue "RGB") are collected for each data point.

[0008] A 3D image of a scene may require multiple scans from different registration positions. The overlapping scans are registered in a joint coordinate system, for example, as described in U.S. Published Patent Application No. 2012/0069352 ('352), the contents of which are incorporated herein by reference. Such registration is performed by matching targets in overlapping regions of the multiple scans. The targets may be artificial targets such as spheres or checkerboards or they may be natural features such as corners or edges of walls. Some registration procedures involve relatively time-consuming manual procedures such as identifying by a user each target and matching the targets obtained by the scanner in each of the different registration positions. Some registration procedures also require establishing an external "control network" of registration targets measured by an external device such as a total station. The registration method disclosed in '352 eliminates the need for user matching of registration targets and establishing of a control network.

[0009] However, even with the simplifications provided by the methods of '352, it is today still difficult to remove the need for a user to carry out the manual registration steps as described above. In a typical case, only 30% of 3D scans can be automatically registered to scans taken from other registration positions. Today such registration is seldom carried out at the site of the 3D measurement but instead in an office following the scanning procedure. In a typical case, a project requiring a week of scanning requires two to five days to manually register the multiple scans. This adds to the cost of the scanning project. Furthermore, the manual registration process sometimes reveals that the overlap between adjacent scans was insufficient to provide proper registration. In other cases, the manual registration process may reveal that certain sections of the scanning environment have been omitted. When such problems occur, the operator must return to the site to obtain additional scans. In some cases, it is not possible to return to a site. A building that was available for scanning at one time may be impossible to access at a later time. A forensics scene of an automobile accident or a homicide is often not available for taking of scans for more than a short time after the incident.

[0010] Accordingly, while existing 3D scanners are suitable for their intended purposes, what is needed is a 3D scanner having certain features of embodiments of the present invention.

BRIEF DESCRIPTION OF THE INVENTION

[0011] According to one aspect of the invention, a three-dimensional (3D) measuring device is provided including: a processor system including at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access; a 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, 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 first light receiver configured to receive first reflected light, the first reflected light being a portion

of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation; a moveable platform configured to carry the 3D scanner; a camera configured to move in conjunction with the 3D scanner; wherein the processor system is responsive to executable instructions which when executed by the processor system is operable to: cause the 3D scanner, while fixedly located at a first registration position, to cooperate with the processor system to determine 3D coordinates of a first collection of points on an object surface; cause the 3D scanner, while moving from the first registration position to a second registration position, to cooperate with the processor system to obtain a plurality of two-dimensional (2D) camera image sets, each of the plurality of 2D camera image sets being a set of 2D coordinates of points on the object surface, each of the plurality of 2D camera image sets being collected by the 3D scanner at a different position relative to the first registration position; determine a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of 2D camera image sets according to a first mathematical criterion; cause the 3D scanner, while fixedly located at the second registration position, to cooperate with the processor system to determine 3D coordinates of a second collection of points on the object surface; identify a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; and determine 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the determined correspondence among the registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points.

[0012] In a further aspect of the invention, a method for measuring and registering three-dimensional (3D) coordinates is provided including: providing a 3D measuring device

that includes a processor system, a 3D scanner, a camera, and a moveable platform, the processor system having at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access, the 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, 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 first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation, the moveable platform configured to carry the 3D scanner; determining with processor system, in cooperation with the 3D scanner, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position; obtaining by the 3D scanner in cooperation with the processor system a plurality of two-dimensional (2D) camera image sets, each of the plurality of 2D camera image sets being collected as the 2D camera moves from the first registration position to a second registration position, each of the plurality of 2D camera image sets being collected by the 3D scanner at a different position relative to the first registration position; determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of 2D camera image sets according to a first mathematical criterion; determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position; identifying by the processor system a correspondence among registration targets

present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points; and storing the 3D coordinates of the registered 3D collection of points.

[0013] These and other advantages and features will become more apparent from the following description taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWING

[0014] The subject matter, which is regarded as the invention, is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0015] FIG. 1 is a perspective view of a laser scanner in accordance with an embodiment of the invention;

[0016] FIG. 2 is a side view of the laser scanner illustrating a method of measurement according to an embodiment;

[0017] FIG. 3 is a schematic illustration of the optical, mechanical, and electrical components of the laser scanner according to an embodiment;

[0018] FIG. 4 depicts a planar view of a 3D scanned image according to an embodiment;

[0019] FIG. 5 depicts an embodiment of a panoramic view of a 3D scanned image generated by mapping a planar view onto a sphere according to an embodiment;

[0020] FIGs. 6A, 6B and 6C depict embodiments of a 3D view of a 3D scanned image according to an embodiment;

[0021] FIG. 7 depicts an embodiment of a 3D view made up of an image of the object of FIG. 6B but viewed from a different perspective and shown only partially, according to an embodiment;

[0022] FIG. 8A is a perspective view of a 3D measuring device according to an embodiment;

[0023] FIG. 8B is a front view of a camera used to collect 2D camera image data while the 3D measuring device moves along a horizontal plane according to an embodiment;

[0024] FIG. 9 is a block diagram depicting a processor system according to an embodiment;

[0025] FIG. 10 is a schematic representation of a 3D scanner measuring an object from two registration positions according to an embodiment;

[0026] FIG. 11 is a schematic representation of a 2D camera capturing 2D camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

[0027] FIG. 12 shows the 2D camera capturing 2D camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

[0028] FIG. 13 shows the 2D camera capturing 2D camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

[0029] FIGs. 14A and 14B illustrate a method for finding changes in the position and orientation of the 3D scanner over time according to an embodiment; and

[0030] FIG. 15 includes steps in a method for measuring and registering 3D coordinates with a 3D measuring device according to an embodiment.

[0031] The detailed description explains embodiments of the invention, together with advantages and features, by way of example with reference to the drawings.

DETAILED DESCRIPTION OF THE INVENTION

[0032] The present invention relates to a 3D measuring device having a 3D scanner and a two-dimensional (2D) camera. The camera may be an integral part of the 3D scanner or a separate camera unit. The 3D measuring device is used in two modes, a first mode in which the 3D scanner obtains 3D coordinates of an object surface over a 3D region of space and a second mode in which camera images are obtained as the camera is moved between positions at which 3D scans are taken. The 2D camera images are used together with the 3D scan data from the 3D scanner to provide automatic registration of the 3D scans.

[0033] Referring now to FIGs. 1 – 3, a laser scanner 20 is shown for optically scanning and measuring the environment surrounding the laser scanner 20. The laser scanner 20 has a measuring head 22 and a base 24. The measuring head 22 is mounted on the base 24 such that the laser scanner 20 may be rotated about a vertical axis 23. In one embodiment, the measuring head 22 includes a gimbal point 27 that is a center of rotation about the vertical axis 23 and a horizontal axis 25. The measuring head 22 has a rotary mirror 26, which may be rotated about the horizontal axis 25. The rotation about the vertical axis may be about the center of the base 24. The terms vertical axis and horizontal axis refer to the scanner in its normal upright position. It is possible to operate a 3D coordinate measurement device on its side or upside down, and so to avoid confusion, the terms azimuth axis and zenith axis may be substituted for the terms vertical axis and horizontal axis, respectively. The term pan axis or standing axis may also be used as an alternative to vertical axis.

[0034] The measuring head 22 is further provided with an electromagnetic radiation emitter, such as light emitter 28, for example, that emits an emitted light beam 30. In one embodiment, the emitted light beam 30 is a coherent light beam such as a laser beam. The laser beam may have a wavelength range of approximately 300 to 1600 nanometers, for example 790 nanometers, 905 nanometers, 1550 nm, or less than 400 nanometers. It should be appreciated that other electromagnetic radiation beams having greater or smaller wavelengths may also be used. The emitted light beam 30 is amplitude or intensity modulated, for example, with a sinusoidal waveform or with a rectangular waveform. The emitted light beam 30 is emitted by the light emitter 28 onto the rotary mirror 26, where it is deflected to the environment. A reflected light beam 32 is reflected from the environment by an object 34. The reflected or scattered light is intercepted by the rotary mirror 26 and

directed into a light receiver 36. The directions of the emitted light beam 30 and the reflected light beam 32 result from the angular positions of the rotary mirror 26 and the measuring head 22 about the axes 25 and 23, respectively. These angular positions in turn depend on the corresponding rotary drives or motors.

[0035] Coupled to the light emitter 28 and the light receiver 36 is a controller 38. The controller 38 determines, for a multitude of measuring points X, a corresponding number of distances d between the laser scanner 20 and the points X on object 34. The distance to a particular point X is determined based at least in part on the speed of light in air through which electromagnetic radiation propagates from the device to the object point X. In one embodiment the phase shift of modulation in light emitted by the laser scanner 20 and the point X is determined and evaluated to obtain a measured distance d.

[0036] The speed of light in air depends on the properties of the air such as the air temperature, barometric pressure, relative humidity, and concentration of carbon dioxide. Such air properties influence the index of refraction n of the air. The speed of light in air is equal to the speed of light in vacuum c divided by the index of refraction. In other words, $c_{air} = c / n$. A laser scanner of the type discussed herein is based on the time-of-flight (TOF) of the light in the air (the round-trip time for the light to travel from the device to the object and back to the device). Examples of TOF scanners include scanners that measure round trip time using the time interval between emitted and returning pulses (pulsed TOF scanners), scanners that modulate light sinusoidally and measure phase shift of the returning light (phase-based scanners), as well as many other types. A method of measuring distance based on the time-of-flight of light depends on the speed of light in air and is therefore easily distinguished from methods of measuring distance based on triangulation. Triangulation-based methods involve projecting light from a light source along a particular direction and then intercepting the light on a camera pixel along a particular direction. By knowing the distance between the camera and the projector and by matching a projected angle with a received angle, the method of triangulation enables the distance to the object to be determined based on one known length and two known angles of a triangle. The method of triangulation, therefore, does not directly depend on the speed of light in air.

[0037] In one mode of operation, the scanning of the volume around the laser scanner 20 takes place by rotating the rotary mirror 26 relatively quickly about axis 25 while rotating

the measuring head 22 relatively slowly about axis 23, thereby moving the assembly in a spiral pattern. In an exemplary embodiment, the rotary mirror rotates at a maximum speed of 5820 revolutions per minute. For such a scan, the gimbal point 27 defines the origin of the local stationary reference system. The base 24 rests in this local stationary reference system.

[0038] In addition to measuring a distance d from the gimbal point 27 to an object point X, the scanner 20 may also collect gray-scale information related to the received optical power (equivalent to the term "brightness.") The gray-scale value may be determined at least in part, for example, by integration of the bandpass-filtered and amplified signal in the light receiver 36 over a measuring period attributed to the object point X.

[0039] The measuring head 22 may include a display device 40 integrated into the laser scanner 20. The display device 40 may include a graphical touch screen 41, as shown in FIG. 1, which allows the operator to set the parameters or initiate the operation of the laser scanner 20. For example, the screen 41 may have a user interface that allows the operator to provide measurement instructions to the device, and the screen may also display measurement results.

[0040] The laser scanner 20 includes a carrying structure 42 that provides a frame for the measuring head 22 and a platform for attaching the components of the laser scanner 20. In one embodiment, the carrying structure 42 is made from a metal such as aluminum. The carrying structure 42 includes a traverse member 44 having a pair of walls 46, 48 on opposing ends. The walls 46, 48 are parallel to each other and extend in a direction opposite the base 24. Shells 50, 52 are coupled to the walls 46, 48 and cover the components of the laser scanner 20. In the exemplary embodiment, the shells 50, 52 are made from a plastic material, such as polycarbonate or polyethylene for example. The shells 50, 52 cooperate with the walls 46, 48 to form a housing for the laser scanner 20.

[0041] On an end of the shells 50, 52 opposite the walls 46, 48 a pair of yokes 54, 56 are arranged to partially cover the respective shells 50, 52. In the exemplary embodiment, the yokes 54, 56 are made from a suitably durable material, such as aluminum for example, that assists in protecting the shells 50, 52 during transport and operation. The yokes 54, 56 each includes a first arm portion 58 that is coupled, such as with a fastener for example, to the traverse 44 adjacent the base 24. The arm portion 58 for each yoke 54, 56 extends from the traverse 44 obliquely to an outer corner of the respective shell 50, 54. From the outer corner

of the shell, the yokes 54, 56 extend along the side edge of the shell to an opposite outer corner of the shell. Each yoke 54, 56 further includes a second arm portion that extends obliquely to the walls 46, 48. It should be appreciated that the yokes 54, 56 may be coupled to the traverse 42, the walls 46, 48 and the shells 50, 54 at multiple locations.

[0042] The pair of yokes 54, 56 cooperate to circumscribe a convex space within which the two shells 50, 52 are arranged. In the exemplary embodiment, the yokes 54, 56 cooperate to cover all of the outer edges of the shells 50, 54, while the top and bottom arm portions project over at least a portion of the top and bottom edges of the shells 50, 52. This provides advantages in protecting the shells 50, 52 and the measuring head 22 from damage during transportation and operation. In other embodiments, the yokes 54, 56 may include additional features, such as handles to facilitate the carrying of the laser scanner 20 or attachment points for accessories for example.

[0043] On top of the traverse 44, a prism 60 is provided. The prism extends parallel to the walls 46, 48. In the exemplary embodiment, the prism 60 is integrally formed as part of the carrying structure 42. In other embodiments, the prism 60 is a separate component that is coupled to the traverse 44. When the mirror 26 rotates, during each rotation the mirror 26 directs the emitted light beam 30 onto the traverse 44 and the prism 60. Due to non-linearities in the electronic components, for example in the light receiver 36, the measured distances d may depend on signal strength, which may be measured in optical power entering the scanner or optical power entering optical detectors within the light receiver 36, for example. In an embodiment, a distance correction is stored in the scanner as a function (possibly a nonlinear function) of distance to a measured point and optical power (generally unscaled quantity of light power sometimes referred to as "brightness") returned from the measured point and sent to an optical detector in the light receiver 36. Since the prism 60 is at a known distance from the gimbal point 27, the measured optical power level of light reflected by the prism 60 may be used to correct distance measurements for other measured points, thereby allowing for compensation to correct for the effects of environmental variables such as temperature. In the exemplary embodiment, the resulting correction of distance is performed by the controller 38.

[0044] In an embodiment, the base 24 is coupled to a swivel assembly (not shown) such as that described in commonly owned U.S. Patent No. 8,705,012 ('012), which is

incorporated by reference herein. The swivel assembly is housed within the carrying structure 42 and includes a motor that is configured to rotate the measuring head 22 about the axis 23.

[0045] An auxiliary image acquisition device 66 may be a device that captures and measures a parameter associated with the scanned volume or the scanned object and provides a signal representing the measured quantities over an image acquisition area. The auxiliary image acquisition device 66 may be, but is not limited to, a pyrometer, a thermal imager, an ionizing radiation detector, or a millimeter-wave detector. In an embodiment, the auxiliary image acquisition device 66 is a color camera.

[0046] In an embodiment, a central color camera (first image acquisition device) 112 is located internally to the scanner and may have the same optical axis as the 3D scanner device. In this embodiment, the first image acquisition device 112 is integrated into the measuring head 22 and arranged to acquire images along the same optical pathway as emitted light beam 30 and reflected light beam 32. In this embodiment, the light from the light emitter 28 reflects off a fixed mirror 116 and travels to dichroic beam-splitter 118 that reflects the light 117 from the light emitter 28 onto the rotary mirror 26. The dichroic beam-splitter 118 allows light to pass through at wavelengths different than the wavelength of light 117. For example, the light emitter 28 may be a near infrared laser light (for example, light at wavelengths of 780 nm or 1150 nm), with the dichroic beam-splitter 118 configured to reflect the infrared laser light while allowing visible light (e.g., wavelengths of 400 to 700 nm) to transmit through. In other embodiments, the determination of whether the light passes through the beam-splitter 118 or is reflected depends on the polarization of the light. The digital camera 112 obtains 2D images of the scanned area to capture color data to add to the scanned image. In the case of a built-in color camera having an optical axis coincident with that of the 3D scanning device, the direction of the camera view may be easily obtained by simply adjusting the steering mechanisms of the scanner – for example, by adjusting the azimuth angle about the axis 23 and by steering the mirror 26 about the axis 25.

[0047] FIG. 4 depicts an example of a planar view of a 3D scanned image 400. The planar view depicted in FIG. 4 maps an image based on direct mapping of data collected by the scanner. The scanner collects data in a spherical pattern but with data points collected near the poles more tightly compressed than those collected nearer the horizon. In other

words, each point collected near a pole represents a smaller solid angle than does each point collected nearer the horizon. Since data from the scanner may be directly represented in rows and column, data in a planar image is conveniently presented in a rectilinear format, as shown in FIG. 4. With planar mapping described above, straight lines appear to be curved, as for example the straight fence railings 420 that appear curved in the planar view of the 3D image. The planar view may be a 3D unprocessed scanned image displaying just the gray-scale values received from the distance sensor arranged in columns and rows as they were recorded. In addition, the 3D unprocessed scanned image of the planar view may be in full resolution or reduced resolution depending on system characteristics (e.g., display device, storage, processor). The planar view may be a 3D processed scanned image that depicts either gray-scale values (resulting from the light irradiance measured by the distance sensor for each pixel) or color values (resulting from camera images which have been mapped onto the scan). Although the planar view extracted from the 3D scanner is ordinarily a gray-scale or color image, FIG. 4 is shown as a line drawing for clarity in document reproduction. The user interface associated with the display unit, which may be integral to the laser scanner, may provide a point selection mechanism, which in FIG. 4 is the cursor 410. The point selection mechanism may be used to reveal dimensional information about the volume of space being measured by the laser scanner. In FIG. 4, the row and column at the location of the cursor are indicated on the display at 430. The two measured angles and one measured distance (the 3D coordinates in a spherical coordinate system) at the cursor location are indicated on the display at 440. Cartesian XYZ coordinate representations of the cursor location are indicated on the display at 450.

[0048] FIG. 5 depicts an example of a panoramic view of a 3D scanned image 600 generated by mapping a planar view onto a sphere, or in some cases a cylinder. A panoramic view can be a 3D processed scanned image (such as that shown in FIG. 5) in which 3D information (e.g., 3D coordinates) is available. The panoramic view may be in full resolution or reduced resolution depending on system characteristics. It should be pointed out that an image such as FIG. 5 is a 2D image that represents a 3D scene when viewed from a particular perspective. In this sense, the image of FIG. 5 is much like an image that might be captured by a 2D camera or a human eye. Although the panoramic view extracted from the 3D scanner is ordinarily a gray-scale or color image, FIG. 5 is shown as a line drawing for clarity in document reproduction.

[0049] The term panoramic view refers to a display in which angular movement is generally possible about a point in space, but translational movement is not possible (for a single panoramic image). In contrast, the term 3D view as used herein refers to generally refers to a display in which provision is made (through user controls) to enable not only rotation about a fixed point but also translational movement from point to point in space.

[0050] FIGs. 6A, 6B and 6C depict an example of a 3D view of a 3D scanned image. In the 3D view a user can leave the origin of the scan and see the scan points from different viewpoints and angles. The 3D view is an example of a 3D processed scanned image. The 3D view may be in full resolution or reduced resolution depending on system characteristics. In addition, the 3D view allows multiple registered scans to be displayed in one view. FIG. 6A is a 3D view 710 over which a selection mask 730 has been placed by a user. FIG. 6B is a 3D view 740 in which only that part of the 3D view 710 covered by the selection mask 730 has been retained. FIG. 6C shows the same 3D measurement data as in FIG. 6B except as rotated to obtain a different view. FIG. 7 shows a different view of FIG. 6B, the view in this instance being obtained from a translation and rotation of the observer viewpoint, as well as a reduction in observed area. Although the 3D views extracted from the 3D scanner are ordinarily a gray-scale or color image, FIGs. 6A-C and 7 are shown as line drawings for clarity in document reproduction.

[0051] FIGs. 8A, 8B and 9 show an embodiment of a 3D measuring device 800 that includes a 3D scanner 20, a processor system 950, an optional moveable platform 820, and a 2D camera, which may be a camera 112 internal to the 3D scanner (as shown in FIG. 3), a camera 70 mounted on the 3D scanner (as shown in FIG. 1), or a camera 840 mounted on the optional moveable platform 820. The 3D measuring device 800 may be a 3D TOF scanner 20 as described in reference to FIG. 1. For the case in which a camera 840 is attached to the moveable platform 820, the attachment may be made at the base of the moveable platform or to an upper portion of the moveable platform, for example to tripod legs.

[0052] The processor system 950 includes one or more processing elements that may include a 3D scanner processor (controller) 38, an external computer 970, and a cloud computer 980. The processors may be microprocessors, field programmable gate arrays (FPGAs), digital signal processors (DSPs), and generally any device capable of performing computing functions. The one or more processors have access to memory for storing

information. In an embodiment illustrated in FIG. 9, the controller 38 represents one or more processors distributed throughout the 3D scanner. Also included in the embodiment of FIG. 9 are an external computer 970 and one or more cloud computers 980 for remote computing capability. In an alternative embodiment, only one or two of the processors 38, 970, and 980 is provided in the processor system. Communication among the processors may be through wired links, wireless links, or a combination of wired and wireless links. In an embodiment, scan results are uploaded after each scanning session to the cloud (remote network) for storage and future use. For the case in which a camera 840 is attached to the moveable platform 820, the camera data may be sent to the processor system through wired or wireless communication channels.

[0053] In one mode of operation of the 3D measuring device 800, the camera (112, 70 or 840) captures overlapping 2D camera images as the 3D measuring device is moved between positions at which 3D scans are taken. For the case in which the camera is an internal camera (such as the central color camera 112) or a camera 70 mounted on the measuring head 22, the camera may be optionally steered about the vertical axis 23 to increase the effective FOV of the camera. In an embodiment, the laser power is turned off as the 2D camera images are collected. In an alternative embodiment, the laser power is left on so that the 3D scanner may make 2D scans in a horizontal plane while the 2D camera images are collected. For the case in which the 2D camera 840 is mounted on the moveable platform 820, the direction at which the camera is pointed is unaffected by rotation of horizontal axis 25 or vertical axis 23.

[0054] The optional position/orientation sensor 920 in the 3D scanner 20 may include inclinometers (accelerometers), gyroscopes, magnetometers, and altimeters. Usually devices that include one or more of an inclinometer and gyroscope are referred to as an inertial measurement unit (IMU). In some cases, the term IMU is used in a broader sense to include a variety of additional devices that indicate position and/or orientation – for example, magnetometers that indicate heading based on changes in magnetic field direction relative to the earth's magnetic north and altimeters that indicate altitude (height). An example of a widely used altimeter is a pressure sensor. By combining readings from a combination of position/orientation sensors with a fusion algorithm that may include a Kalman filter, relatively accurate position and orientation measurements can be obtained using relatively low-cost sensor devices.

[0055] The optional moveable platform 820 enables the 3D measuring device 20 to be moved from place to place, typically along a floor that is approximately horizontal. In an embodiment, the optional moveable platform 820 is a tripod that includes wheels 822. In an embodiment, the wheels 822 may be locked in place using wheel brakes 824. In another embodiment, the wheels 822 are retractable, enabling the tripod to sit stably on three feet attached to the tripod. In another embodiment, the tripod has no wheels but is simply pushed or pulled along a surface that is approximately horizontal, for example, a floor. In another embodiment, the optional moveable platform 820 is a wheeled cart that may be hand pushed/pulled or motorized.

[0056] FIG. 10 shows the 3D measuring device 800 moved to a first registration position 1112 in front of an object 1102 that is to be measured. The object 1102 might for example be a wall in a room. In an embodiment, the 3D measuring device 800 is brought to a stop and is held in place with brakes, which in an embodiment are brakes 824 on wheels 822. The 3D scanner 20 in the 3D measuring device 800 takes a first 3D scan of the object 1102. In an embodiment, the 3D scanner 20 may if desired obtain 3D measurements in all directions except in downward directions blocked by the structure of the 3D measuring device 800. However, in the example of FIG. 10, in which 3D scanner 20 measures a long, mostly flat structure 1102, a smaller effective FOV 1130 may be selected to provide a more face-on view of features on the structure.

[0057] When the first 3D scan is completed, the processor system 950 causes the 3D measuring device 800 to change from 3D scanning mode to a 2D camera imaging mode. The 2D camera imaging data is sent from the camera (112, 70 or 840) to the processor system 950 for mathematical analysis. In an embodiment, the scanner begins collecting camera imaging data as the 3D scanning stops. In another embodiment, the collection of camera imaging data starts when the processor receives a signal such as a signal form the position/orientation sensor 920, a signal from a brake release sensor, or a signal sent in response to a command from an operator. The processor system 950 may cause camera imaging data to be collected when the 3D measuring device 800 starts to move, or it may cause camera imaging data to be continually collected, even when the 3D measuring device 800 is stationary.

[0058] In an embodiment, the camera imaging data is collected as the 3D measuring device 800 is moved toward the second registration position 1114. In an embodiment, the

camera imaging data is collected and processed as the 3D scanner 20 passes through a plurality of 2D measuring positions 1120. At each measuring position 1120, the camera collects camera imaging data over an effective FOV 1140. Using methods described in more detail below, the processor system 950 uses the camera imaging data from a plurality of camera images at positions 1120 to determine a position and orientation of the 3D scanner 20 at the second registration position 1114 relative to the first registration position 1112, where the first registration position and the second registration position are known in a 3D coordinate system common to both. In an embodiment, the common coordinate system is represented by 2D Cartesian coordinates x, y and by an angle of rotation θ relative to the x or y axis. In an embodiment, the x and y axes lie in the horizontal x-y plane of the 3D scanner 20 and may be further based on a direction of a "front" of the 3D scanner 20. An example of such an (x, y, θ) coordinate system is the coordinate system 1410 of FIG. 14A.

[0059] On the object 1102, there is a region of overlap 1150 between the first 3D scan (collected at the first registration position 1112) and the second 3D scan (collected at the second registration position 1114). In the overlap region 1150 there are registration targets (which may be natural features of the object 1102) that are seen in both the first 3D scan and the second 3D scan. A problem that often occurs in practice is that, in moving the 3D scanner 20 from the first registration position 1112 to the second registration position 1114, the processor system 950 loses track of the position and orientation of the 3D scanner 20 and hence is unable to correctly associate the registration targets in the overlap regions to enable the registration procedure to be performed reliably. By using the succession of camera images, the processor system 950 is able to determine the position and orientation of the 3D scanner 20 at the second registration position 1114 relative to the first registration position 1112. This information enables the processor system 950 to correctly match registration targets in the region of overlap 1150, thereby enabling the registration procedure to be properly completed.

[0060] FIG. 12 shows the 3D scanner 20 collecting camera imaging data at selected positions 1120 over an effective FOV 1140. At different positions 1120, the camera captures a portion of the object 1102 marked A, B, C, D, and E. FIG. 12 shows 2D camera moving in time relative to a fixed frame of reference of the object 1102.

[0061] FIG. 13 includes the same information as FIG. 12 but shows it from the frame of reference of the 3D scanner 20 while collecting camera images rather than the frame of reference of the object 1102. This figure makes clear that in the scanner frame of reference, the position of features on the object change over time. Hence it is clear that the distance traveled by the 3D scanner 20 between registration position 1 and registration position 2 can be determined from the camera imaging data sent from the camera to the processor system 950.

[0062] FIG. 14A shows a coordinate system that may be used in FIGs. 14B and 14C. In an embodiment, the 2D coordinates x and y are selected to lie on a plane parallel to the horizontal plane of movement of the moveable platform. The angle θ is selected as a rotation angle in the plane, the rotation angle relative to an axis such as x or y. FIGs. 14B, 14C represent a realistic case in which the 3D scanner 20 is moved not exactly on a straight line, for example, nominally parallel to the object 1102, but also to the side. Furthermore, the 3D scanner 20 may be rotated as it is moved.

[0063] FIG. 14B shows the movement of the object 1102 as seen from the frame of reference of the 3D scanner 20 in traveling from the first registration position to the second registration position. In the scanner frame of reference (that is, as seen from the scanner's point of view), the object 1102 is moving while the camera is fixed in place. In this frame of reference, the portions of the object 1102 seen by the camera appear to translate and rotate in time. The camera provides a succession of such translated and rotated 2D camera images to the processor system 950. In the example shown in FIGs. 14A, B, the scanner translates in the $+y$ direction by a distance 1420 shown in FIG. 14B and rotates by an angle 1430, which in this example is +5 degrees. Of course, the scanner could equally well have moved in the $+x$ or $-x$ direction by a small amount. To determine the movement of the camera in the x, y, θ directions, the processor system 950 uses the data recorded in successive camera images as seen in the frame of reference of the scanner 20, as shown in FIG. 14B. In an embodiment, the processor system 950 performs a best-fit calculation using methods well known in the art to match the two scans or features in the two scans as closely as possible.

[0064] As the 3D scanner 20 collects successive 2D camera images and performs best-fit calculations, the processor system 950 keeps track of the translation and rotation of the 3D scanner 20. In this way, the processor system 950 is able to accurately determine the

change in the values of x, y, θ as the measuring device 800 moves from the first registration position 1112 to the second registration position 1114.

[0065] It is important to understand that the processor system 950 determines the position and orientation of the 3D measuring device 800 based on a comparison of the succession of 2D camera images and not on fusion of the camera imaging data with 3D scan data provided by the 3D scanner 20 at the first registration position 1112 or the second registration position 1114.

[0066] Instead, the processor system 950 is configured to determine a first translation value, a second translation value, and a first rotation value that, when applied to a combination of the first 2D camera image data and second 2D camera image data, results in transformed first 2D data that matches transformed second 2D data as closely as possible according to an objective mathematical criterion. In general, the translation and rotation may be applied to the first scan data, the second scan data, or to a combination of the two. For example, a translation applied to the first data set is equivalent to a negative of the translation applied to the second data set in the sense that both actions produce the same match in the transformed data sets. An example of an "objective mathematical criterion" is that of minimizing the sum of squared residual errors for those portions of the scan data judged to overlap. Another type of objective mathematical criterion may involve a matching of multiple features identified on the object. For example, such features might be the edge transitions 1103, 1104, and 1105 shown in FIG. 11B.

[0067] A mathematical method known in the art to evaluate camera images collected sequentially as overlapping images to extract information on movement is "optical flow." This method is adapted from the studies of American psychologist James Gibson in the 1940s. A tutorial on optical flow estimation as used today is given in "Mathematical Models in Computer Vision: The Handbook" by N. Paragios, Y. Chen, and O. Faugeras (editors), Chapter 15, Springer 2005, pp. 239-258, the contents of which are incorporated by reference herein. Additional mathematical methods known in the art may also be used to extract information on movement from the sequential 2D camera images.

[0068] The mathematical criterion may involve processing of the raw camera image data provided by the camera to the processor system 950, or it may involve a first

intermediate level of processing in which features are represented as a collection of line segments using methods that are known in the art, for example, methods based on the Iterative Closest Point (ICP). Such a method based on ICP is described in Censi, A., "An ICP variant using a point-to-line metric," IEEE International Conference on Robotics and Automation (ICRA) 2008.

[0069] In an embodiment, the first translation value is dx, the second translation value is dy, and the first rotation value $d\theta$. If first 2D camera image data has translational and rotational coordinates (in a reference coordinate system) of (x_1, y_1, θ_1), then the second 2D camera image data collected at a second location has coordinates given by $(x_2, y_2, \theta_2) = (x_1+ dx, y_1+ dy, \theta_1+ d\theta)$. In an embodiment, the processor system 950 is further configured to determine a third translation value (for example, dz) and a second and third rotation values (for example, pitch and roll). The third translation value, second rotation value, and third rotation value may be determined based at least in part on readings from the position/orientation sensor 920.

[0070] The 3D scanner 20 collects 2D camera image data at the first registration position 1112 and more 2D camera image data at the second registration position 1114. In some cases, these 2D camera images may suffice to determine the position and orientation of the 3D measuring device at the second registration position 1114 relative to the first registration position 1112. In other cases, the two sets of 2D camera image data are not sufficient to enable the processor system 950 to accurately determine the first translation value, the second translation value, and the first rotation value. This problem may be avoided by collecting 2D camera image data at intermediate locations 1120. In an embodiment, the 2D camera image data is collected and processed at regular intervals, for example, once per second. In this way, features are easily identified in successive 2D camera images 1120. If more than two 2D camera images are obtained, the processor system 950 may choose to use the information from all the successive 2D camera images in determining the translation and rotation values in moving from the first registration position 1112 to the second registration position 1114. Alternatively, the processor may choose to use only the first and last 2D camera images in the final calculation, simply using the intermediate 2D camera images to ensure proper correspondence of matching features. In most cases, accuracy of matching is improved by incorporating information from multiple successive 2D camera images.

[0071] The 3D measuring device 800 is moved to the second registration position 1114. In an embodiment, the 3D measuring device 800 is brought to a stop and brakes are locked to hold the 3D scanner stationary. In an alternative embodiment, the processor system 950 starts the 3D scan automatically when the moveable platform is brought to a stop, for example, by the position/orientation sensor 920 noting the lack of movement. The 3D scanner 20 in the 3D measuring device 800 takes a 3D scan of the object 1102. This 3D scan is referred to as the second 3D scan to distinguish it from the first 3D scan taken at the first registration position.

[0072] The processor system 950 applies the already calculated first translation value, the second translation value, and the first rotation value to adjust the position and orientation of the second 3D scan relative to the first 3D scan. This adjustment, which may be considered to provide a "first alignment," brings the registration targets (which may be natural features in the overlap region 1150) into close proximity. The processor system 950 performs a fine registration in which it makes fine adjustments to the six degrees of freedom of the second 3D scan relative to the first 3D scan. It makes the fine adjustment based on an objective mathematical criterion, which may be the same as or different than the mathematical criterion applied to the 2D camera image data. For example, the objective mathematical criterion may be that of minimizing the sum of squared residual errors for those portions of the scan data judged to overlap. Alternatively, the objective mathematical criterion may be applied to a plurality of features in the overlap region. The mathematical calculations in the registration may be applied to raw 3D scan data or to geometrical representations of the 3D scan data, for example, by a collection of line segments.

[0073] Outside the overlap region 1150, the aligned values of the first 3D scan and the second 3D scan are combined in a registered 3D data set. Inside the overlap region, the 3D scan values included in the registered 3D data set are based on some combination of 3D scanner data from the aligned values of the first 3D scan and the second 3D scan.

[0074] FIG. 15 shows elements of a method 1500 for measuring and registering 3D coordinates.

[0075] An element 1505 includes providing a 3D measuring device that includes a processor system, a 3D scanner, a camera, and a moveable platform. The processor system has at least one of a 3D scanner controller, an external computer, and a cloud computer

configured for remote network access. Any of these processing elements within the processor system may include a single processor or multiple distributed processing elements, the processing elements being a microprocessor, digital signal processor, FPGA, or any other type of computing device. The processing elements have access to computer memory. The 3D scanner has a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver. The first light source is configured to emit a first beam of light, which in an embodiment is a beam of laser light. The first beam steering unit is provided to steer the first beam of light to a first direction onto a first object point. The beam steering unit may be a rotating mirror such as the mirror 26 or it may be another type of beam steering mechanism. For example, the 3D scanner may contain a base onto which is placed a first structure that rotates about a vertical axis, and onto this structure may be placed a second structure that rotates about a horizontal axis. With this type of mechanical assembly, the beam of light may be emitted directly from the second structure and point in a desired direction. Many other types of beam steering mechanisms are possible. In most cases, a beam steering mechanism includes one or two motors. The first direction is determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis. The first angle measuring device is configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation. The first light receiver is configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point. The first light receiver is further configured to produce a first electrical signal in response to the first reflected light. The first light receiver is further configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, and the 3D scanner is configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation. The moveable platform is configured to carry the 3D scanner. The camera is configured to obtain 2D camera images and to send the image data to the processor system 950. The camera may be located internal to the 3D scanner, mounted on the 3D scanner, or attached to the moveable platform.

[0076] An element 1510 includes determining with processor system, in cooperation with the 3D scanner, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position.

[0077] An element 1515 includes obtaining by the 3D scanner in cooperation with the processor system a plurality of 2D camera image sets. Each of the plurality of 2D camera image sets is a set of 2D coordinates of points on the object surface collected as the 3D scanner moves from the first registration position to a second registration position. Each of the plurality of 2D camera image sets is collected by the 2D camera at a different position relative to the first registration position.

[0078] An element 1520 includes determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of 2D camera image sets according to a first mathematical criterion. In an embodiment, the first orientation axis is a vertical axis perpendicular to the planes in which the 2D camera image sets are collected.

[0079] An element 1525 includes determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position.

[0080] An element 1535 includes identifying by the processor system a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value.

[0081] An element 1545 includes determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points. An element 1550 includes storing the 3D coordinates of the registered 3D collection of points.

[0082] Terms such as processor, controller, computer, DSP, FPGA are understood in this document to mean a computing device that may be located within an instrument, distributed in multiple elements throughout an instrument, or placed external to an instrument.

[0083] While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

CLAIMS

What is claimed is:

1. A three-dimensional (3D) measuring device comprising:

a processor system including at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access;

a 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, 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 first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation;

a moveable platform configured to carry the 3D scanner;

a camera configured to move in conjunction with the 3D scanner;

wherein the processor system is responsive to executable instructions which when executed by the processor system is operable to:

cause the 3D scanner, while fixedly located at a first registration position, to cooperate with the processor system to determine 3D coordinates of a first collection of points on an object surface;

cause the 3D scanner, while moving from the first registration position to a second registration position, to cooperate with the processor system to obtain a plurality of 2D camera image sets, each of the plurality of 2D camera image sets being a set of 2D coordinates of points on the object surface, each of the plurality of

2D camera image sets being collected by the 3D scanner at a different position relative to the first registration position;

determine a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of 2D camera image sets according to a first mathematical criterion;

cause the 3D scanner, while fixedly located at the second registration position, to cooperate with the processor system to determine 3D coordinates of a second collection of points on the object surface;

identify a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; and

determine 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the determined correspondence among the registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points.

2. The 3D measuring device of claim 1 wherein the 2D camera further includes a position/orientation sensor, the position orientation sensor includes at least one sensor selected from the group consisting of an inclinometer, a gyroscope, a magnetometer, and an altimeter.

3. The 3D measuring device of claim 1 wherein the moveable platform is a tripod having wheels and a brake.

4. The 3D measuring device of claim 1 wherein the first beam steering unit includes a first mirror configured to rotate about a horizontal axis and a carriage that holds the first mirror configured to rotate about a vertical axis, the rotation about the horizontal axis being driven by a first motor and the rotation about the vertical axis being driven by a second

motor.

5. The 3D measuring device of claim 1 wherein the processor is further configured to respond to a stopping signal to cause the 3D scanner, while fixedly located at the second registration position, to automatically begin cooperating with the processor system to determine 3D coordinates of a second collection of points on the object surface.

6. The 3D measuring device of claim 5 wherein the stopping signal is generated in response to a signal received by the processor system from the position/orientation sensor.

7. The 3D measuring device of claim 1, wherein the registration targets are natural features of the object surface.

8. The 3D measuring device of claim 1, wherein the camera is selected from the group consisting of a 2D camera internal to the 3D scanner, a 2D camera mounted on the 3D scanner, and a 2D camera mounted on the moveable platform.

9. A method for measuring and registering three-dimensional (3D) coordinates comprising:

providing a 3D measuring device that includes a processor system, a 3D scanner, a camera, and a moveable platform,

the processor system having at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access,

the 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, 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 first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured

to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation,

the moveable platform configured to carry the 3D scanner;

determining with processor system, in cooperation with the 3D scanner, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position;

obtaining by the 3D scanner in cooperation with the processor system a plurality of 2D camera image sets, each of the plurality of 2D camera image sets being collected as the 2D camera moves from the first registration position to a second registration position, each of the plurality of 2D camera image sets being collected by the 3D scanner at a different position relative to the first registration position;

determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of 2D camera image sets according to a first mathematical criterion;

determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position;

identifying by the processor system a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value;

determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points; and

storing the 3D coordinates of the registered 3D collection of points.

10. The method of claim 9 wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a camera, and a moveable platform, the 3D measuring device further includes a position/orientation sensor, the position orientation sensor including at least one sensor selected from the group consisting of an inclinometer, a gyroscope, a magnetometer, and an altimeter.

11. The method of claim 9 wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a camera, and a moveable platform, the moveable platform is a tripod having wheels and a brake.

12. The method of claim 9 wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a camera, and a moveable platform, the first beam steering unit includes a first mirror configured to rotate about a horizontal axis and a carriage that holds the first mirror, the carriage configured to rotate about a vertical axis, the rotation about the horizontal axis being driven by a first motor and the rotation about the vertical axis being driven by a second motor.

13. The method of claim 12 wherein, in the element of obtaining by the 3D scanner in cooperation with the processor system a plurality of 2D camera image sets, the first mirror is held fixed and the second mirror is held fixed.

14. The method of claim 12 wherein, in the element of obtaining by the 3D scanner in cooperation with the processor system a plurality of 2D camera image sets, the first mirror rotates about the vertical axis while the horizontal axis is held fixed.

15. The method of claim 9 wherein in the element of determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object, the processor is further configured to respond to a stopping signal to cause the 3D scanner to automatically start measurement of the second collection of points.

16. The method of claim 15 wherein in the element of determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object, the stopping signal is generated in response to a signal received by the processor system from the position/orientation sensor.

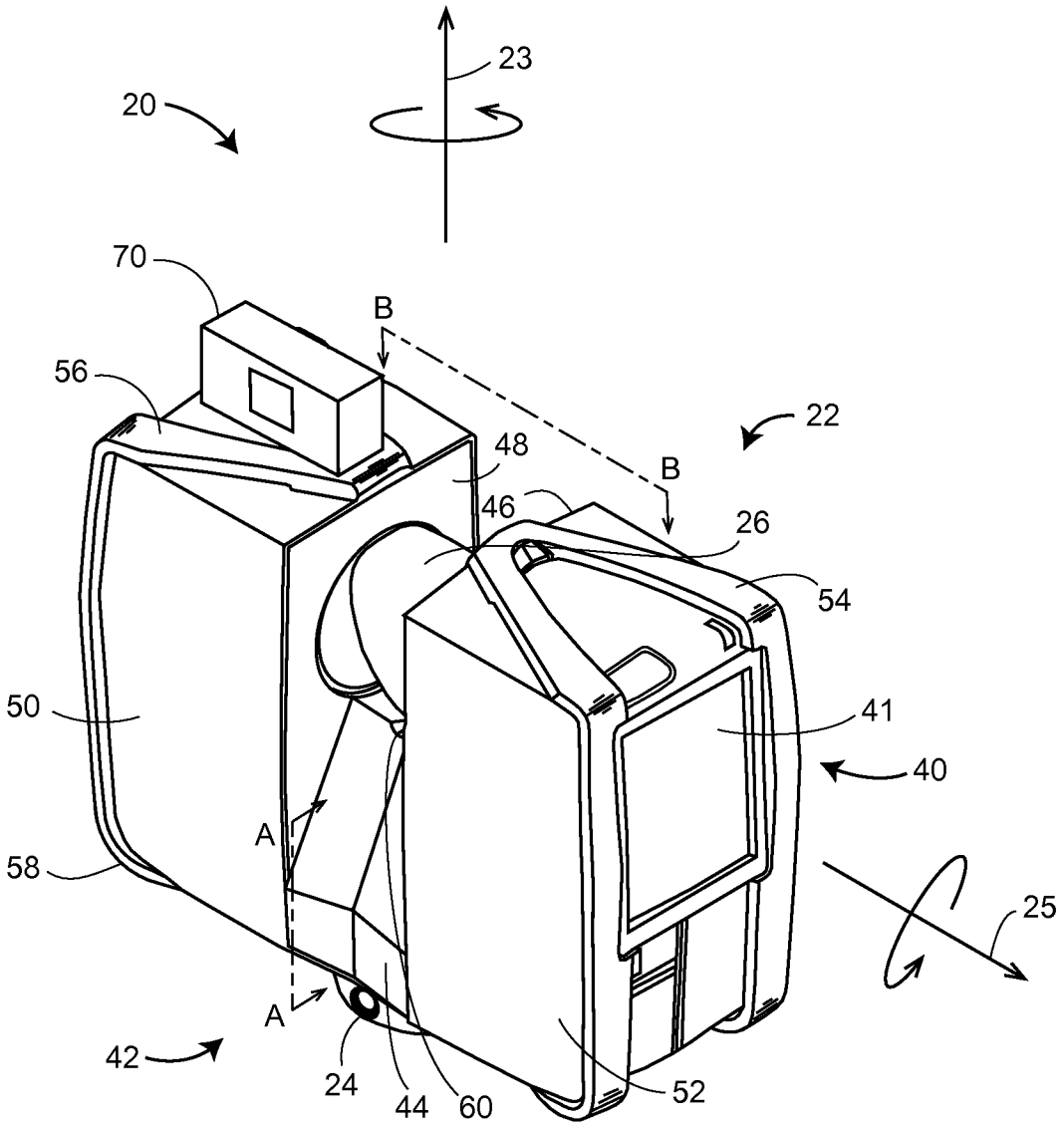


FIG. 1

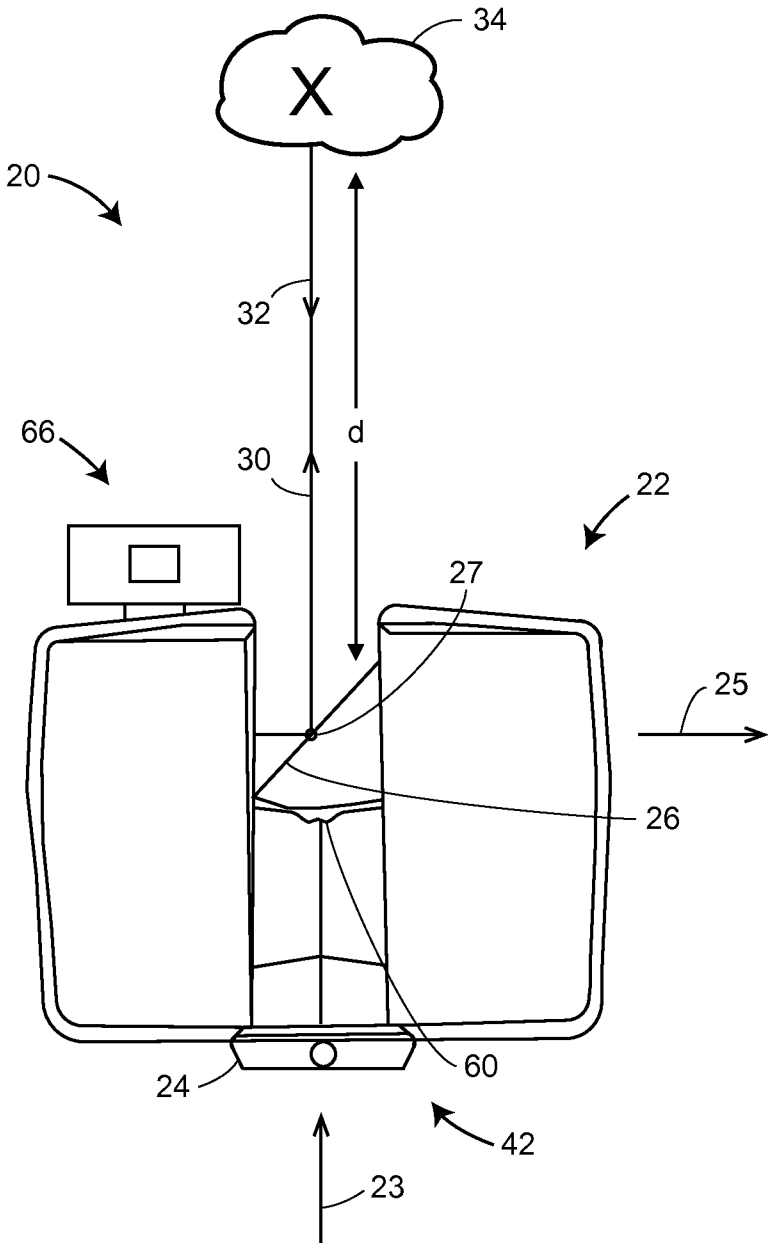


FIG. 2

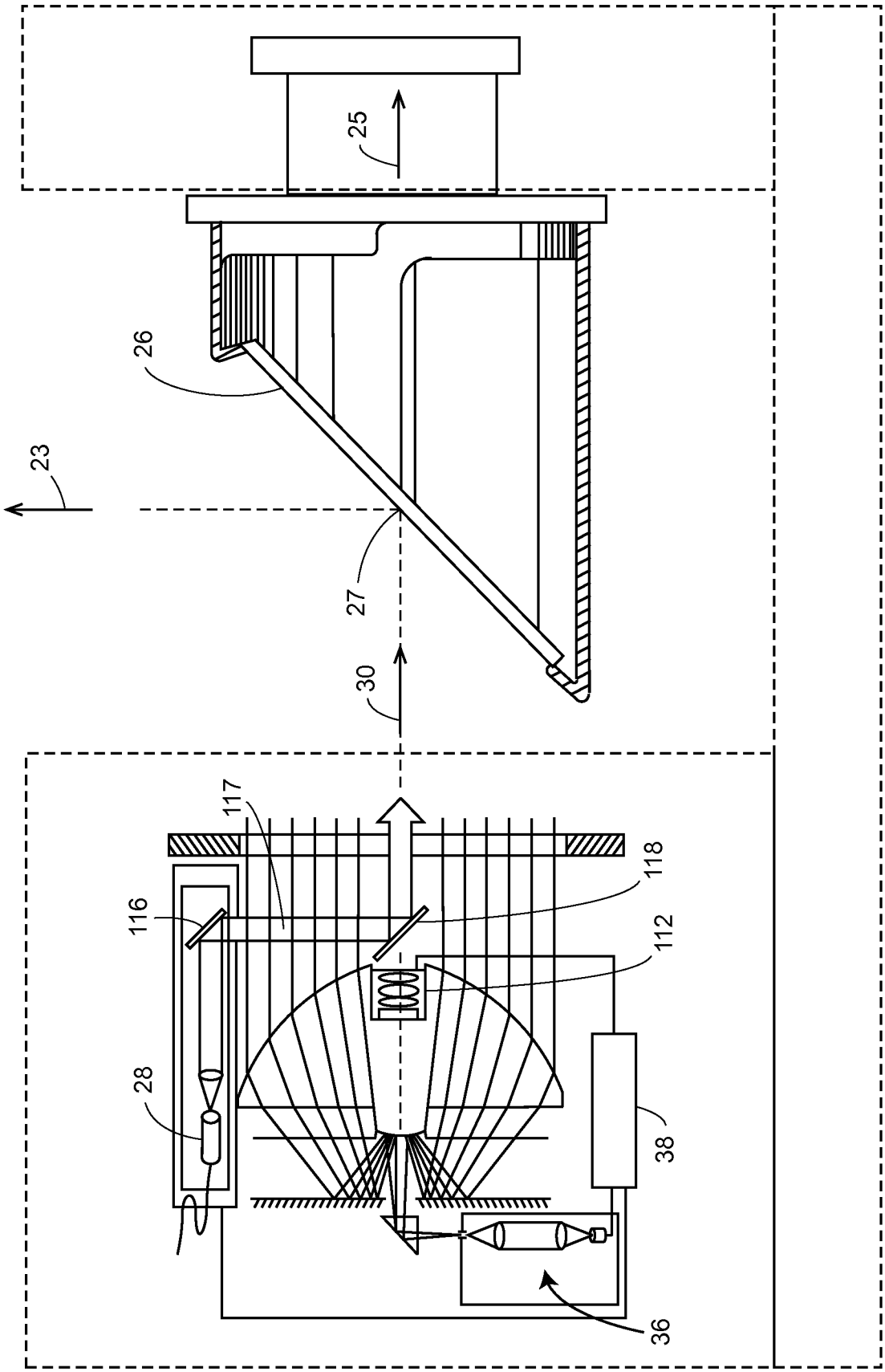


FIG. 3

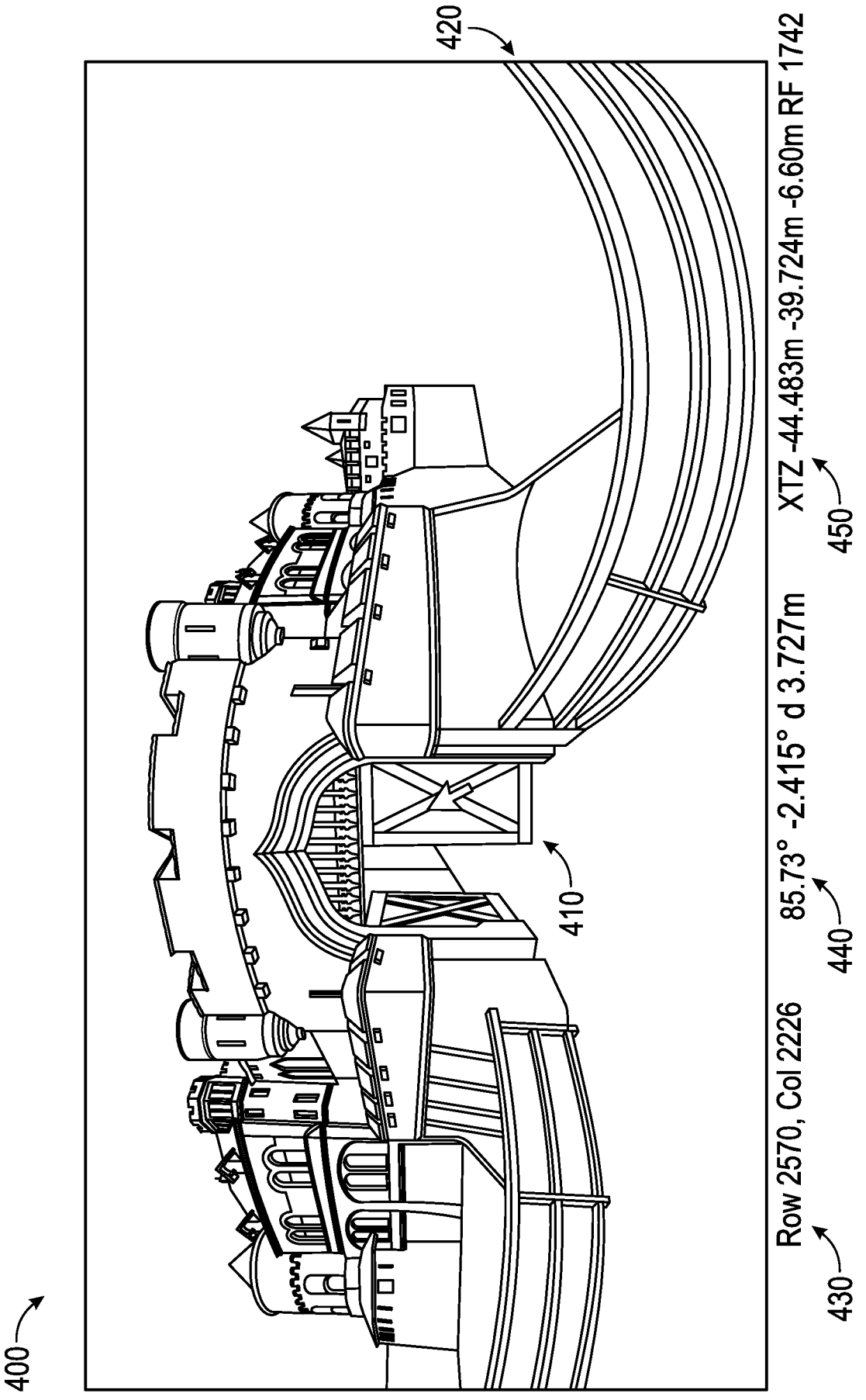

400
420
410
Row 2570, Col 2226
430
85.73° -2.415° d 3.727m
440
XTZ -44.483m -39.724m -6.60m RF 1742
450

FIG. 4

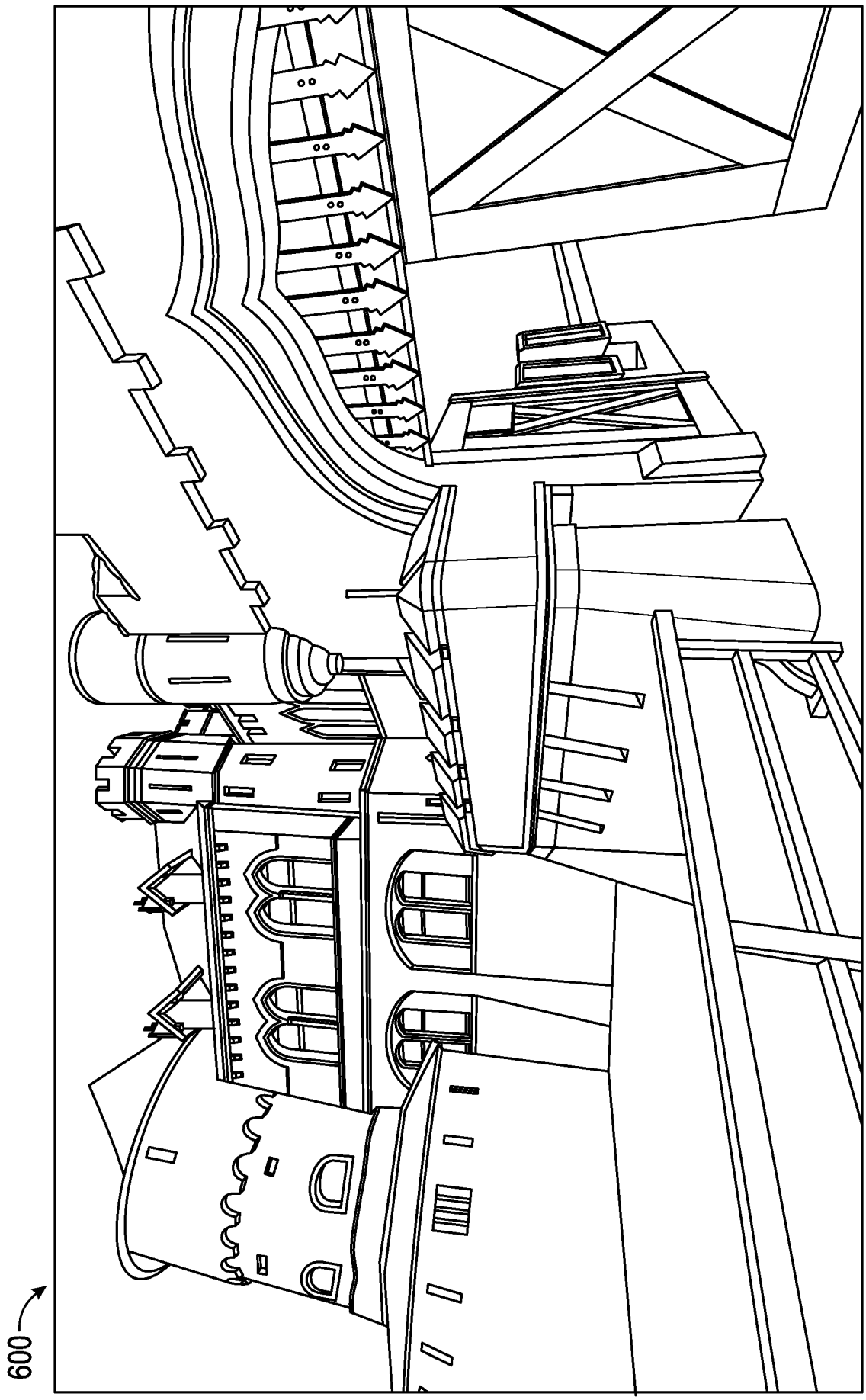


FIG. 5

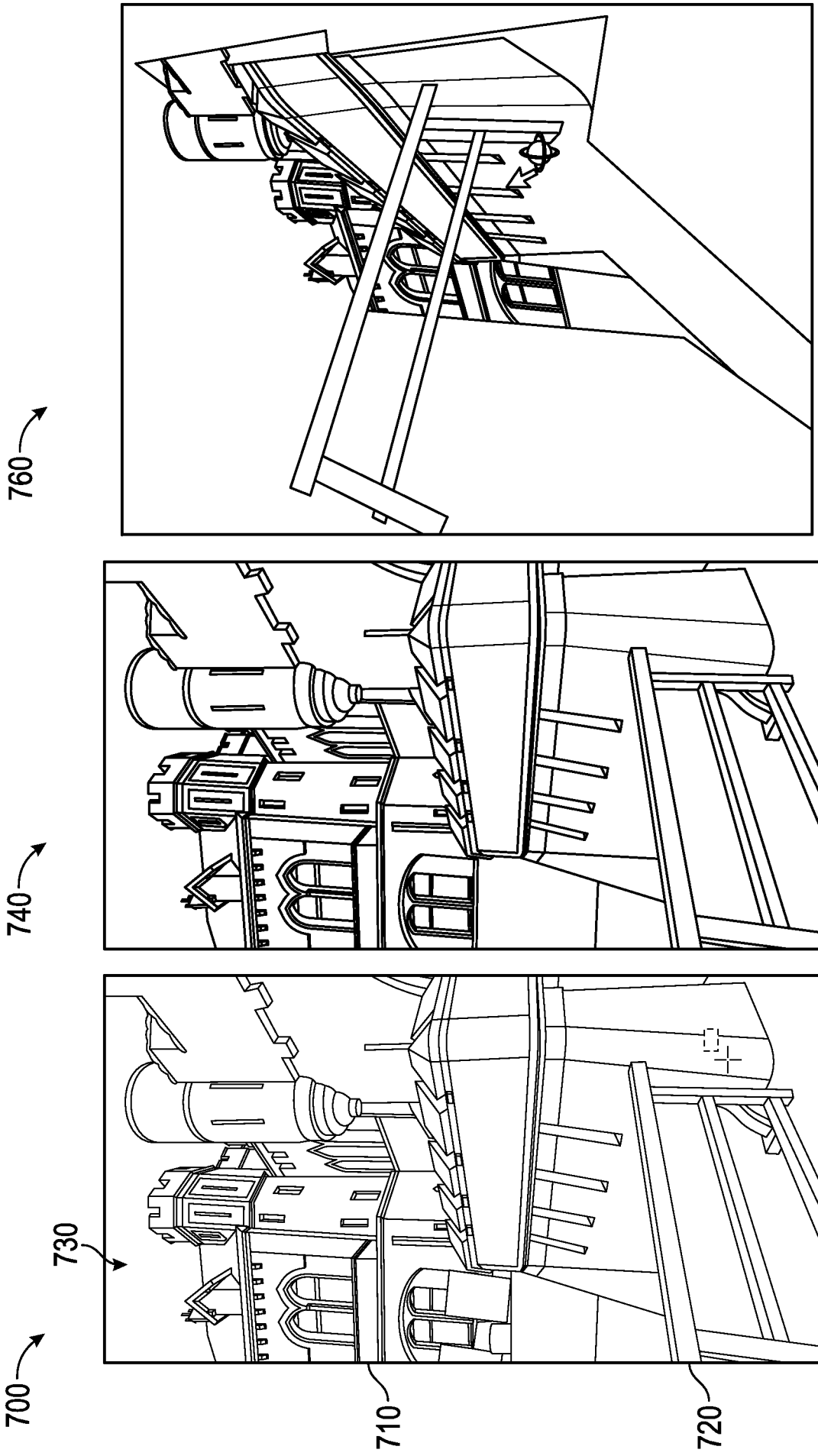


FIG. 6A

FIG. 6B

FIG. 6C

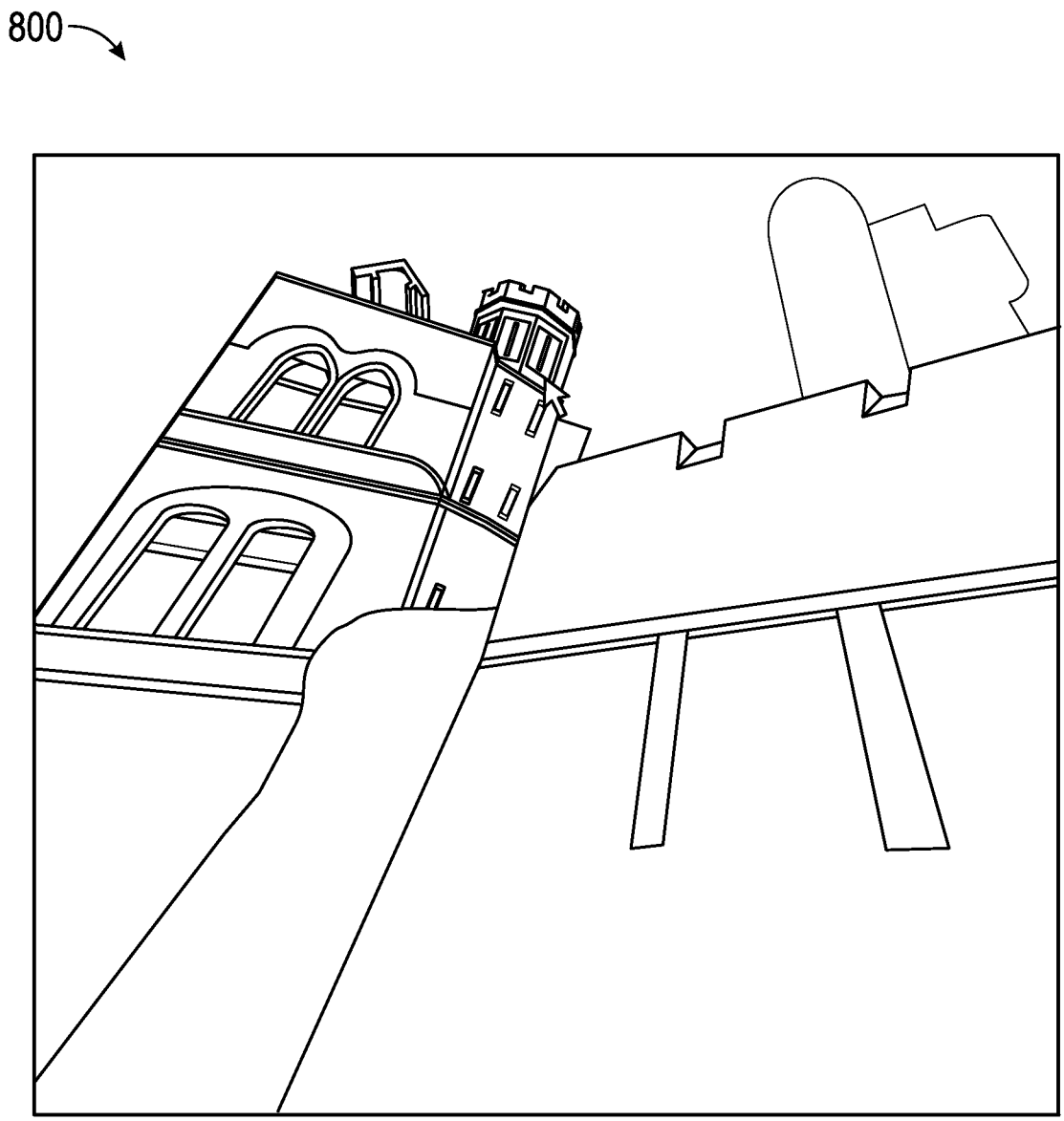


FIG. 7

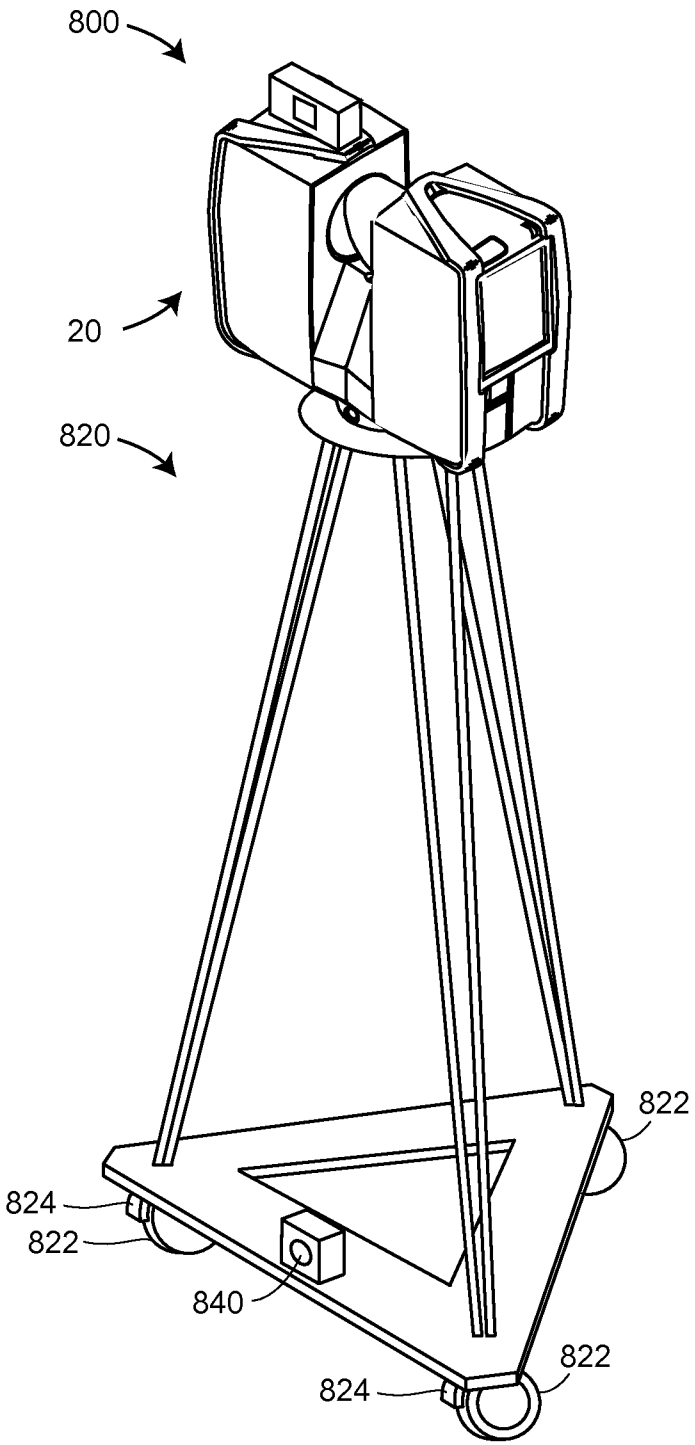


FIG. 8A

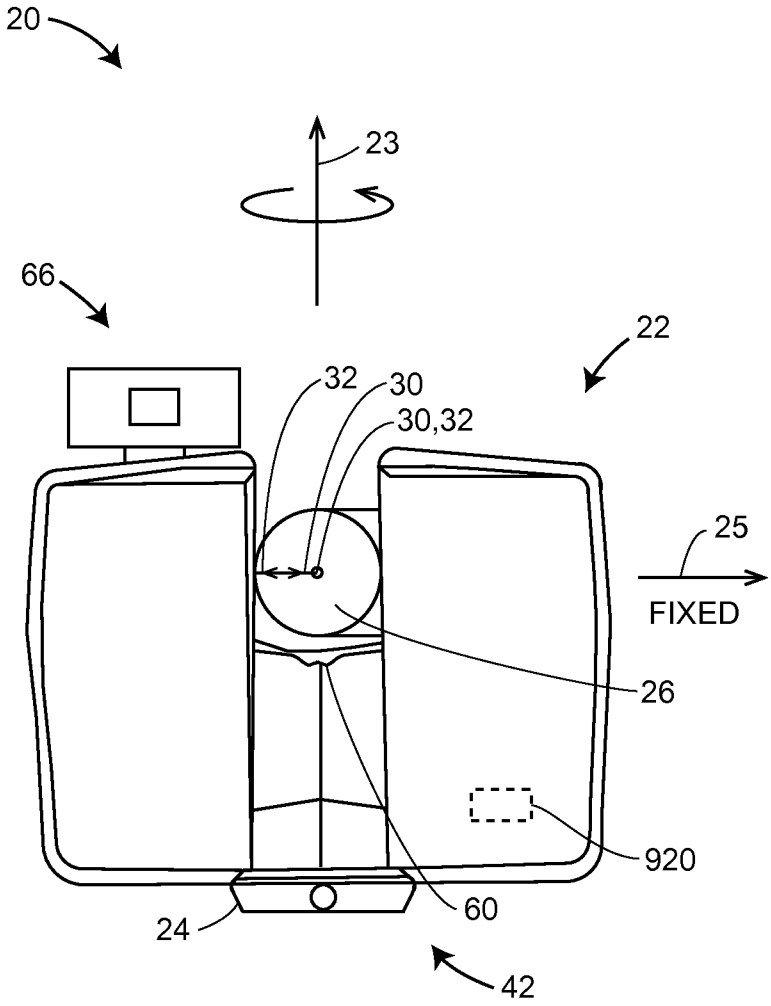


FIG. 8B

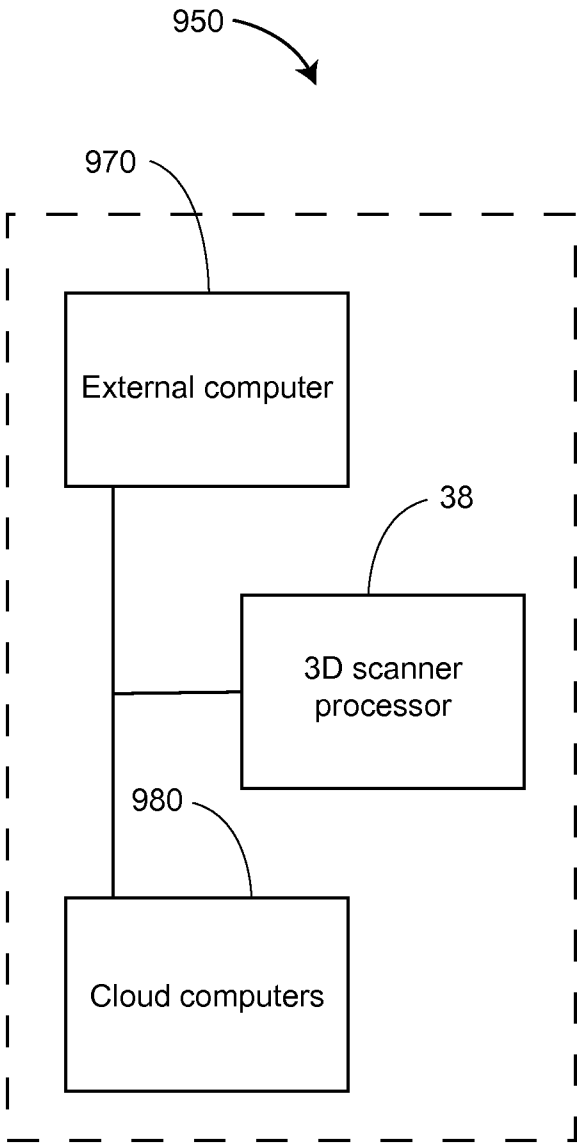

950
970
External computer
38
3D scanner processor
980
Cloud computers

FIG. 9

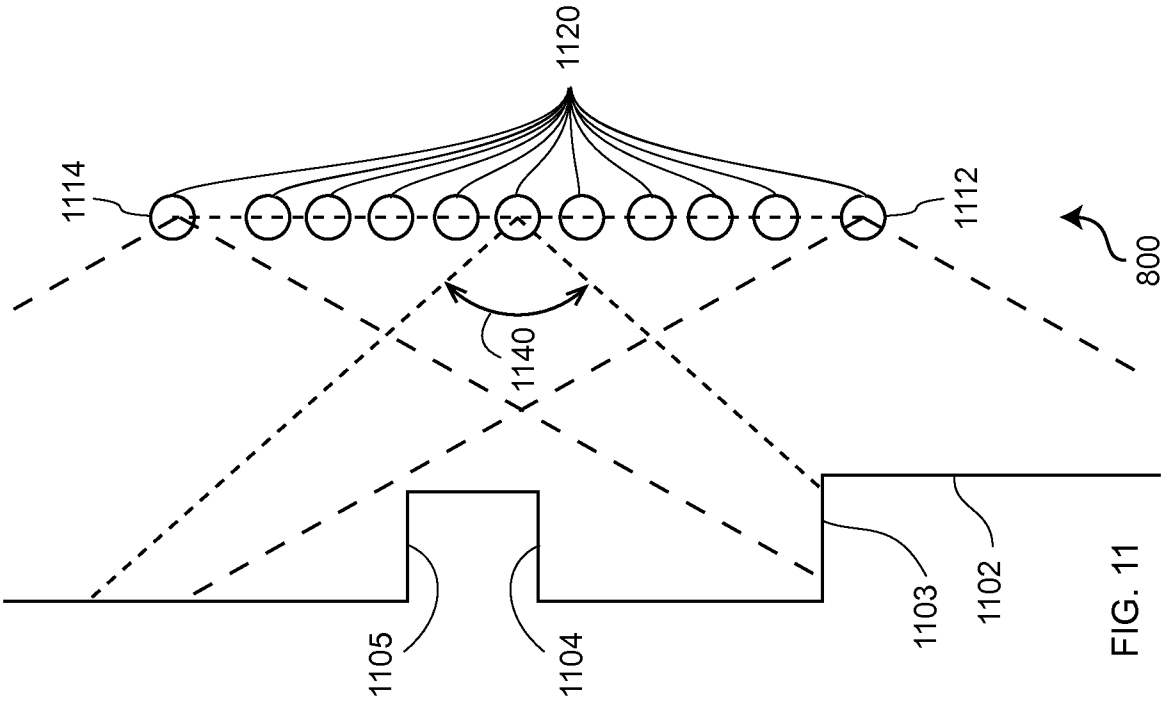

1120
1114
1112
800
1140
1105
1104
1103
1102

FIG. 11

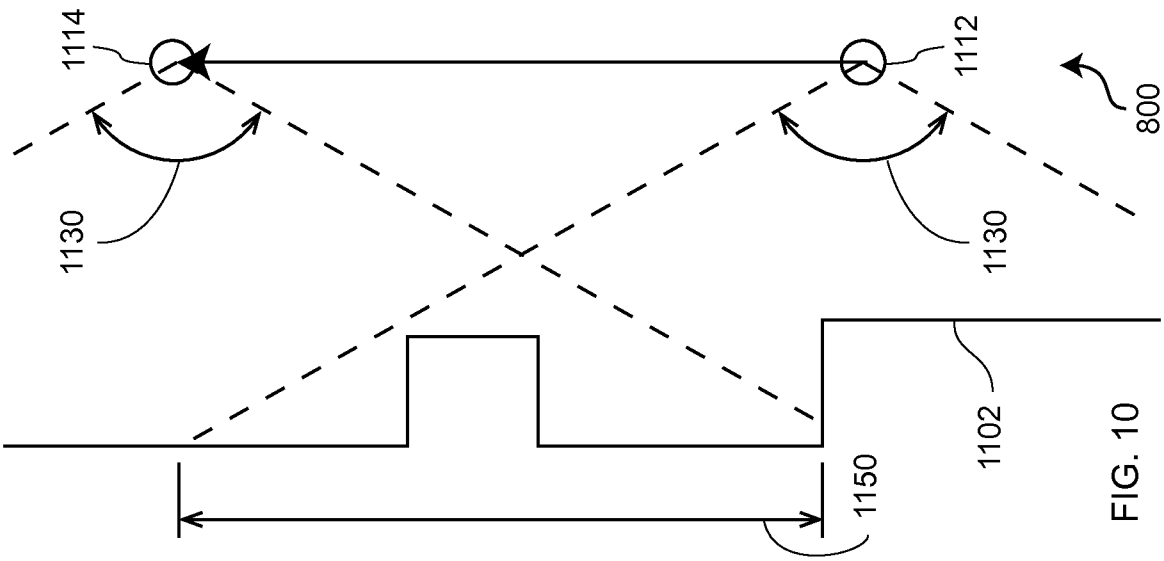

1114
1112
800
1130
1130
1102
1150

FIG. 10

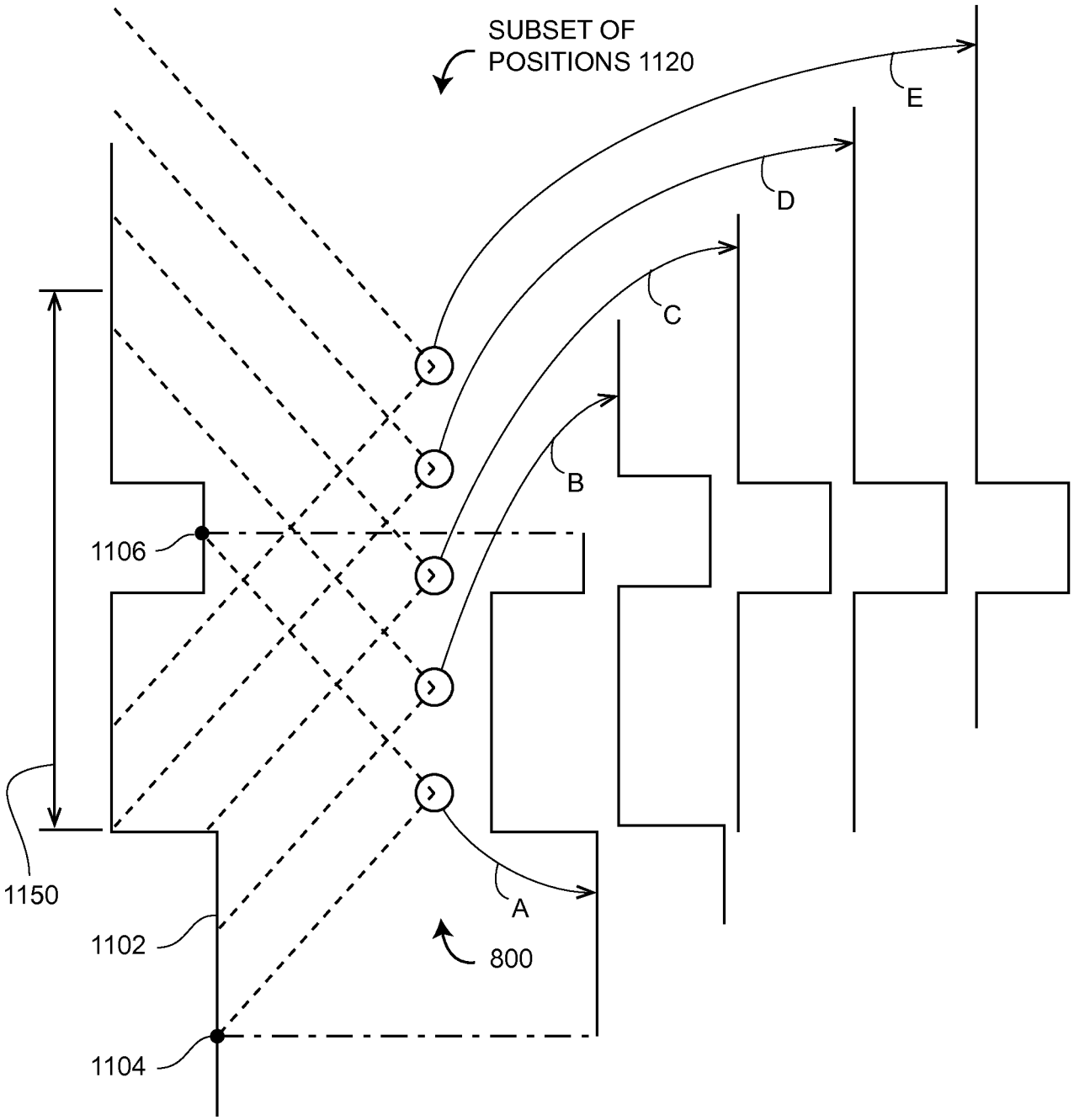


FIG. 12

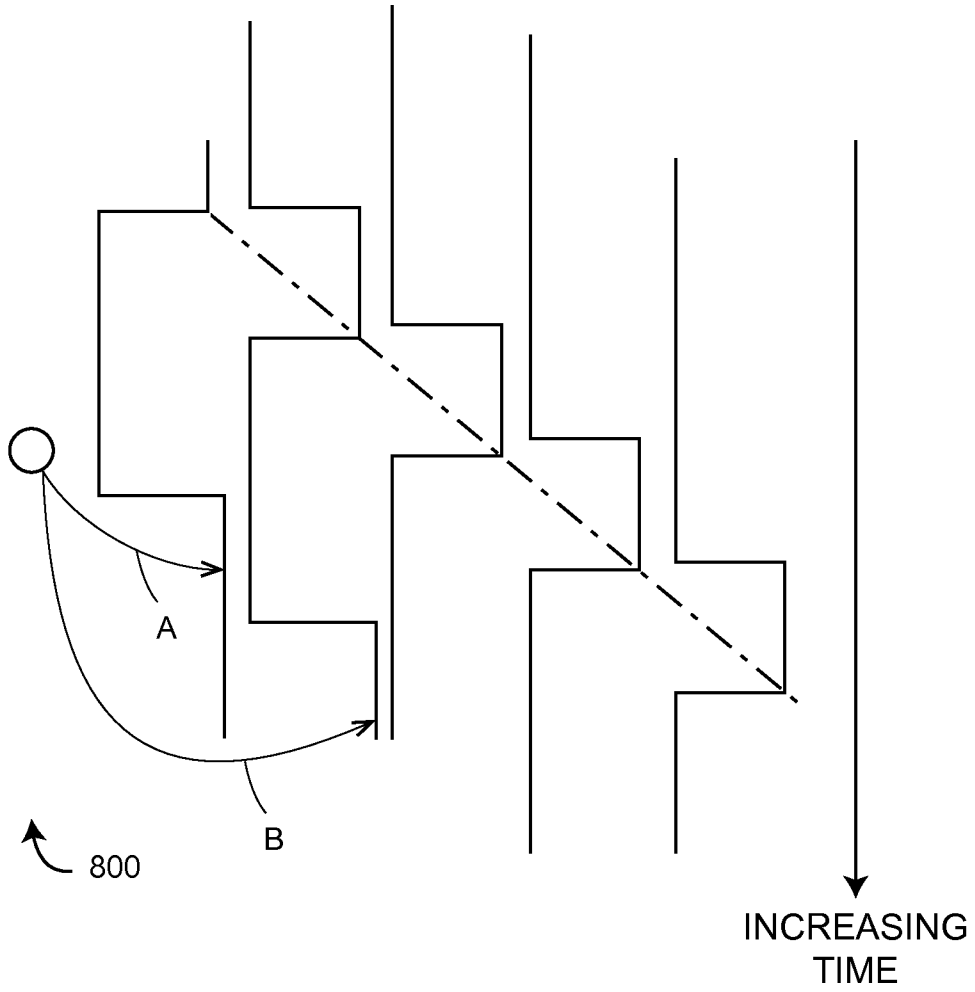


FIG. 13

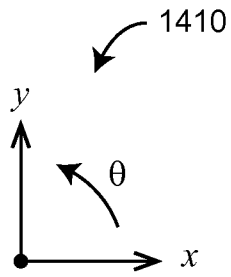
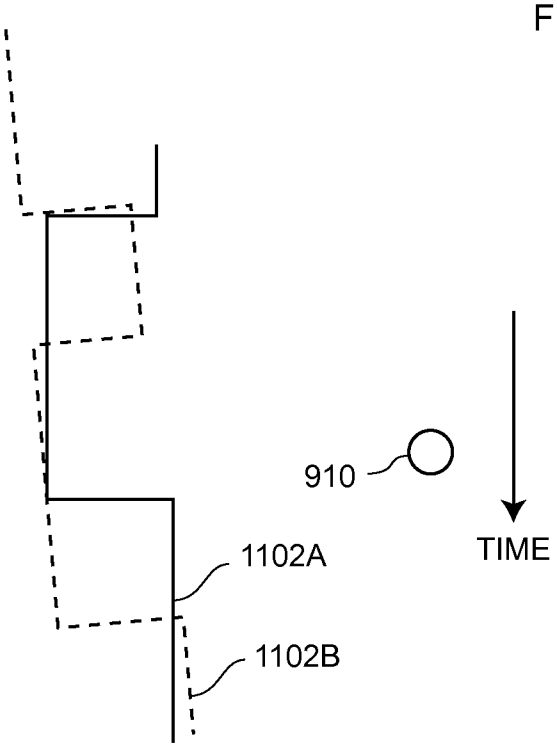
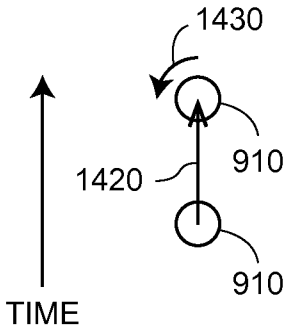


FIG. 14A



SCANNER
FRAME OF REFERENCE

FIG. 14B



OBJECT
FRAME OF REFERENCE

FIG. 14C

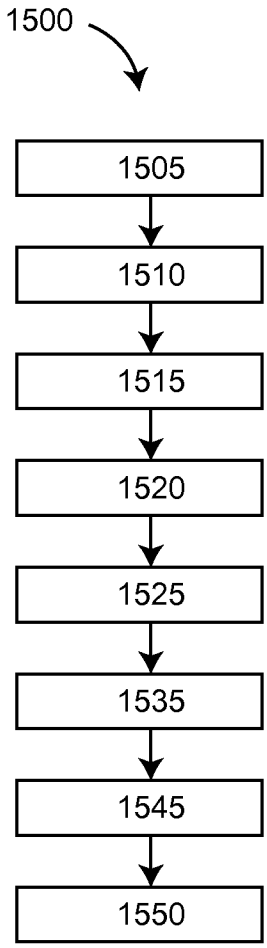


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/069184

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S17/42 G01S17/89 G01S7/48
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 G01C G06T G06K

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, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 10 2012 109481 A1 (FARO TECH INC [US]) 10 April 2014 (2014-04-10) cited in the application paragraphs [0015] - [0030]; claim 1; figures 1,3,4	1-16

Y	ANDREW J DAVISON ET AL: "MonoSLAM: Real-Time Single Camera SLAM", IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, IEEE COMPUTER SOCIETY, USA, vol. 29, no. 6, 1 June 2007 (2007-06-01), pages 1052-1067, XP011179664, ISSN: 0162-8828, DOI: 10.1109/TPAMI.2007.1049 abstract sections 1, 3	1-16

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 July 2015	14/07/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Grübl, Alexander

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Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/069184

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2009 035336 B3 (FARO TECH INC [US]) 18 November 2010 (2010-11-18) paragraphs [0002] - [0006], [0014] - [0023]; claim 1; figures 1,2,4	1-4,8-14
A	US 2009/323121 A1 (VALKENBURG ROBERT JAN [NZ] ET AL) 31 December 2009 (2009-12-31) abstract; figure 4 paragraphs [0019], [0081], [0089], [0104] - [0113]	1-16
A	WO 2014/128498 A2 (ISIS INNOVATION [GB]) 28 August 2014 (2014-08-28) pages 1-3,5-8	1-16

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/069184

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102012109481 A1	10-04-2014	DE 102012109481 A1	10-04-2014
		US 2015160342 A1	11-06-2015
		US 2015160343 A1	11-06-2015
		US 2015160347 A1	11-06-2015
		US 2015160348 A1	11-06-2015
		WO 2014068406 A2	08-05-2014
DE 102009035336 B3	18-11-2010	CN 102232197 A	02-11-2011
		DE 102009035336 B3	18-11-2010
		GB 2484646 A	18-04-2012
		JP 2012533749 A	27-12-2012
		US 2012188559 A1	26-07-2012
		WO 2011010226 A1	27-01-2011
US 2009323121 A1	31-12-2009	US 2009323121 A1	31-12-2009
		US 2014176677 A1	26-06-2014
		WO 2007030026 A1	15-03-2007
WO 2014128498 A2	28-08-2014	NONE	