



- (51) International Patent Classification:
G01B 5/008 (2006.01) *G01B 11/00* (2006.01)
- (21) International Application Number:
PCT/US2013/040321
- (22) International Filing Date:
9 May 2013 (09.05.2013)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
13/493,639 11 June 2012 (11.06.2012) US
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- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))

[Continued on next page]

(54) Title: COORDINATE MEASUREMENT MACHINES WITH REMOVABLE ACCESSORIES

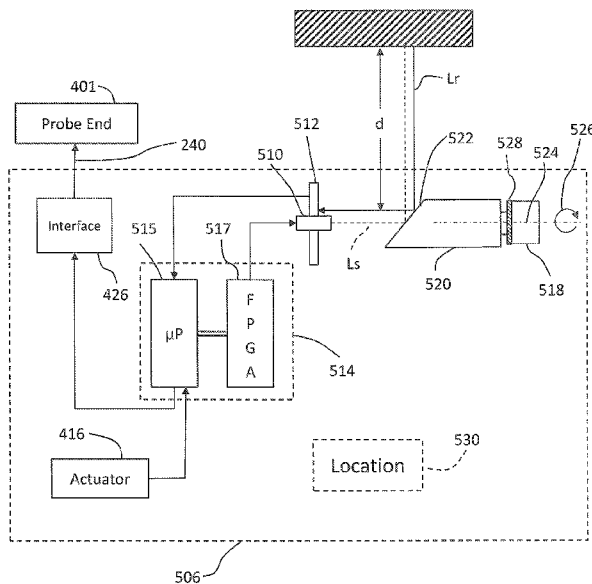


FIG. 10

(57) Abstract: A portable articulated arm coordinate measuring machine for measuring the coordinates of an object in space is provided. The AACMM includes a base and an arm portion having an opposed first end and second end. The arm portion includes a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal. An electronic circuit is provided that receives the position signal from the at least one position transducer. A probe member is disposed is coupled to the first end. A noncontact measuring device is coupled to the probe member, the device having an electromagnetic radiation transmitter and is configured to determine a distance to an object based at least in part on the propagation time of the emitted and reflected light beams.

WO 2013/188026 A1

- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))* **Published:**
— *with international search report (Art. 21(3))*

COORDINATE MEASUREMENT MACHINES WITH REMOVABLE ACCESSORIES

BACKGROUND

[0001] The present disclosure relates to a coordinate measuring machine, and more particularly to a portable articulated arm coordinate measuring machine having a connector on a probe member of the coordinate measuring machine that allows for the coupling of accessory devices which determine distance based in part on the propagation time of the emitted and reflected light beams.

[0002] Portable articulated arm coordinate measuring machines (AACMMs) have found widespread use in the manufacturing or production of parts where there is a need to rapidly and accurately verify the dimensions of the part during various stages of the manufacturing or production (e.g., machining) of the part. Portable AACMMs represent a vast improvement over known stationary or fixed, cost-intensive and relatively difficult to use measurement installations, particularly in the amount of time it takes to perform dimensional measurements of relatively complex parts. Typically, a user of a portable AACMM simply guides a probe along the surface of the part or object to be measured. The measurement data are then recorded and provided to the user. In some cases, the data are provided to the user in visual form, for example, three-dimensional (3-D) form on a computer screen. In other cases, the data are provided to the user in numeric form, for example when measuring the diameter of a hole, the text "Diameter = 1.0034" is displayed on a computer screen.

[0003] An example of a prior art portable articulated arm CMM is disclosed in commonly assigned U.S. Patent No. 5,402,582 ('582). The '582 patent discloses a 3-D measuring system comprised of a manually-operated articulated arm CMM having a support base on one end and a measurement probe at the other end. Commonly assigned U.S. Patent No. 5,611,147 ('147) discloses a similar articulated arm CMM. In the '147 patent, the articulated arm CMM includes a number of features including an additional rotational axis at the probe member, thereby providing for an arm with either a two-two-two or a two-two-three axis configuration (the latter case being a seven axis arm).

[0004] Three-dimensional surfaces may be measured using non-contact techniques as well. One type of non-contact device, sometimes referred to as a laser line probe, emits a

laser light either on a spot, or along a line. A imaging device, such as a charge-coupled device (CCD) for example, is positioned adjacent the laser to capture an image of the reflected light from the surface. The surface of the object being measured causes a diffuse reflection. The image on the sensor will change as the distance between the sensor and the surface changes. By knowing the relationship between the imaging sensor and the laser and the position of the laser image on the sensor, triangulation methods may be used to measure points on the surface.

[0005] While existing CMM's are suitable for their intended purposes, what is needed is a portable AACMM that has certain features of embodiments of the present invention.

SUMMARY OF THE INVENTION

[0006] In accordance with one embodiment of the invention, a portable articulated arm coordinate measuring machine (AACMM) for measuring three-dimensional coordinates of an object in space is provided. The AACMM includes a base. A manually positionable arm portion having an opposed first end and second end is provided that is rotationally coupled to the base. The arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal. An electronic circuit is provided which receives the position signal from the at least one position transducer. A probe member is coupled to the first end. A noncontact three-dimensional measuring device is coupled to the probe member, the noncontact three-dimensional measuring device having an electromagnetic radiation transmitter configured to send out at least one measuring beam and a receiver configured to receive at least one reflected beam. The noncontact three-dimensional measuring device having a mirror positioned to reflect both the at least one measuring beam and the at least one reflected beam. The noncontact three-dimensional measuring device further having a controller configured to determine a distance to the object based at least in part on a combined propagation time of the at least one measuring beam and the at least one reflected beams and on the speed of light in air. A processor is electrically coupled to the electronic circuit, the processor configured to determine the three-dimensional coordinates of a point on the object in response to receiving the position signals from the position transducers and in response to receiving the measured distance from the controller.

[0007] In accordance with one embodiment of the invention, a method of operating a

portable articulated arm coordinate measuring machine for measuring three-dimensional coordinates of an object in space is provided. The method includes providing a manually positionable arm portion having an opposed first end and second end, the arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal. The position signals are received at an electronic circuit from the position transducers. A three-dimensional measurement device is electrically coupled to the electronic circuit, the three-dimensional measurement device having an electromagnetic radiation transmitter, a sensor and a movable first mirror. The first mirror is moved. A measuring beam of electromagnetic radiation is reflected with the first mirror onto the object. A reflected beam of electromagnetic radiation is received with the first mirror and transferring the reflected beam of electromagnetic radiation to the sensor. A distance to the object is determined from the reflected beam of electromagnetic radiation received by the sensor and based at least in part on a combined propagation time of the measuring beam and the reflected beam and on the speed of light in air. The three-dimensional coordinates of a point on the object are determined based at least in part on the determined distance and the position signals.

[0008] In accordance with another embodiment of the invention, a portable articulated arm coordinate measuring machine (AACMM) for measuring three-dimensional coordinates of an object in space is provided. The AACMM has a base. A manually positionable arm portion having an opposed first end and second end is rotationally coupled to the base. The arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal. An electronic circuit receives the position signal from the at least one position transducer. A noncontact three-dimensional measuring device is removably coupled to the arm portion, the noncontact three-dimensional measuring device having a light source and an optical receiver and a mirror is arranged to reflect a first light beam emitted from the light source and reflect a second light beam reflected off the object. The noncontact three-dimensional measuring device is configured to determine a distance to the object based at least in part on a combined propagation time of the first light beam and the second light beam and on the speed of light in air. A processor is electrically coupled to the electronic circuit, the processor configured to determine the three-dimensional coordinates of a point on the object in response to receiving the position signals from the position transducers and in response to receiving the measured distance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Referring now to the drawings, exemplary embodiments are shown which should not be construed to be limiting regarding the entire scope of the disclosure, and wherein the elements are numbered alike in several FIGURES:

[0010] FIG. 1, including FIGs. 1A and 1B, are perspective views of a portable articulated arm coordinate measuring machine (AACMM) having embodiments of various aspects of the present invention therewithin;

[0011] FIG. 2, including FIGS. 2A – 2D taken together, is a block diagram of electronics utilized as part of the AACMM of FIG. 1 in accordance with an embodiment;

[0012] FIG. 3, including FIGs. 3A and 3B taken together, is a block diagram describing detailed features of the electronic data processing system of FIG. 2 in accordance with an embodiment;

[0013] FIG. 4 is an isometric view of the probe member of the AACMM of FIG. 1;

[0014] FIG. 5 is a side view of the probe member of FIG. 4 with the handle being coupled thereto;

[0015] FIG. 6 is a side view of the probe member of FIG. 4 with the handle attached;

[0016] FIG. 7 is an enlarged partial side view of the interface portion of the probe member of FIG. 6;

[0017] FIG. 8 is another enlarged partial side view of the interface portion of the probe member of FIG. 5;

[0018] FIG. 9 is an isometric view partially in section of the handle of FIG. 4;

[0019] FIG. 10 is a schematic view of a noncontact distance measurement device attached to the probe member of the AACMM of Figure 1;

[0020] FIG. 11 is a side view of the noncontact distance measurement device of Figure 10 in accordance with an embodiment of the invention;

[0021] FIG. 12 is an perspective view of the noncontact distance measurement device

of Figure 11;

[0022] FIG. 13 is another perspective view of the noncontact distance measurement device of Figure 11;

[0023] FIG. 14 is a schematic view of a noncontact distance measurement device having a galvo mirror arrangement in accordance with an embodiment of the invention; and,

[0024] FIG. 15 is a schematic view of a noncontact distance measurement device having a micro-electromechanical system (MEMS) mirror in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

[0025] Portable articulated arm coordinate measuring machines (“AACMM”) are used in a variety of applications to obtain measurements of objects. Embodiments of the present invention provide advantages in allowing an operator to easily and quickly couple accessory devices to a probe member of the AACMM that use projected light to provide for the non-contact measuring a three-dimensional object. Embodiments of the present invention provide further advantages in providing for communicating data representing a distance to an object measured by the accessory. Embodiments of the present invention provide still further advantages in providing power and data communications to a removable accessory without having external connections or wiring.

[0026] FIGs. 1A and 1B illustrate, in perspective, an AACMM 100 according to various embodiments of the present invention, an articulated arm being one type of coordinate measuring machine. As shown in FIGs. 1A and 1B, the exemplary AACMM 100 may comprise a six or seven axis articulated measurement device having a probe member 401 (FIG. 4) that includes a measurement probe housing 102 coupled to an arm portion 104 of the AACMM 100 at one end. The arm portion 104 comprises a first arm segment 106 coupled to a second arm segment 108 by a first grouping of bearing cartridges 110 (e.g., two bearing cartridges). A second grouping of bearing cartridges 112 (e.g., two bearing cartridges) couples the second arm segment 108 to the measurement probe housing 102. A third grouping of bearing cartridges 114 (e.g., three bearing cartridges) couples the first arm segment 106 to a base 116 located at the other end of the arm portion 104 of the AACMM 100. Each grouping of bearing cartridges 110, 112, 114 provides for multiple axes of

articulated movement. Also, the probe member 401 may include a measurement probe housing 102 that comprises the shaft of an axis of rotation for the AACMM 100 (e.g., a cartridge containing an encoder system that determines movement of the measurement device, for example a probe 118, in an axis of rotation for the AACMM 100). In this embodiment, the probe member 401 may rotate about an axis extending through the center of measurement probe housing 102. In use of the AACMM 100, the base 116 is typically affixed to a work surface.

[0027] Each bearing cartridge within each bearing cartridge grouping 110, 112, 114 typically contains an encoder system (e.g., an optical angular encoder system). The encoder system (i.e., transducer) provides an indication of the position of the respective arm segments 106, 108 and corresponding bearing cartridge groupings 110, 112, 114 that all together provide an indication of the position of the probe 118 with respect to the base 116 (and, thus, the position of the object being measured by the AACMM 100 in a certain frame of reference – for example a local or global frame of reference). The arm segments 106, 108 may be made from a suitably rigid material such as but not limited to a carbon composite material for example. A portable AACMM 100 with six or seven axes of articulated movement (i.e., degrees of freedom) provides advantages in allowing the operator to position the probe 118 in a desired location within a 360° area about the base 116 while providing an arm portion 104 that may be easily handled by the operator. However, it should be appreciated that the illustration of an arm portion 104 having two arm segments 106, 108 is for exemplary purposes, and the claimed invention should not be so limited. An AACMM 100 may have any number of arm segments coupled together by bearing cartridges (and, thus, more or less than six or seven axes of articulated movement or degrees of freedom).

[0028] The probe 118 is detachably mounted to the measurement probe housing 102, which is connected to bearing cartridge grouping 112. A handle 126 is removable with respect to the measurement probe housing 102 by way of, for example, a quick-connect interface. As will be discussed in more detail below, the handle 126 may be replaced with another device configured to provide non-contact distance measurement of an object, thereby providing advantages in allowing the operator to make both contact and non-contact measurements with the same AACMM 100. In exemplary embodiments, the probe 118 is a contacting measurement device and is removable. The probe 118 may have different tips 118 that physically contact the object to be measured, including, but not limited to: ball, touch-

sensitive, curved and extension type probes. In other embodiments, the measurement is performed, for example, by a non-contacting device such as a laser scanner device. In an embodiment, the handle 126 is replaced with the laser scanner device using the quick-connect interface. Other types of measurement devices may replace the removable handle 126 to provide additional functionality. Examples of such measurement devices include, but are not limited to, one or more illumination lights, a temperature sensor, a thermal scanner, a bar code scanner, a projector, a paint sprayer, a camera, or the like, for example.

[0029] As shown in FIGs. 1A and 1B, the AACMM 100 includes the removable handle 126 that provides advantages in allowing accessories or functionality to be changed without removing the measurement probe housing 102 from the bearing cartridge grouping 112. As discussed in more detail below with respect to FIG. 2, the removable handle 126 may also include an electrical connector that allows electrical power and data to be exchanged with the handle 126 and the corresponding electronics located in the probe member 401.

[0030] In various embodiments, each grouping of bearing cartridges 110, 112, 114 allow the arm portion 104 of the AACMM 100 to move about multiple axes of rotation. As mentioned, each bearing cartridge grouping 110, 112, 114 includes corresponding encoder systems, such as optical angular encoders for example, that are each arranged coaxially with the corresponding axis of rotation of, e.g., the arm segments 106, 108. The optical encoder system detects rotational (swivel) or transverse (hinge) movement of, e.g., each one of the arm segments 106, 108 about the corresponding axis and transmits a signal to an electronic data processing system within the AACMM 100 as described in more detail herein below. Each individual raw encoder count is sent separately to the electronic data processing system as a signal where it is further processed into measurement data. No position calculator separate from the AACMM 100 itself (e.g., a serial box) is required, as disclosed in commonly assigned U.S. Patent No. 5,402,582 ('582).

[0031] The base 116 may include an attachment device or mounting device 120. The mounting device 120 allows the AACMM 100 to be removably mounted to a desired location, such as an inspection table, a machining center, a wall or the floor for example. In one embodiment, the base 116 includes a handle portion 122 that provides a convenient location for the operator to hold the base 116 as the AACMM 100 is being moved. In one embodiment, the base 116 further includes a movable cover portion 124 that folds down to reveal a user interface, such as a display screen.

[0032] In accordance with an embodiment, the base 116 of the portable AACMM 100 contains or houses an electronic circuit having an electronic data processing system that includes two primary components: a base processing system that processes the data from the various encoder systems within the AACMM 100 as well as data representing other arm parameters to support three-dimensional (3-D) positional calculations; and a user interface processing system that includes an on-board operating system, a touch screen display, and resident application software that allows for relatively complete metrology functions to be implemented within the AACMM 100 without the need for connection to an external computer.

[0033] The electronic data processing system in the base 116 may communicate with the encoder systems, sensors, and other peripheral hardware located away from the base 116 (e.g., a noncontact distance measurement device that can be mounted to the removable handle 126 on the AACMM 100). The electronics that support these peripheral hardware devices or features may be located in each of the bearing cartridge groupings 110, 112, 114 located within the portable AACMM 100.

[0034] FIG. 2 is a block diagram of electronics utilized in an AACMM 100 in accordance with an embodiment. The embodiment shown in FIG. 2A includes an electronic data processing system 210 including a base processor board 204 for implementing the base processing system, a user interface board 202, a base power board 206 for providing power, a Bluetooth module 232, and a base tilt board 208. The user interface board 202 includes a computer processor for executing application software to perform user interface, display, and other functions described herein.

[0035] As shown in FIG. 2A, the electronic data processing system 210 is in communication with the aforementioned plurality of encoder systems via one or more arm buses 218. In the embodiment depicted in FIG. 2B and FIG. 2C, each encoder system generates encoder data and includes: an encoder arm bus interface 214, an encoder digital signal processor (DSP) 216, an encoder read head interface 234, and a temperature sensor 212. Other devices, such as strain sensors, may be attached to the arm bus 218.

[0036] Also shown in FIG. 2D are probe member electronics 230 that are in communication with the arm bus 218. The probe member electronics 230 include a probe member DSP 228, a temperature sensor 212, a handle/device interface bus 240 that connects

with the handle 126 or the noncontact distance measurement device 242 via the quick-connect interface in an embodiment, and a probe interface 226. The quick-connect interface allows access by the handle 126 to the data bus, control lines, and power bus used by the noncontact distance measurement device 242 and other accessories. In an embodiment, the probe member electronics 230 are located in the measurement probe housing 102 on the AACMM 100. In an embodiment, the handle 126 may be removed from the quick-connect interface and measurement may be performed by the noncontact distance measurement device 242 communicating with the probe member electronics 230 of the AACMM 100 via the interface bus 240. In an embodiment, the electronic data processing system 210 is located in the base 116 of the AACMM 100, the probe member electronics 230 are located in the measurement probe housing 102 of the AACMM 100, and the encoder systems are located in the bearing cartridge groupings 110, 112, 114. The probe interface 226 may connect with the probe member DSP 228 by any suitable communications protocol, including commercially-available products from Maxim Integrated Products, Inc. that embody the 1-wire® communications protocol 236.

[0037] FIG. 3A is a block diagram describing detailed features of the electronic data processing system 210 of the AACMM 100 in accordance with an embodiment. In an embodiment, the electronic data processing system 210 is located in the base 116 of the AACMM 100 and includes the base processor board 204, the user interface board 202, a base power board 206, a Bluetooth module 232, and a base tilt module 208.

[0038] In an embodiment shown in FIG. 3A, the base processor board 204 includes the various functional blocks illustrated therein. For example, a base processor function 302 is utilized to support the collection of measurement data from the AACMM 100 and receives raw arm data (e.g., encoder system data) via the arm bus 218 and a bus control module function 308. The memory function 304 stores programs and static arm configuration data. The base processor board 204 also includes an external hardware option port function 310 for communicating with any external hardware devices or accessories such as a noncontact distance measurement device 242. A real time clock (RTC) and log 306, a battery pack interface (IF) 316, and a diagnostic port 318 are also included in the functionality in an embodiment of the base processor board 204 depicted in FIG. 3.

[0039] The base processor board 204 also manages all the wired and wireless data communication with external (host computer) and internal (display processor 202) devices.

The base processor board 204 has the capability of communicating with an Ethernet network via an Ethernet function 320 (e.g., using a clock synchronization standard such as Institute of Electrical and Electronics Engineers (IEEE) 1588), with a wireless local area network (WLAN) via a LAN function 322, and with Bluetooth module 232 via a parallel to serial communications (PSC) function 314. The base processor board 204 also includes a connection to a universal serial bus (USB) device 312.

[0040] The base processor board 204 transmits and collects raw measurement data (e.g., encoder system counts, temperature readings) for processing into measurement data without the need for any preprocessing, such as disclosed in the serial box of the aforementioned '582 patent. The base processor 204 sends the processed data to the display processor 328 on the user interface board 202 via an RS485 interface (IF) 326. In an embodiment, the base processor 204 also sends the raw measurement data to an external computer.

[0041] Turning now to the user interface board 202 in FIG. 3B, the angle and positional data received by the base processor is utilized by applications executing on the display processor 328 to provide an autonomous metrology system within the AACMM 100. Applications may be executed on the display processor 328 to support functions such as, but not limited to: measurement of features, guidance and training graphics, remote diagnostics, temperature corrections, control of various operational features, connection to various networks, and display of measured objects. Along with the display processor 328 and a liquid crystal display (LCD) 338 (e.g., a touch screen LCD) user interface, the user interface board 202 includes several interface options including a secure digital (SD) card interface 330, a memory 332, a USB Host interface 334, a diagnostic port 336, a camera port 340, an audio/video interface 342, a dial-up/ cell modem 344 and a global positioning system (GPS) port 346.

[0042] The electronic data processing system 210 shown in FIG. 3A also includes a base power board 206 with an environmental recorder 362 for recording environmental data. The base power board 206 also provides power to the electronic data processing system 210 using an AC/DC converter 358 and a battery charger control 360. The base power board 206 communicates with the base processor board 204 using inter-integrated circuit (I2C) serial single ended bus 354 as well as via a DMA serial peripheral interface (DSPI) 357. The base power board 206 is connected to a tilt sensor and radio frequency identification (RFID)

module 208 via an input/output (I/O) expansion function 364 implemented in the base power board 206.

[0043] Though shown as separate components, in other embodiments all or a subset of the components may be physically located in different locations and/or functions combined in different manners than that shown in FIG. 3. For example, in one embodiment, the base processor board 204 and the user interface board 202 are combined into one physical board.

[0044] Referring now to FIGS. 4 – 9, an exemplary embodiment of a probe member 401 is illustrated having a measurement probe housing 102 with a quick-connect mechanical and electrical interface that allows removable and interchangeable device 400 to couple with AACMM 100. In the exemplary embodiment, the device 400 includes an enclosure 402 that includes a handle portion 404 that is sized and shaped to be held in an operator's hand, such as in a pistol grip for example. The enclosure 402 is a thin wall structure having a cavity 406 (FIG. 9). The cavity 406 is sized and configured to receive a controller 408. The controller 408 may be a digital circuit, having a microprocessor for example, or an analog circuit. In one embodiment, the controller 408 is in asynchronous bidirectional communication with the electronic data processing system 210 (FIGs. 2 and 3). The communication connection between the controller 408 and the electronic data processing system 210 may be wired (e.g. via controller 420) or may be a direct or indirect wireless connection (e.g. Bluetooth or IEEE 802.11) or a combination of wired and wireless connections. In the exemplary embodiment, the enclosure 402 is formed in two halves 410, 412, such as from an injection molded plastic material for example. The halves 410, 412 may be secured together by fasteners, such as screws 414 for example. In other embodiments, the enclosure halves 410, 412 may be secured together by adhesives or ultrasonic welding for example.

[0045] The handle portion 404 also includes buttons or actuators 416, 418 that may be manually activated by the operator. The actuators 416, 418 are coupled to the controller 408 that transmits a signal to a controller 420 within the probe housing 102. In the exemplary embodiments, the actuators 416, 418 perform the functions of actuators 422, 424 located on the probe housing 102 opposite the device 400. It should be appreciated that the device 400 may have additional switches, buttons or other actuators that may also be used to control the device 400, the AACMM 100 or vice versa. Also, the device 400 may include indicators, such as light emitting diodes (LEDs), sound generators, meters, displays or gauges for example. In one embodiment, the device 400 may include a digital voice recorder that allows

for synchronization of verbal comments with a measured point. In yet another embodiment, the device 400 includes a microphone that allows the operator to transmit voice activated commands to the electronic data processing system 210.

[0046] In one embodiment, the handle portion 404 may be configured to be used with either operator hand or for a particular hand (e.g. left handed or right handed). The handle portion 404 may also be configured to facilitate operators with disabilities (e.g. operators with missing fingers or operators with prosthetic arms). Further, the handle portion 404 may be removed and the probe housing 102 used by itself when clearance space is limited. As discussed above, the probe member 401 may also comprise the shaft of an axis of rotation for AACMM 100.

[0047] The probe member 401 includes a mechanical and electrical interface 426 having a first connector 429 (Fig. 8) on the device 400 that cooperates with a second connector 428 on the probe housing 102. The connectors 428, 429 may include electrical and mechanical features that allow for coupling of the device 400 to the probe housing 102. In one embodiment, the interface 426 includes a first surface 430 having a mechanical coupler 432 and an electrical connector 434 thereon. The enclosure 402 also includes a second surface 436 positioned adjacent to and offset from the first surface 430. In the exemplary embodiment, the second surface 436 is a planar surface offset a distance of approximately 0.5 inches from the first surface 430. This offset provides a clearance for the operator's fingers when tightening or loosening a fastener such as collar 438. The interface 426 provides for a relatively quick and secure electronic connection between the device 400 and the probe housing 102 without the need to align connector pins, and without the need for separate cables or connectors.

[0048] The electrical connector 434 extends from the first surface 430 and includes one or more connector pins 440 that are electrically coupled in asynchronous bidirectional communication with the electronic data processing system 210 (FIGs. 2 and 3), such as via one or more arm buses 218 for example. The bidirectional communication connection may be wired (e.g. via arm bus 218), wireless (e.g. Bluetooth or IEEE 802.11), or a combination of wired and wireless connections. In one embodiment, the electrical connector 434 is electrically coupled to the controller 420. The controller 420 may be in asynchronous bidirectional communication with the electronic data processing system 210 such as via one or more arm buses 218 for example. The electrical connector 434 is positioned to provide a

relatively quick and secure electronic connection with electrical connector 442 on probe housing 102. The electrical connectors 434, 442 connect with each other when the device 400 is attached to the probe housing 102. The electrical connectors 434, 442 may each comprise a metal encased connector housing that provides shielding from electromagnetic interference as well as protecting the connector pins and assisting with pin alignment during the process of attaching the device 400 to the probe housing 102.

[0049] The mechanical coupler 432 provides relatively rigid mechanical coupling between the device 400 and the probe housing 102 to support relatively precise applications in which the location of the device 400 on the end of the arm portion 104 of the AACMM 100 preferably does not shift or move. Any such movement may typically cause an undesirable degradation in the accuracy of the measurement result. These desired results are achieved using various structural features of the mechanical attachment configuration portion of the quick connect mechanical and electronic interface of an embodiment of the present invention.

[0050] In one embodiment, the mechanical coupler 432 includes a first projection 444 positioned on one end 448 (the leading edge or “front” of the device 400). The first projection 444 may include a keyed, notched or ramped interface that forms a lip 446 that extends from the first projection 444. The lip 446 is sized to be received in a slot 450 defined by a projection 452 extending from the probe housing 102 (FIG. 8). It should be appreciated that the first projection 444 and the slot 450 along with the collar 438 form a coupler arrangement such that when the lip 446 is positioned within the slot 450, the slot 450 may be used to restrict both the longitudinal and lateral movement of the device 400 when attached to the probe housing 102. As will be discussed in more detail below, the rotation of the collar 438 may be used to secure the lip 446 within the slot 450.

[0051] Opposite the first projection 444, the mechanical coupler 432 may include a second projection 454. The second projection 454 may have a keyed, notched-lip or ramped interface surface 456 (FIG. 5). The second projection 454 is positioned to engage a fastener associated with the probe housing 102, such as collar 438 for example. As will be discussed in more detail below, the mechanical coupler 432 includes a raised surface projecting from surface 430 that adjacent to or disposed about the electrical connector 434 which provides a pivot point for the interface 426 (FIGs. 7 and 8). This serves as the third of three points of mechanical contact between the device 400 and the probe housing 102 when the device 400

is attached thereto.

[0052] The probe housing 102 includes a collar 438 arranged co-axially on one end. The collar 438 includes a threaded portion that is movable between a first position (FIG. 5) and a second position (FIG. 7). By rotating the collar 438, the collar 438 may be used to secure or remove the device 400 without the need for external tools. Rotation of the collar 438 moves the collar 438 along a relatively coarse, square-threaded cylinder 474. The use of such relatively large size, square-thread and contoured surfaces allows for significant clamping force with minimal rotational torque. The coarse pitch of the threads of the cylinder 474 further allows the collar 438 to be tightened or loosened with minimal rotation.

[0053] To couple the device 400 to the probe housing 102, the lip 446 is inserted into the slot 450 and the device is pivoted to rotate the second projection 454 toward surface 458 as indicated by arrow 464 (FIG. 5). The collar 438 is rotated causing the collar 438 to move or translate in the direction indicated by arrow 462 into engagement with surface 456. The movement of the collar 438 against the angled surface 456 drives the mechanical coupler 432 against the raised surface 460. This assists in overcoming potential issues with distortion of the interface or foreign objects on the surface of the interface that could interfere with the rigid seating of the device 400 to the probe housing 102. The application of force by the collar 438 on the second projection 454 causes the mechanical coupler 432 to move forward pressing the lip 446 into a seat on the probe housing 102. As the collar 438 continues to be tightened, the second projection 454 is pressed upward toward the probe housing 102 applying pressure on a pivot point. This provides a see-saw type arrangement, applying pressure to the second projection 454, the lip 446 and the center pivot point to reduce or eliminate shifting or rocking of the device 400. The pivot point presses directly against the bottom on the probe housing 102 while the lip 446 is applies a downward force on the end of probe housing 102. FIG. 5 includes arrows 462, 464 to show the direction of movement of the device 400 and the collar 438. FIG. 7 includes arrows 466, 468, 470 to show the direction of applied pressure within the interface 426 when the collar 438 is tightened. It should be appreciated that the offset distance of the surface 436 of device 400 provides a gap 472 between the collar 438 and the surface 436 (FIG. 6). The gap 472 allows the operator to obtain a firmer grip on the collar 438 while reducing the risk of pinching fingers as the collar 438 is rotated. In one embodiment, the probe housing 102 is of sufficient stiffness to reduce or prevent the distortion when the collar 438 is tightened.

[0054] Embodiments of the interface 426 allow for the proper alignment of the mechanical coupler 432 and electrical connector 434 and also protect the electronics interface from applied stresses that may otherwise arise due to the clamping action of the collar 438, the lip 446 and the surface 456. This provides advantages in reducing or eliminating stress damage to circuit board 476 mounted electrical connectors 434, 442 that may have soldered terminals. Also, embodiments provide advantages over known approaches in that no tools are required for a user to connect or disconnect the device 400 from the probe housing 102. This allows the operator to manually connect and disconnect the device 400 from the probe housing 102 with relative ease.

[0055] Due to the relatively large number of shielded electrical connections possible with the interface 426, a relatively large number of functions may be shared between the AACMM 100 and the device 400. For example, switches, buttons or other actuators located on the AACMM 100 may be used to control the device 400 or vice versa. Further, commands and data may be transmitted from electronic data processing system 210 to the device 400. In one embodiment, the device 400 is a video camera that transmits data of a recorded image to be stored in memory on the base processor 204 or displayed on the display 328. In another embodiment the device 400 is an image projector that receives data from the electronic data processing system 210. In addition, temperature sensors located in either the AACMM 100 or the device 400 may be shared by the other. It should be appreciated that embodiments of the present invention provide advantages in providing a flexible interface that allows a wide variety of accessory devices 400 to be quickly, easily and reliably coupled to the AACMM 100. Further, the capability of sharing functions between the AACMM 100 and the device 400 may allow a reduction in size, power consumption and complexity of the AACMM 100 by eliminating duplicity.

[0056] In one embodiment, the controller 408 may alter the operation or functionality of the probe member 401 of the AACMM 100. For example, the controller 408 may alter indicator lights on the probe housing 102 to either emit a different color light, a different intensity of light, or turn on/off at different times when the device 400 is attached versus when the probe housing 102 is used by itself. In one embodiment, the device 400 includes a range finding sensor (not shown) that measures the distance to an object. In this embodiment, the controller 408 may change indicator lights on the probe housing 102 in order to provide an indication to the operator how far away the object is from the probe tip

118. In another embodiment, the controller 408 may change the color of the indicator lights based on the quality of the image acquired by a laser scanner device. This provides advantages in simplifying the requirements of controller 420 and allows for upgraded or increased functionality through the addition of accessory devices.

[0057] The FIGs. 10 – 15 refer to distance measuring devices operably coupled to an articulated arm CMM, wherein the distance to a point on an object 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. 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, $c_{\text{air}} = c / n$. A distance measuring device of the sort discussed herein is based on the time-of-flight 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). A method of measuring distance based on the time-of-flight of light (or any type of electromagnetic radiation) 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 using one known side length and two known angles of a triangle. The method of triangulation, therefore, does not directly depend on the speed of light in air.

[0058] Referring to FIGS. 10 – 13, a device 500 is shown that allows for non-contact three-dimensional measurement of an object using a laser scanner. In one embodiment, the device 500 is removably coupled to the probe member 401 via coupler mechanism and interface 426. The device 500 may be configured to operate independently from the probe member 401. In another embodiment, the device 500 is integrally connected to the probe member 401.

[0059] The device 500 includes a body 502 having a handle 504 that allows the operator to hold and manipulate the orientation of the device 500. The interface 426 is arranged adjacent the handle 504 for mechanical and electrical coupling of the device 500 to the AACMM 100. Extending from one side is a scanning head 506. The scanning head 506

has a first housing portion 508 for a light transmitter 510, an optical receiver 512 and controller 514. The light transmitter 510 is a light source suitable electromagnetic radiation emitter such as a coherent laser light for example. The laser light may have a wavelength in the visible or non-visible spectrum. In one embodiment, the device 500 is a laser detection and ranging device (LIDAR). The controller 514 is in asynchronous bidirectional communication with the electronic data processing system 210. In one embodiment, the controller 514 includes an evaluation and control unit 515 and a field programmable gate array (FPGA) 517. The evaluation and control unit 515 is a computer processor based controlling unit which is in bidirectional communication with the FPGA 517. The FPGA 517 drives the light transmitter 510 in such a manner that it generates a modulated measuring beam L_s . The beam L_s is reflected off of the mirror 522 towards the object. The evaluation and control unit 515 receives a signal from the receiver 512 for determining the distance "d" and the light intensity of the reflected light beam L_r . In the exemplary embodiment, the distance is determined using the propagation time of the emitted light in making a round trip to the target and back. In other words, the distance is determined based on the combined propagation time of a measuring beam L_s and a reflected beam L_r . In FIG. 10, the outgoing light L_s is shown as a single dotted line. The outgoing light is a collimated beam of light, which means that the rays of light traveling outward toward the object under test are approximately parallel. The target may be a cooperative or non-cooperative target. A cooperative target is a target designed to return a large fraction of the light that strikes it. A common example of a cooperative target is a retroreflective target such as a cube-corner retroreflector having an apex centered in a metallic sphere. A non-cooperative target is one not specially designed to return a large portion of the beam power. An example of a non-cooperative target is a surface of an object under test, for example, a metallic or plastic surface. In the case of a non-cooperative target that scatters light, for example, the light returns in a relatively wide angular spread and usually fills up the mirror 522. This expanding aspect of the beam L_r is not shown in FIG. 10 but is shown in FIG. 14 as discussed herein below. For the example shown in FIG. 10, the light is shown emitted from a central light source 510 and returning through an outer portion of an optical receiver 512. The outer portion of optical receiver 512 might for example be the outer portion of a lens. In the case of a cooperative target such as a retroreflector, the light returned is collimated.

[0060] Adjacent the first housing portion 508 is a second housing portion 516 for a drive 518, and a rotor 520. A mirror 522 is disposed on an end of the rotor 520 opposite the

light transmitter 510 within a gap 527 defined by the first housing 508 and the second housing 516. In the exemplary embodiment, the mirror 522 is arranged on a 45 degree angle with respect to the light transmitter 510 and the receiver 512. The drive 518 is arranged to rotate the rotor 520 about an axis 524 as indicated by the arrow 526. In one embodiment, the axis 524 is parallel or collinear with the measurement beam emitted from the light transmitter 510. In one embodiment, a pair of angled surfaces 523, 525 are arranged on one side of the gap 527 to allow a wider field of view for the scanner.

[0061] In operation, the device 500 activates the light transmitter 510 in response to an action by the operator, such as by depressing actuator 416 for example. The measuring beam L_s exits the first housing 508 via an opening 509 and is reflected by the mirror 522. Since the drive 518 is rotating the mirror 522, the measuring beam L_s is emitted in a “fan” shape such that the measuring beam L_s can illuminate virtually all object points in approximately a planar region in a single rotation of the mirror. By rotating the mirror as the operators moves the device 500, a wide region of space may be measured by the device. In order to correlate the distance and intensity information with the individual measuring points, the drive 518 is provided with an angular transducer such as an angular encoder 528. From the distance and encoder data, the controller 514 can determine the coordinate data for each measured point. It should be appreciated that since the device 500 is coupled to the probe member 401 of the AACMM 100, the electronic data processing system 210 can determine the location and orientation of the device 500 from the encoder 214 data. In one embodiment, the controller 514 transmits the coordinate and intensity data to the probe member 401 via bus 240, which transmits the coordinate and intensity data to the electronic data processing system 210. In one embodiment, the electronic data processing system may determine the X, Y, Z coordinate data (relative to the AACMM 100) for each measured object point by combining the arm encoder data with the distance data.

[0062] In one embodiment, the device 500 may be operated independently from the probe member 401. In this embodiment, the device 500 may further include one or more location devices 530. The location device 530 may include one or more inertial navigation sensors, such as a gyroscopic sensor, a global positioning system (GPS) sensor, compass sensors, or accelerometers for example. Such sensors may be electrically coupled to the controller 514. Gyroscopic and accelerometer sensors may be single-axis or multiple-axis devices. The location device 530 is configured to allow the controller 514 to measure or

maintain the orientation of the device when detached from the AACMM 100. A gyroscope within the location device 530 may be a MEMS gyroscopic device, a solid-state ring-laser device, a fiber-optic device or other type of inertial device.

[0063] When the device 500 is removed from the AACMM 100, a method is needed to combine images obtained from multiple scans. One way to combine multiple images captured by the device 704 is to ensure that there is at least some overlap between adjacent images so that point cloud features may be matched. This matching function may be assisted by the inertial navigation devices described above.

[0064] Another method that can be used to assist in accurate registration of images collected by the device 500 is the use of reference markers. In an embodiment, the reference markers are small sticky markers having an adhesive or sticky backing, for example, circular markers that are placed on an object or objects being measured. Even a relatively small number of such markers can be useful in registering multiple images, especially if the object being measured has a relatively small number of features to use for registration. In an embodiment, the reference markers may be projected as spots of light onto the object or objects under inspection. For example, a small portable projector capable of emitting a plurality of small dots may be placed in front of the object or objects to be measured. An advantage of projected dots over sticky dots is that the dots do not have to be attached and later removed.

[0065] In one embodiment, when the device 500 is removed from the AACMM 100, the controller 514 includes a memory device (not shown) for storing data during operation. This stored data is then transmitted to the electronic data processing system 210 when the device 500 is once again coupled to the probe member 401. In another embodiment, the device includes a communication device that allows the device 500 to transmit the distance and intensity data wirelessly to the AACMM 100 or another computing device.

[0066] Another embodiment of the noncontact measuring device 500 is shown in FIG. 14. In this embodiment, the mirror 522 is replaced by a galvanometer mirror system 532. A galvanometer, commonly referred to as a galvo 534A, 534B, is a device that moves in response to an electrical current. By arranging a first galvo 534A orthogonally to a second galvo 534B, the galvos 534A, 534B can move mirrors 536A, 536B about two axes 538, 540, respectively. In one embodiment, the axes 538, 540 are mutually orthogonal and the mirrors

536A, 536B are mutually orthogonal. As a result, the measuring beam Ls may be directed to illuminate points over an area 541 on the object rather than in a radial fanned line. In one embodiment, the galvos 534A, 534B are electrically coupled to the controller 514. In an embodiment, in order to correlate the distance and intensity information with the individual measuring points, each galvo includes an angle transducer, such as an angular encoder 542, to measure the position of the associated galvo 534. In another embodiment, the angle is determined based on the current applied to each galvo. Although the target 541 may be a cooperative or non-cooperative type of target, FIG. 14 illustrates the beam spreading that occurs for the case in which the target is a non-cooperative target having a target spot 541 that scatters the light. Such scattering would occur for example in a diffusely scattering surface. In this case, the light spreads on the return path and enters an outer portion of the receiver 512.

[0067] In one embodiment, the controller 514 determines the distance to an object point and correlates this with the encoder 542 data to determine the three-dimensional coordinate data (for example, X, Y, Z) from the device 500. This coordinate data is transmitted, along with the intensity data to the probe member 401 via bus 240. In one embodiment, the electronic data processing system may determine the X, Y, Z coordinate data (relative to the AACMM 100) for each measured object point by combining the arm encoder data with the distance data and the angle data from the galvos.

[0068] In an embodiment, a single galvo 534A is used without galvo 534B so that the beam of light is moved along a single dimension rather than along two dimensions. In this case, the movement of the noncontact measuring device 500 by the operator to obtain three-dimensional coordinates along both dimensions.

[0069] As discussed above, the device 500 may include a location device 530, such as an inertial navigation device for example, to allow the acquisition of coordinate data with the device 500 detached and operating independently from the probe member 401.

[0070] Another embodiment of the non-contact measuring device 500 is shown in Figure 15. In this embodiment, the mirror is a micro electro-mechanical system (MEMS) device 544. In an embodiment, the MEMS device 544 includes a mirror 546 mounted to a semi-conductor device 548. In one embodiment the MEMS system 544 is a Mirrorcle Technologies, Inc. dual-axis scanning mirror mounted on a 24 pin chip. A MEMS system

544 uses a large voltage potential across capacitive plates to move the mirror 546 about two orthogonal axes 550, 552. In the exemplary embodiment, the MEMS system can rotate the mirror 546 at scanning angles of -10° to $+10^{\circ}$ for each axis. Similar to the galvo mirror system discussed above, the MEMS system 544 allows the illuminations of measured points over an area 541 rather than a line.

[0071] In the exemplary embodiment, the orientation of the mirror 546 is directly proportional to the voltage applied. This provides advantages in that the encoder may be eliminated since the controller 514 may correlate the distance and intensity data to the angle of the mirror 546 based on the applied voltage to determine the coordinate data (X, Y, Z) of the measured object points. This coordinate data is transmitted, along with the intensity data to the probe member 401 via bus 240. In one embodiment, the electronic data processing system may determine the X, Y, Z coordinate data (relative to the AACMM 100) for each measured object point by combining the arm encoder data with the distance and intensity data.

[0072] In another embodiment, the MEMS device 546 includes an array of small mirror elements that can be rotated to a desired direction.

[0073] As discussed above, the device 500 may include a location device 530, such as an inertial navigation device for example, to allow the acquisition of coordinate data with the device 500 detached and operating independently from the probe member 401.

[0074] It should be appreciated that while embodiments herein illustrate the device 500 as emitting the measuring beam perpendicular to the longitudinal axis of the device 500, this is for exemplary purposes and the claimed invention should not be so limited. In other embodiments, the measuring beam is emitted from an end of the device 500 (e.g. parallel to the length of the device 500). In still other embodiments, the measuring beam is emitted on an angle relative to the longitudinal axis of the device 500.

[0075] While the invention has been described with reference to example embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular

embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims. Moreover, the use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another. Furthermore, the use of the terms a, an, etc. do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item.

CLAIMS

What is claimed is:

1. A portable articulated arm coordinate measuring machine (AACMM) for measuring three-dimensional coordinates of an object in space, comprising:
 - a base;
 - a manually positionable arm portion having an opposed first end and second end, the arm portion being rotationally coupled to the base, the arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal;
 - an electronic circuit which receives the position signal from the at least one position transducer;
 - a probe member coupled to the first end;
 - a noncontact measuring device coupled to the probe member, the noncontact measuring device having an electromagnetic radiation transmitter configured to send out at least one measuring beam and a receiver configured to receive at least one reflected beam, the noncontact measuring device having a mirror positioned to reflect both the at least one measuring beam and the at least one reflected beam, the noncontact three-dimensional measuring device further having a controller configured to determine a distance to the object based at least in part on a combined propagation time of the at least one measuring beam and the at least one reflected beams and on a speed of light in air; and
 - a processor electrically coupled to the electronic circuit, the processor configured to determine a set of three-dimensional coordinates of a point on the object in response to receiving the position signals from the position transducers and in response to receiving the measured distance from the controller.
2. The AACMM of claim 1 wherein the noncontact three-dimensional measuring device is configured to:
 - send out a plurality of measuring beams over a period of time;
 - receive a plurality of reflected beams over the period of time; and,
 - determine a plurality of sets of three-dimensional coordinates in response to sending the plurality of measuring beams and receiving the plurality of reflected beams.
3. The AACMM of claim 1 wherein the mirror is movable about an axis.

4. The AACMM of claim 3 wherein the noncontact measuring device further includes a rotor coupled to the mirror and a driver, the driver being configured to rotate the rotor about the axis.
5. The AACMM of claim 3 wherein the mirror is a galvanometer mirror.
6. The AACMM of claim 5 wherein the galvanometer mirror includes a first galvo device and a second galvo device, the first galvo device and the second galvo device being in an orthogonal arrangement to move the mirror about two axes.
7. The AACMM of claim 3 wherein the mirror is a micro-electromechanical system (MEMS) mirror.
8. The AACMM of claim 1 wherein the MEMS mirror is configured to move about two orthogonal axes.
9. The AACMM of claim 1 wherein the electromagnetic radiation transmitter is a laser.
10. The AACMM of claim 1 further comprising a contact measurement device coupled to the probe member.
11. The AACMM of claim 10 wherein the processor is located within the noncontact measuring device.
12. The AACMM of claim 1 wherein the noncontact measurement device is removably coupled to the probe member.
13. A method of operating a portable articulated arm coordinate measuring machine for measuring three-dimensional coordinates of an object in space, comprising:
 - providing a manually positionable arm portion having an opposed first end and second end, the arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal;
 - receiving at an electronic circuit the position signals from the position transducers;

providing a noncontact device electrically coupled to the electronic circuit, the noncontact measurement device having an electromagnetic radiation transmitter, a sensor and a movable first mirror;

moving the first mirror;

reflecting a measuring beam of electromagnetic radiation with the first mirror onto the object;

receiving a reflected beam of electromagnetic radiation with the first mirror and transferring the reflected beam of electromagnetic radiation to the sensor;

determining a distance to the object from the reflected beam of electromagnetic radiation received by the sensor and based at least in part on a combined propagation time of the measuring beam and the reflected beam and on a speed of light in air; and

determining three-dimensional coordinates of a point on the object based at least in part on the determined distance and the position signals.

14. The method of claim 13 wherein the step of moving the first mirror includes rotating the first mirror about a first axis.

15. The method of claim 14 further including the step of moving the first mirror about a second axis.

16. The method of claim 14 further including steps of:
providing a movable second mirror;
rotating the second mirror about a second axis;
reflecting the measuring beam of electromagnetic radiation with the second mirror onto the first mirror; and
receiving the reflected beam with the first mirror and sending it to the second mirror.
17. The method of claim 14 further comprising rotating the first mirror with a galvo device.
18. The method of claim 13 wherein the mirror is a MEMS mirror.
19. The method of claim 13 further including steps of:
providing a contact measurement device coupled to the first end; and
measuring three-dimensional coordinates of a second point on the object with the contact measurement device.
20. The method of claim 13 wherein, in the step of providing an electromagnetic radiation transmitter, the electromagnetic radiation transmitter is a laser device.
21. The method of claim 13 further comprising decoupling the noncontact measurement device from the manually positionable arm portion prior to reflecting a measuring beam.
22. A portable articulated arm coordinate measuring machine (AACMM) for measuring three-dimensional coordinates of an object in space, comprising:
a base;
a manually positionable arm portion having an opposed first end and second end, the arm portion being rotationally coupled to the base, the arm portion including a plurality of connected arm segments, each arm segment including at least one position transducer for producing a position signal;
an electronic circuit which receives the position signal from the at least one position transducer;
a noncontact measuring device removably coupled to the arm portion, the noncontact measuring device having a light source and an optical receiver and a mirror is arranged to

reflect a first light beam emitted from the light source and reflect a second light beam reflected off the object, the noncontact measuring device is configured to determine a distance to the object based at least in part on a combined propagation time of the first light beam and the second light beam and on a speed of light in air; and

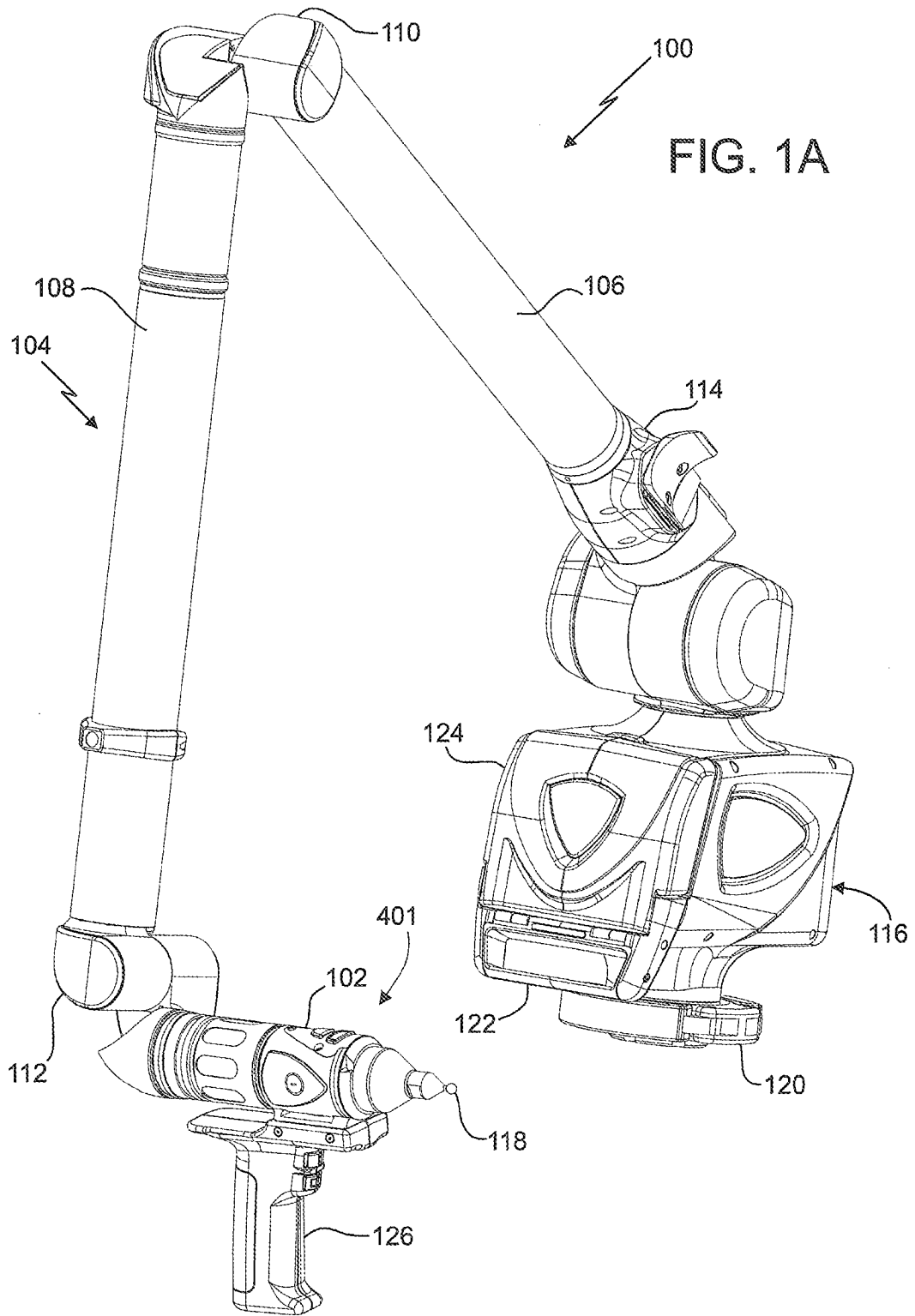
a processor electrically coupled to the electronic circuit, the processor configured to determine the three-dimensional coordinates of a point on the object in response to receiving the position signals from the position transducers and in response to receiving the measured distance.

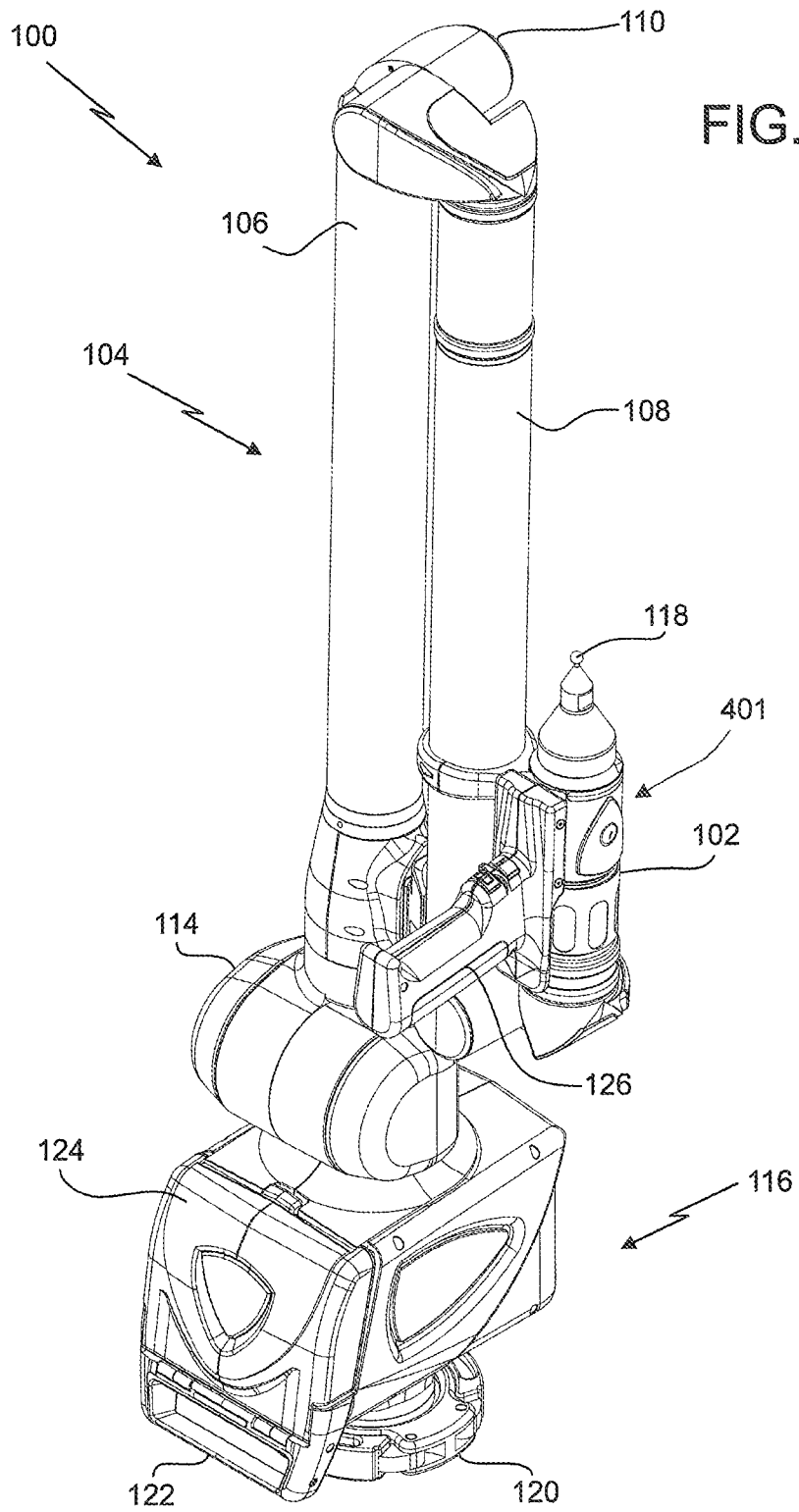
23. The AACMM of claim 22 wherein the mirror is disposed on a 45 degree angle relative to the light source and rotates about an axis substantially collinear with the first light beam.

24. The AACMM of claim 22 wherein the mirror rotates about two orthogonal axes.

25. The AACMM of claim 22 wherein the mirror is a galvanometer mirror.

26. The AACMM of claim 22 wherein the mirror is a MEMS mirror.





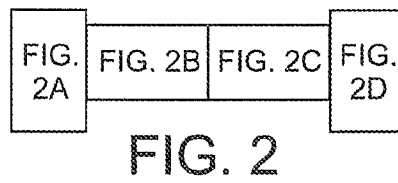


FIG. 2A

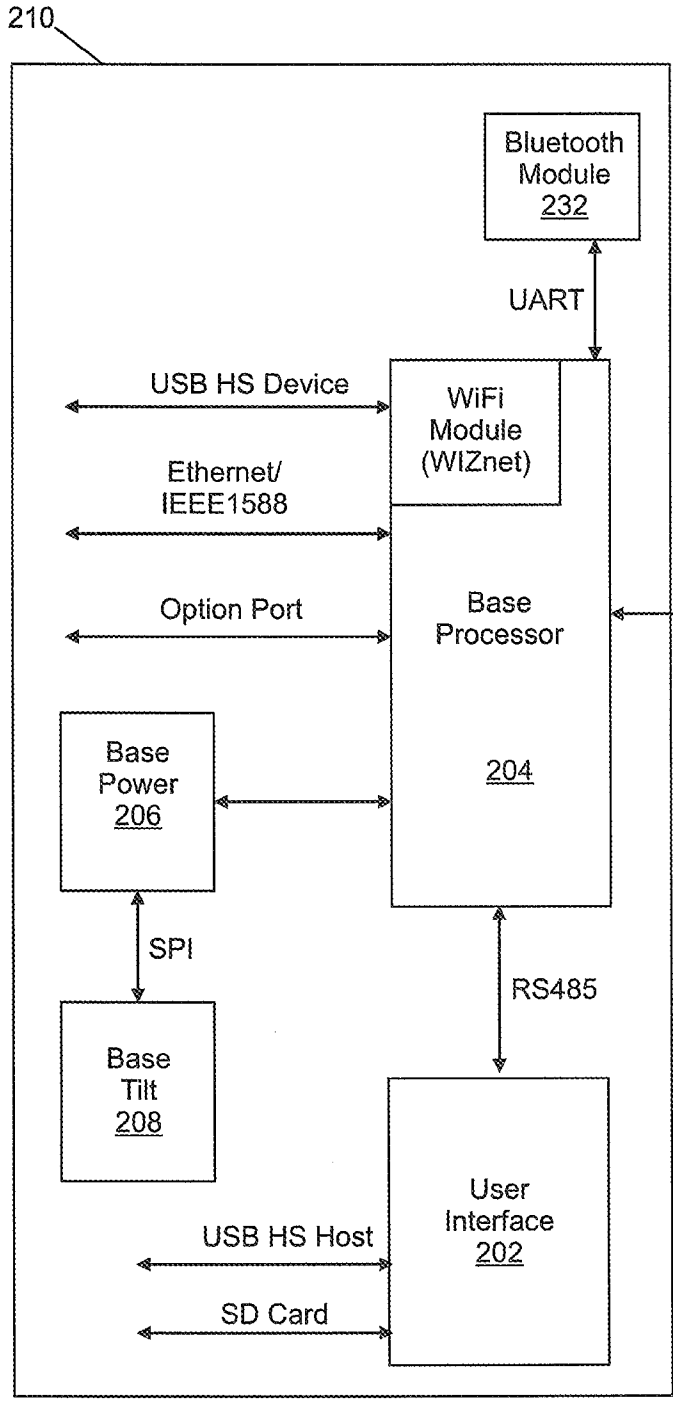


FIG. 2B

FIG. 2B

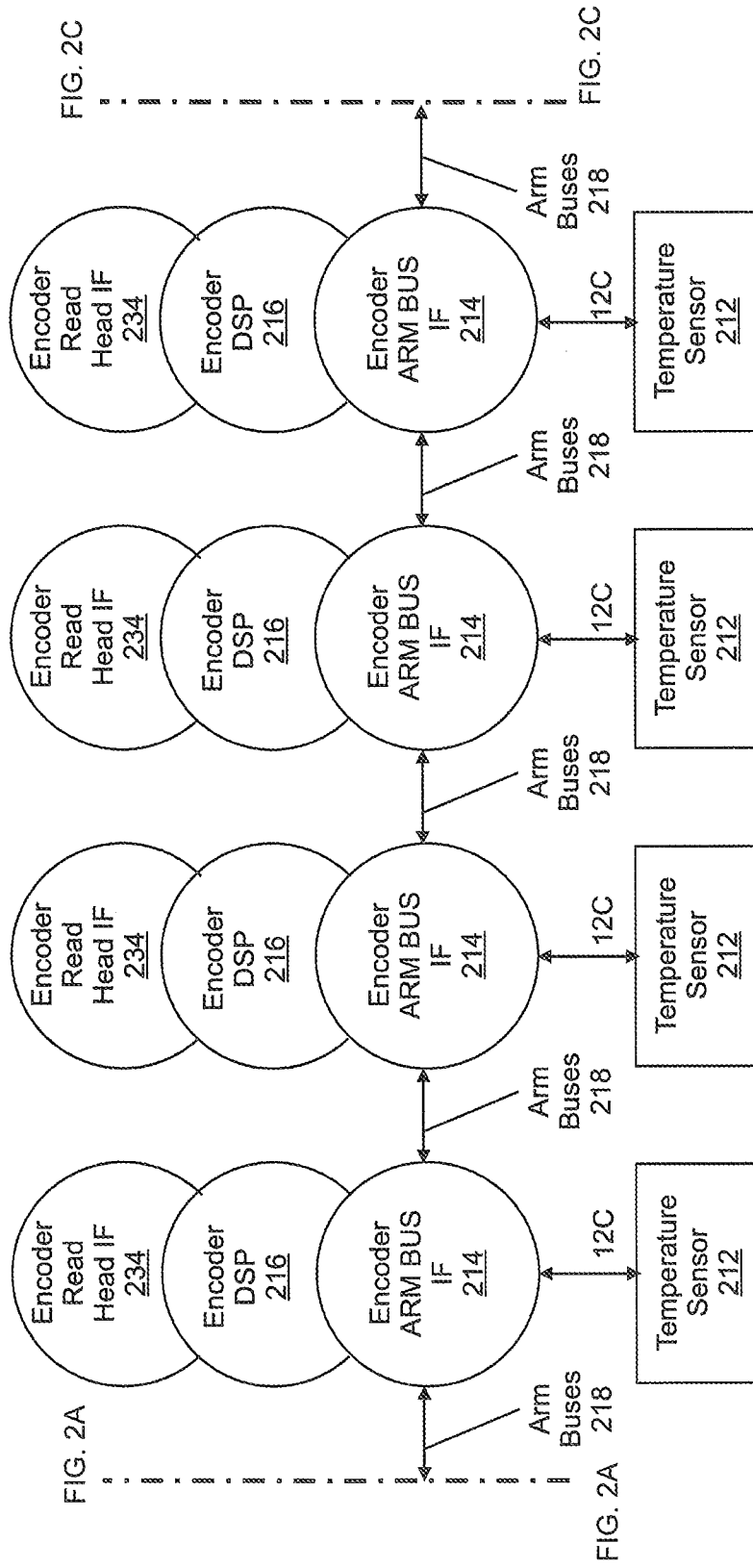


FIG. 2B

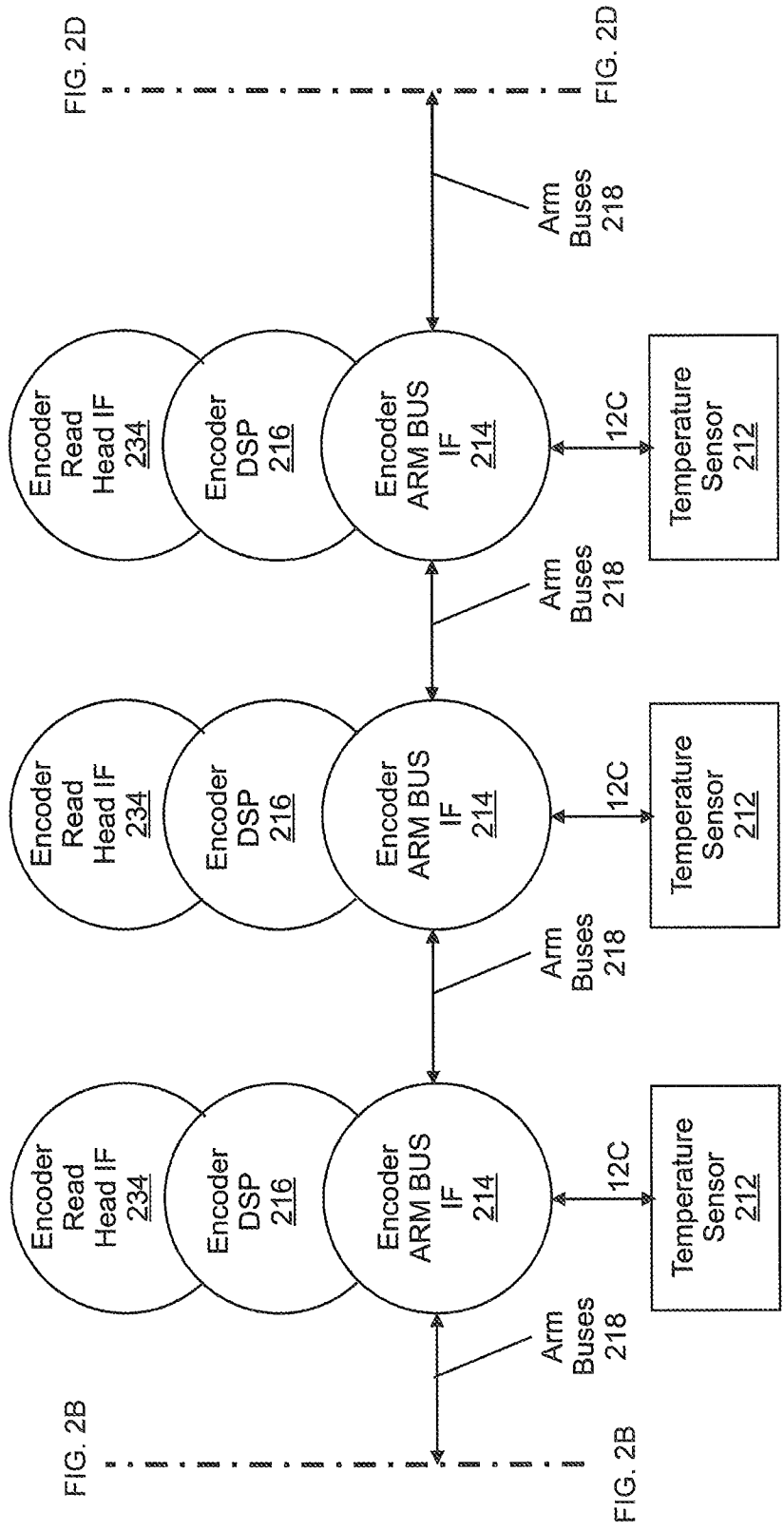
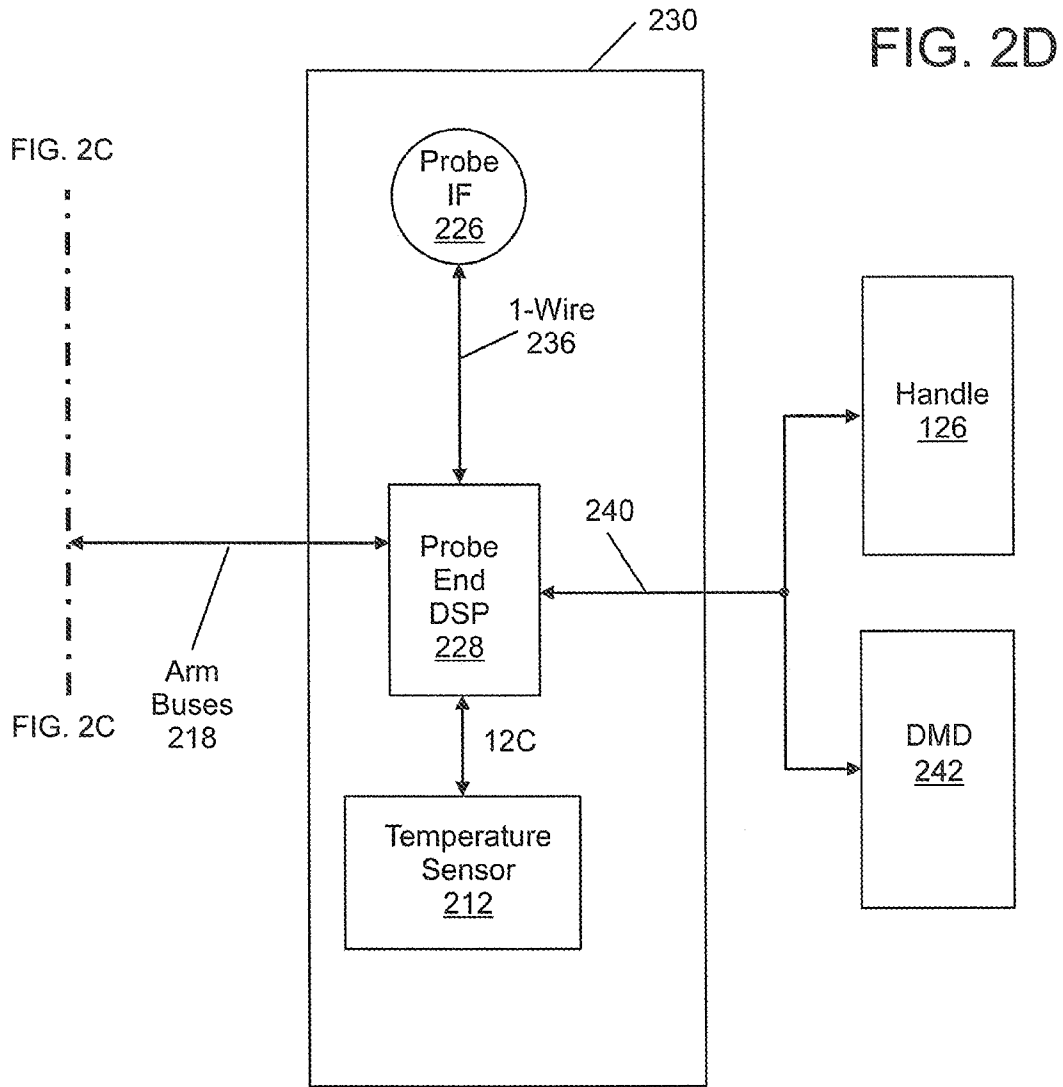
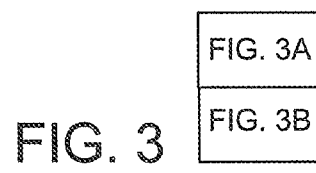


FIG. 2C





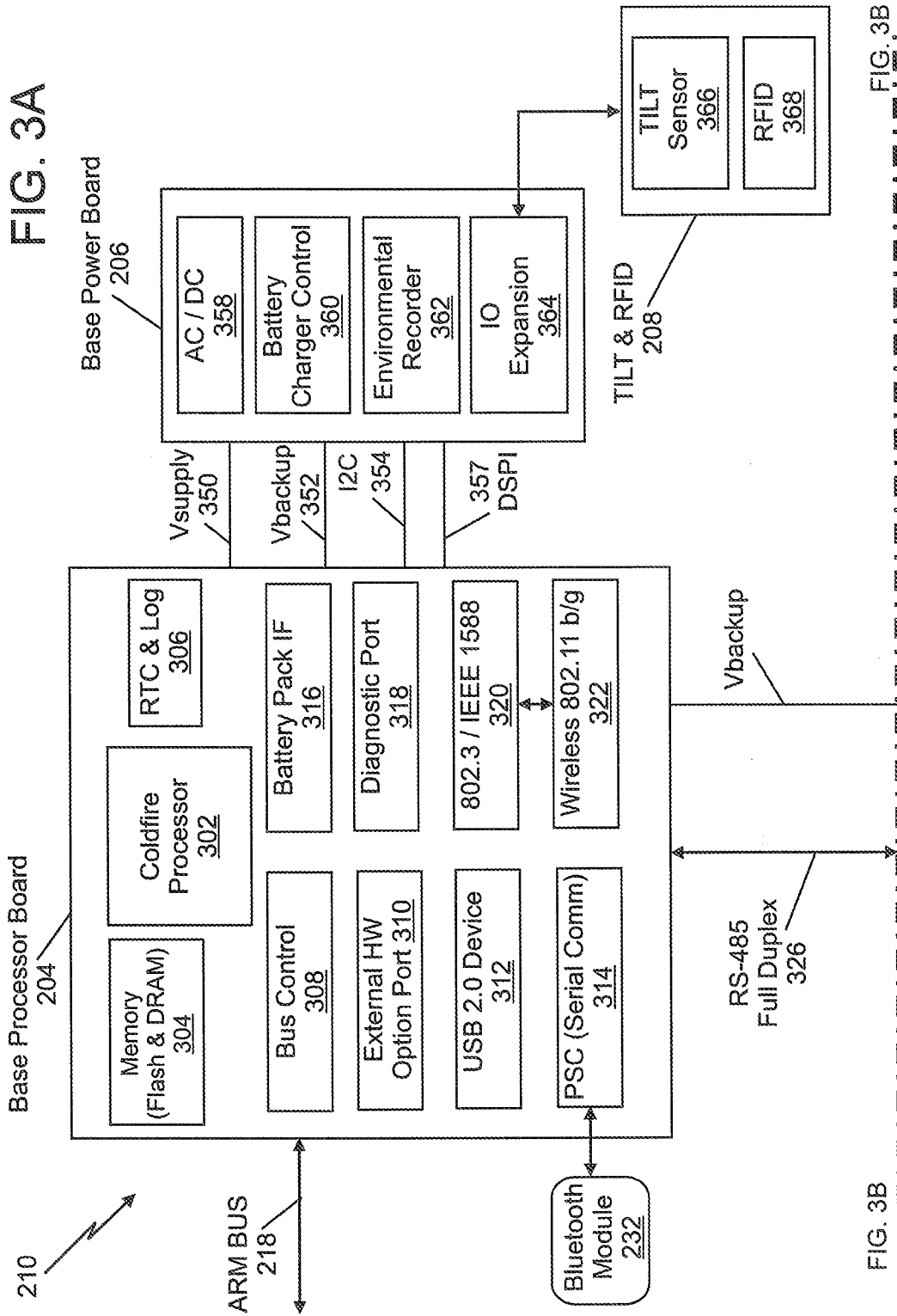


FIG. 3A

FIG. 3B

FIG. 3A



FIG. 3B

FIG. 4

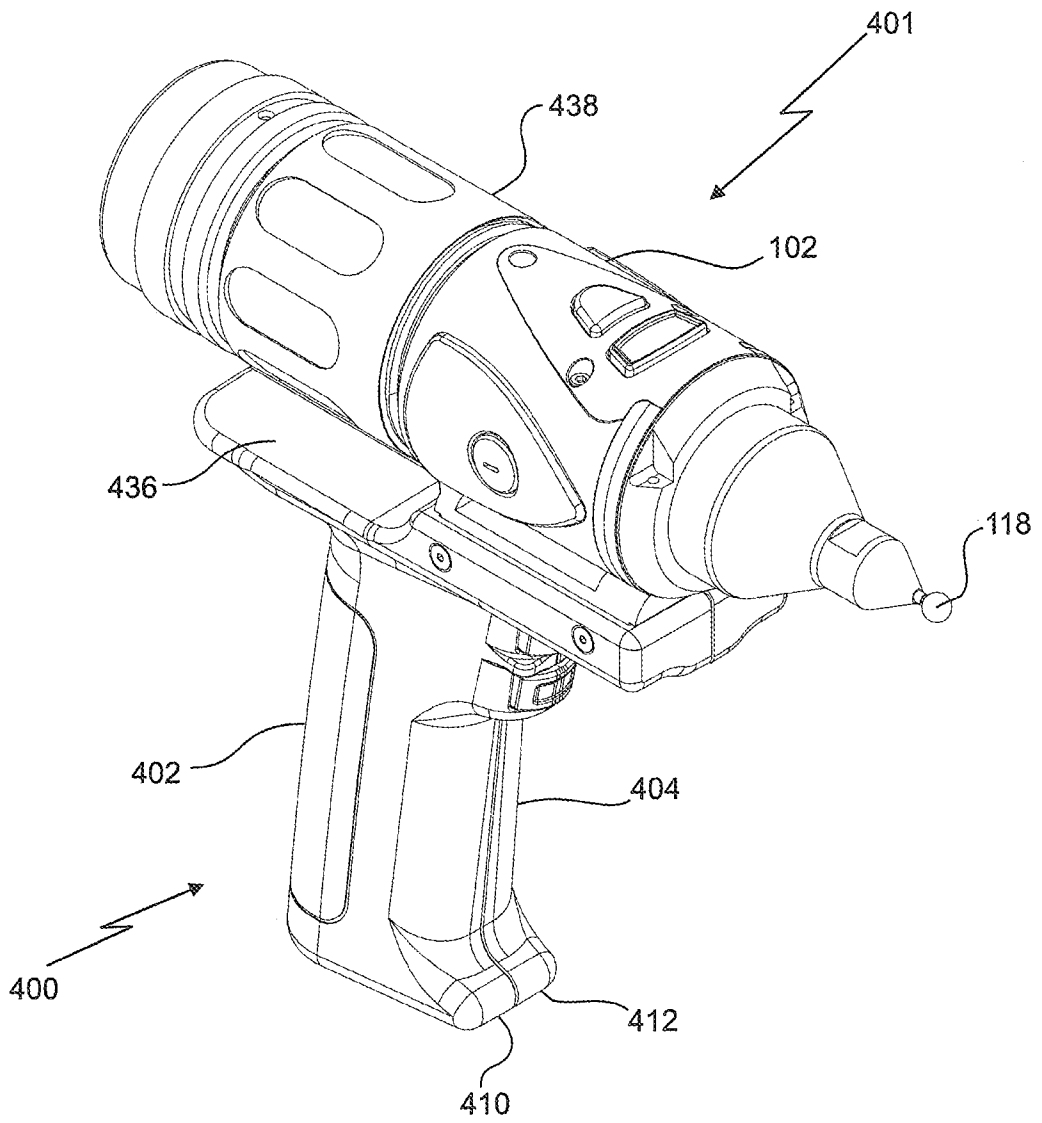


FIG. 5

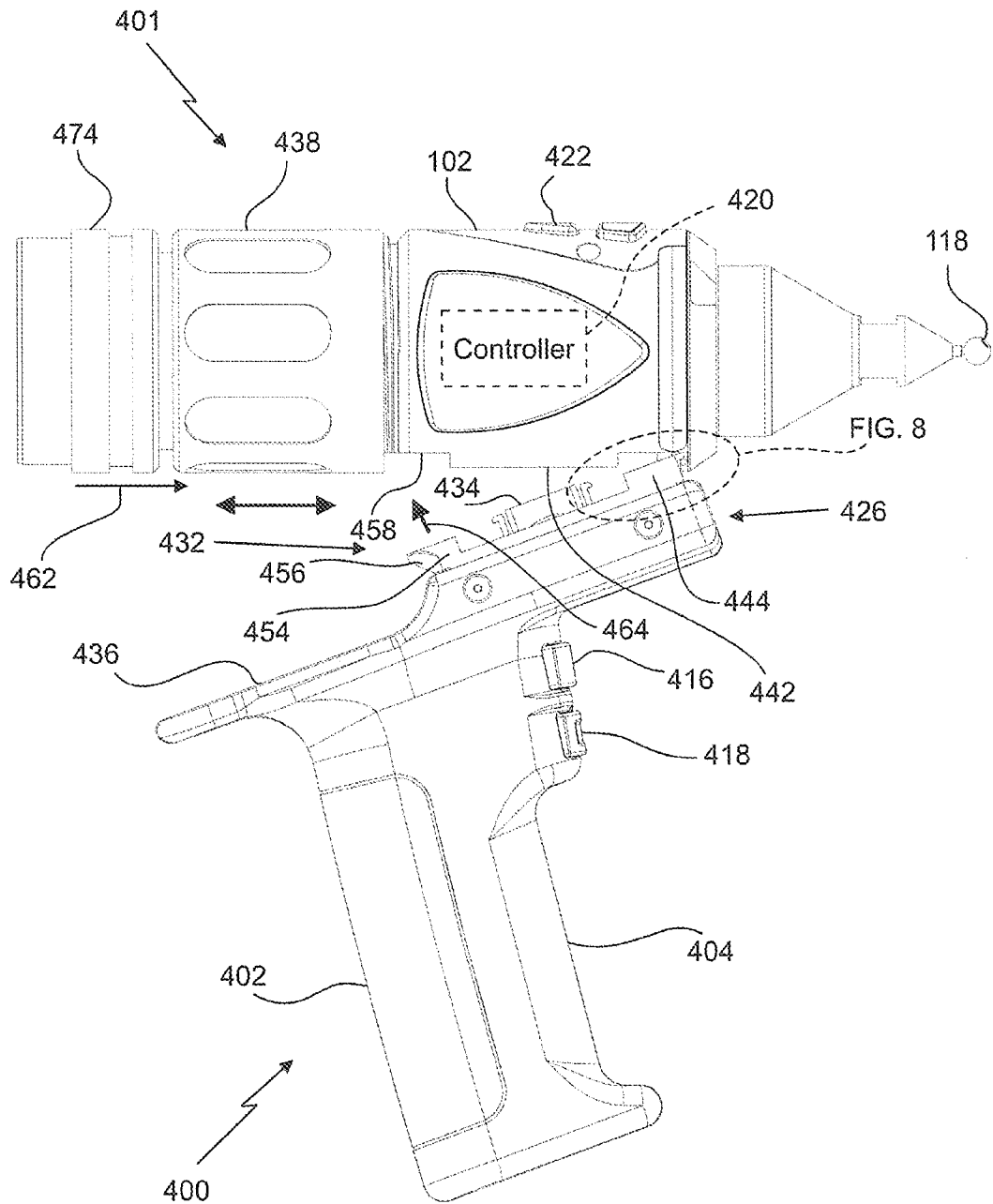


FIG. 6

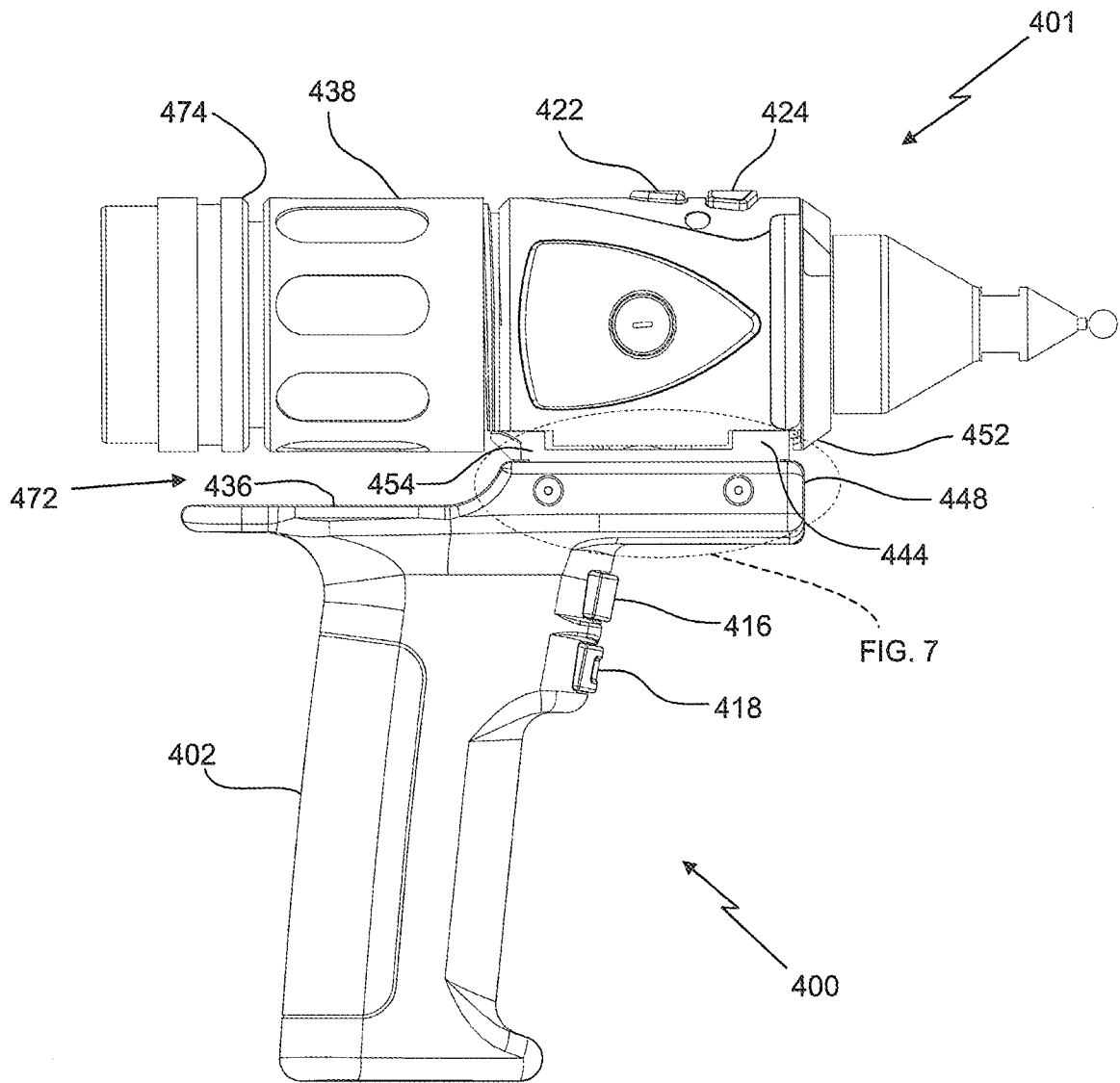


FIG. 7

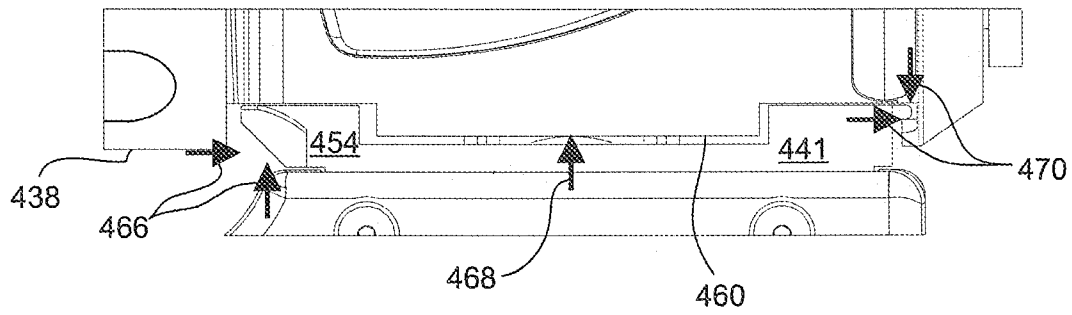


FIG. 8

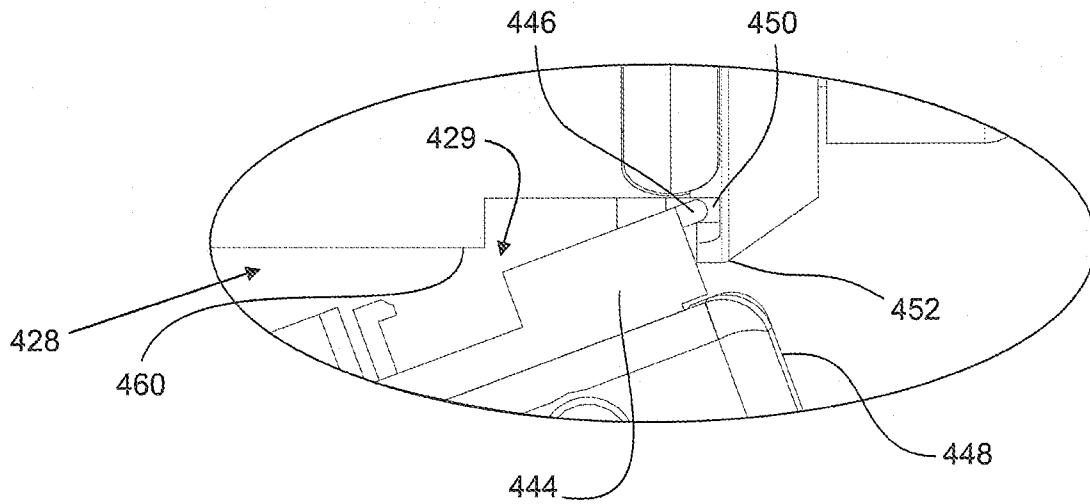
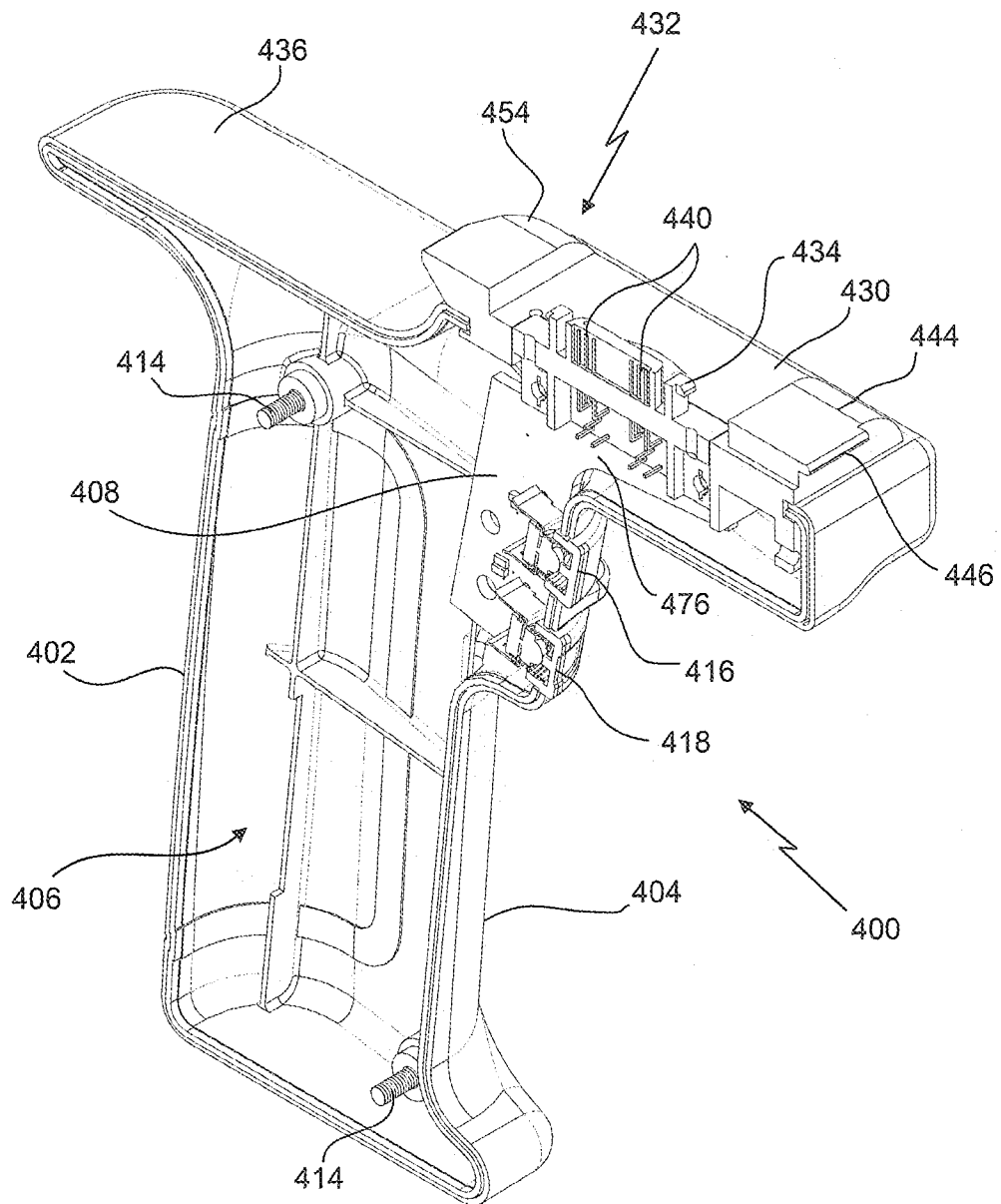


FIG. 9



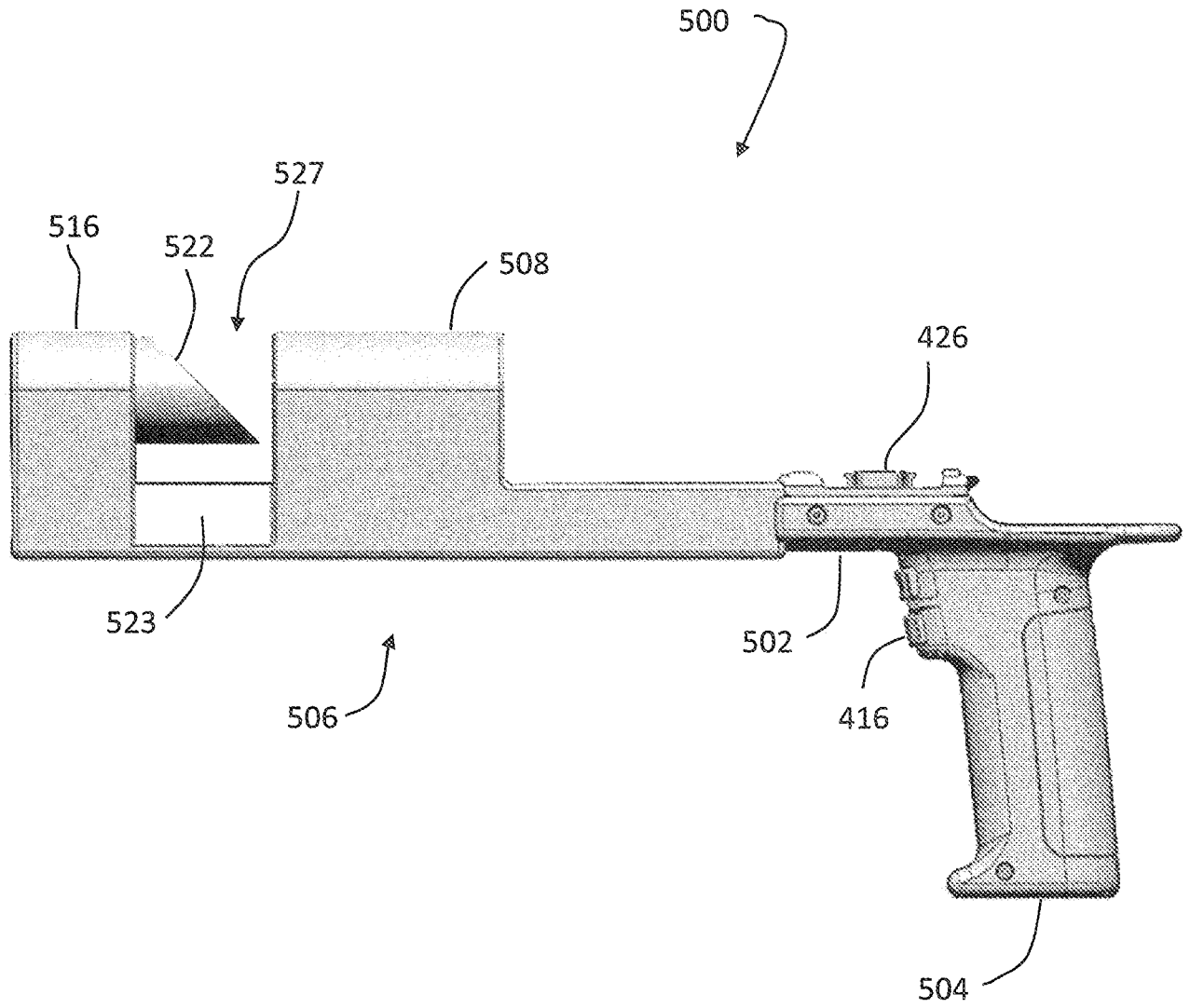


FIG. 11

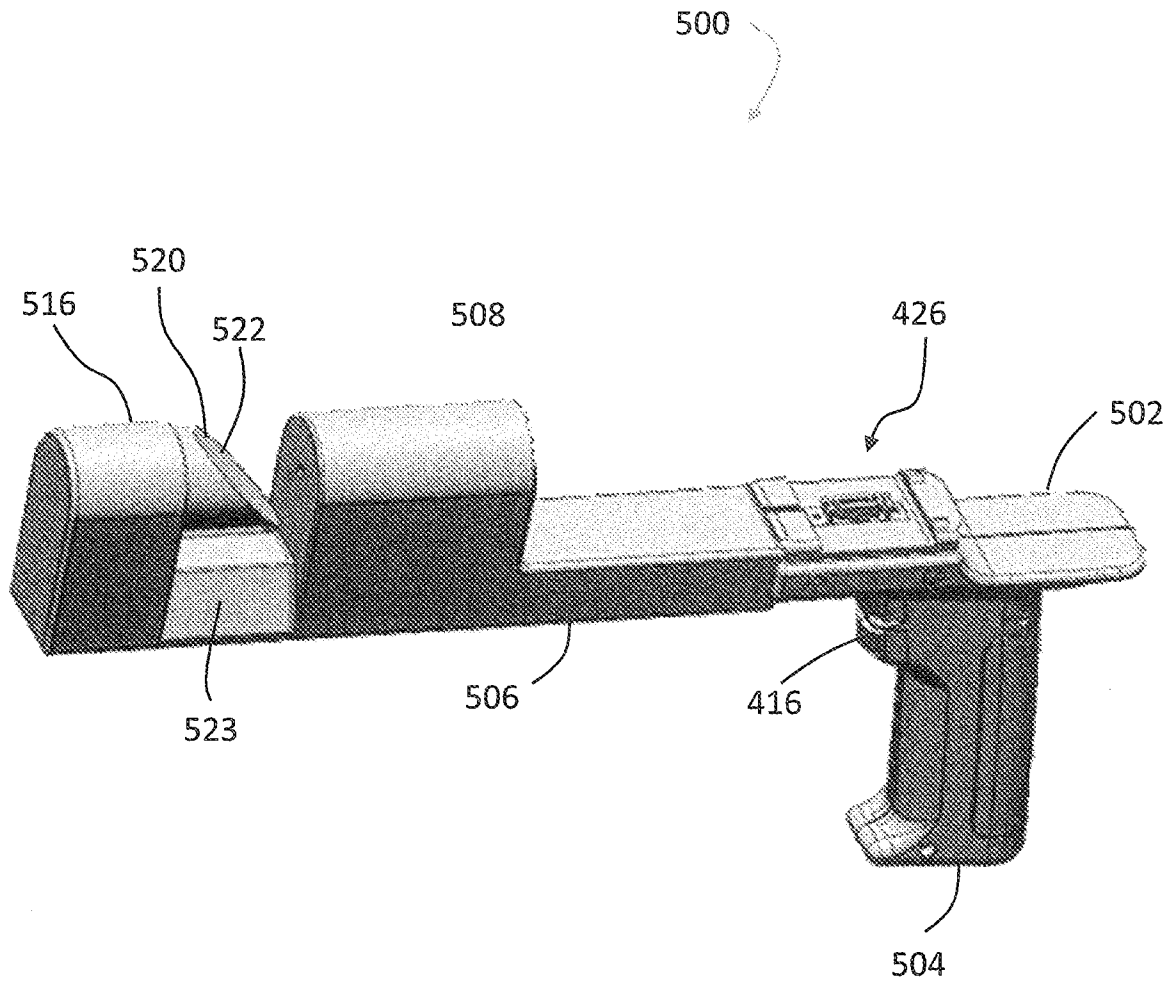


FIG. 12

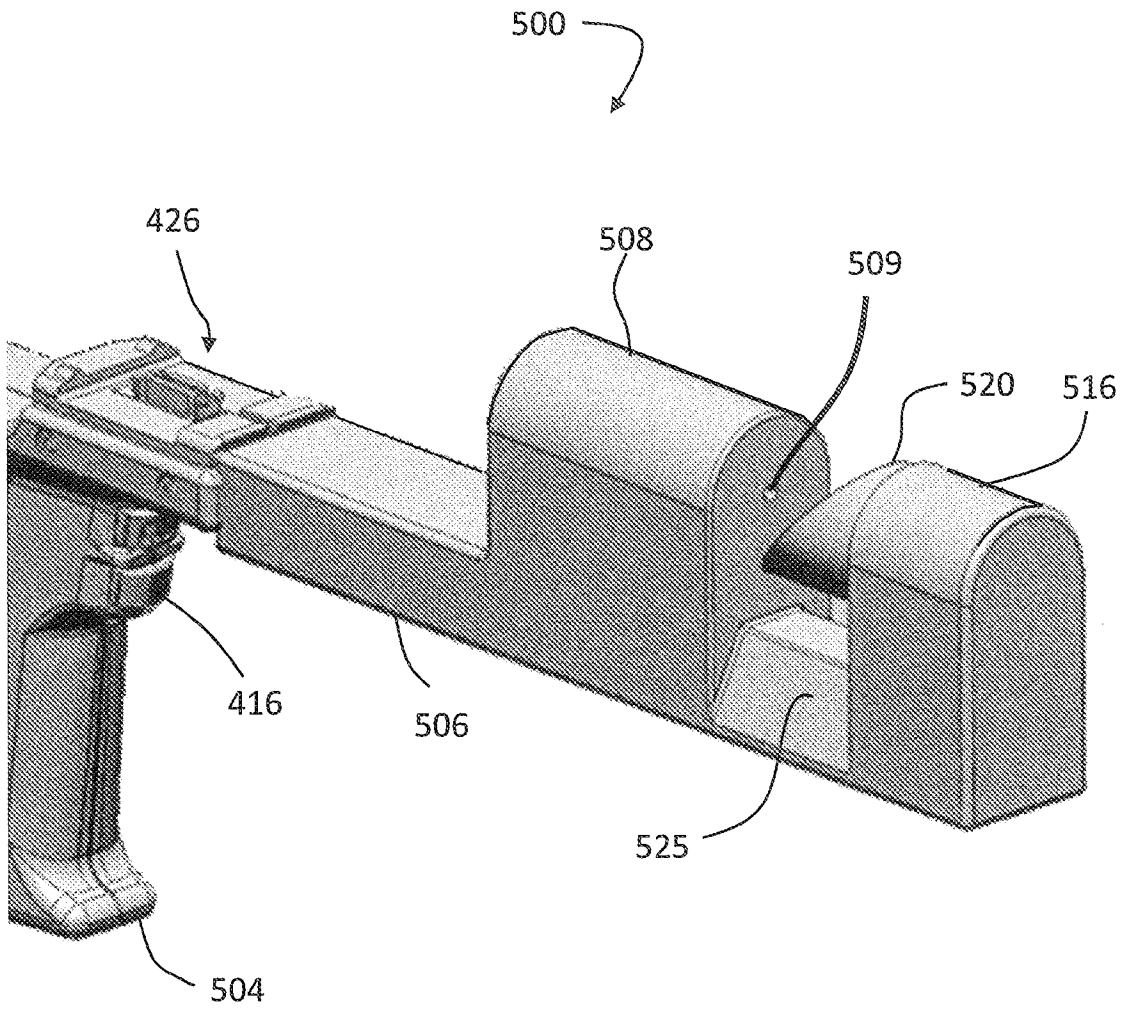


FIG. 13

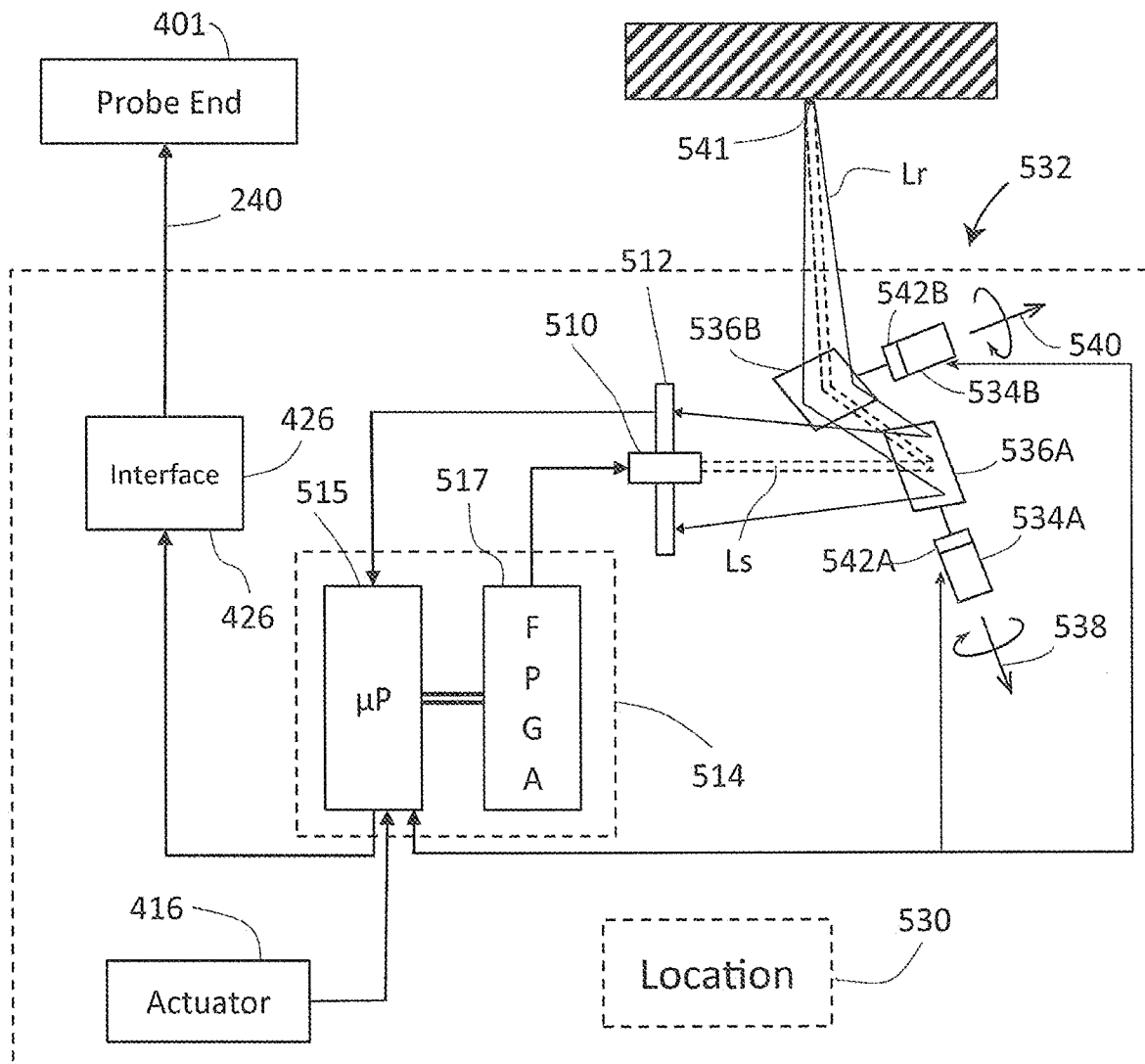


FIG. 14

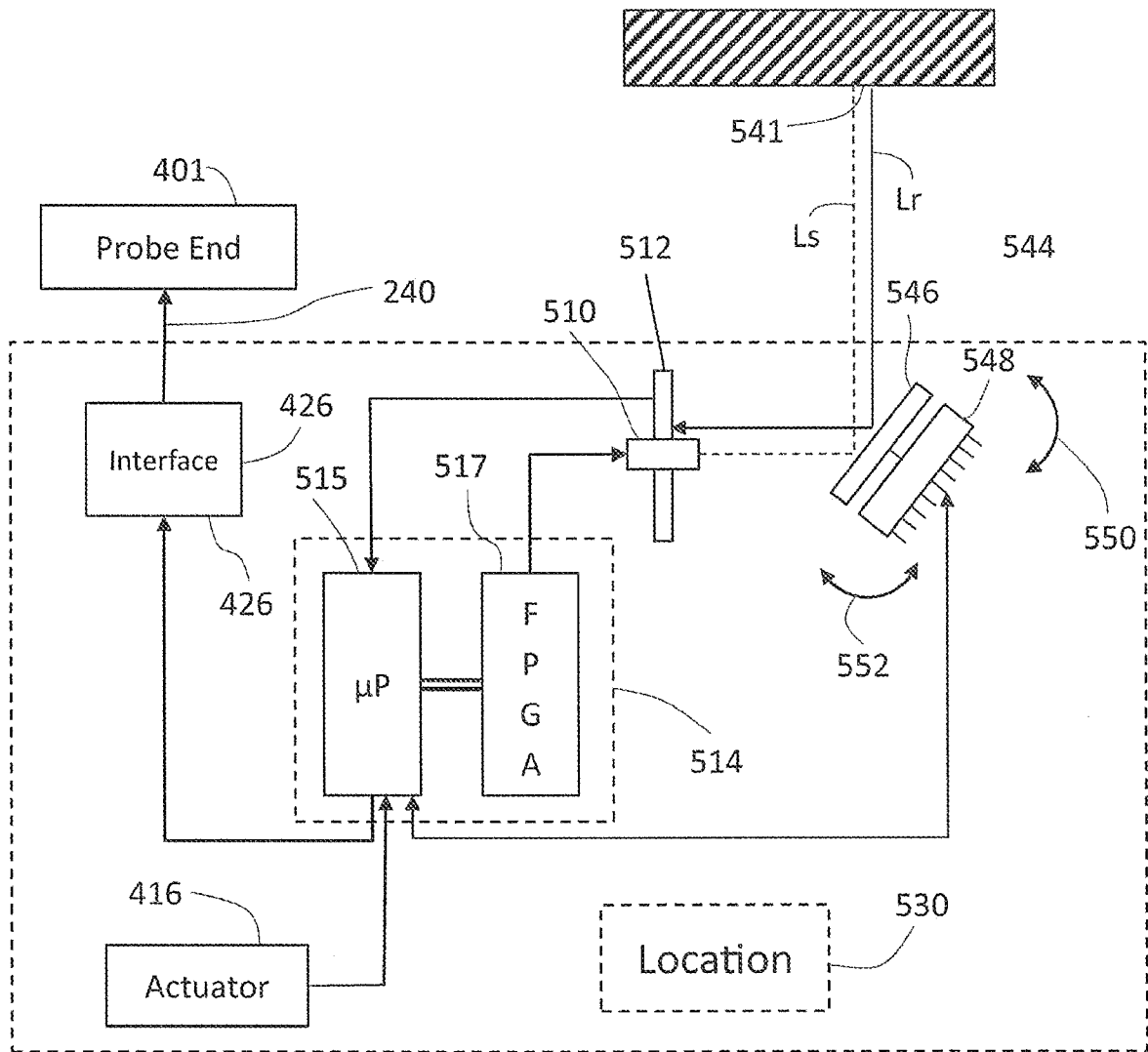


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No PCT/US2013/040321

A. CLASSIFICATION OF SUBJECT MATTER INV. G01B5/008 G01B11/00 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) G01B B25J G01S G01C		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MIN-GU LEE ET AL: "<title>Compact 3D lidar based on optically coupled horizontal and vertical scanning mechanism for the autonomous navigation of robots</title>", PROCEEDINGS OF SPIE, vol. 8037, 10 May 2011 (2011-05-10), page 80371H, XP055069052, ISSN: 0277-786X, DOI: 10.1117/12.884476 the whole document ----- <div style="text-align: right;">-/--</div>	1-26
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
* Special categories of cited documents :		
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3 July 2013	15/07/2013	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Rueda Gomez, Adriana	

INTERNATIONAL SEARCH REPORT

International application No PCT/US2013/040321

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>BEN-TZVI P ET AL: "Extraction of 3D images using pitch-actuated 2D laser range finder for robotic vision", ROBOTIC AND SENSORS ENVIRONMENTS (ROSE), 2010 IEEE INTERNATIONAL WORKSHOP ON, IEEE, PISCATAWAY, NJ, USA, 15 October 2010 (2010-10-15), pages 1-6, XP031840390, ISBN: 978-1-4244-7147-8 the whole document</p> <p align="center">-----</p>	1-26
A	<p>Yong K. Cho ET AL: "Light-weight 3D LADAR System for Construction Robotic Operations", 26th International Symposium on Automation and Robotics in Construction (ISARC 2009), 2009, XP55068755, Retrieved from the Internet: URL:http://www.iaarc.org/publications/full_text/Light-weight_3D_LADAR_System_for_Construction_Robotic_Operations.pdf [retrieved on 2013-06-28] the whole document</p> <p align="center">-----</p>	1-26