

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
12 May 2011 (12.05.2011)

(10) International Publication Number
WO 2011/057130 A2

(51) International Patent Classification:
G01B 5/012 (2006.01)

(21) International Application Number:
PCT/US2010/055713

(22) International Filing Date:
5 November 2010 (05.11.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/259,105 6 November 2009 (06.11.2009) US
12/748,267 26 March 2010 (26.03.2010) US
12/748,243 26 March 2010 (26.03.2010) US
12/748,278 26 March 2010 (26.03.2010) US
12/748,169 26 March 2010 (26.03.2010) US
12/748,206 26 March 2010 (26.03.2010) US

(71) Applicant (for all designated States except US):
HEXAGON METROLOGY AB [SE/SE]; Lilla Bantorget 15, Nacka Strand, S-13152 Stockholm (SE).

(72) Inventors: **CHAMP, Peter**; 58 Barrow Point Avenue, Pinner, HA5 3HG (GB). **DESFORGES, Laurent**; 1, rue de Villersfaux, F-41310 Ambloy (FR). **DELEMOS, Jean-Paul**; 1, rue de Chollet, F-37110 Monthodon (FR). **DUPORTAL, Thibault**; Le Cassereau, F-41310 Prunay-Cassereau (FR). **FAMECHON, Jean-Luc**; 13, rue des Gombaudes, F-41700 Villerable (FR). **GERENT, Jerry**; 1255 Grandview Rd., Vista, CA 92084 (US). **HONG, Dongmei**; 4020 Santa Nella Pl., San Diego, CA 92130 (US). **LIPPUNER, Heinz**; Im Fuertli 9, CH-9445 Rebstein (CH). **ROUX, Denny**; 5, rue de Saint Lubin,

F-41190 Landes le Gaulois (FR). **SHAMMAS, Elie**; 7590 Melotte St., San Diego, CA 92119 (US). **SIERCKS, Knut**; Augartenstrasse 29, CH-9402 Morschwil (CH). **TAIT, Hogar**; 5145 Avenida Encinas, Carlsbad, CA 92008 (US).

(72) Inventor; and
(75) Inventor/Applicant (for US only): **FERRARI, Paul** [US/US]; 3485 Pleasant Vale, Carlsbad, CA 92010 (US).

(74) Agent: **DELANEY, Karoline, A.**; Knobbe, Martens, Olson & Bear, LLP, 2040 Main Street, 14th Floor, Irvine, CA 92614 (US).

(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, 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, PE, PG, PH, PL, PT, RO, RS, RU, 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, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, 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).

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(54) Title: IMPROVED ARTICULATED ARM

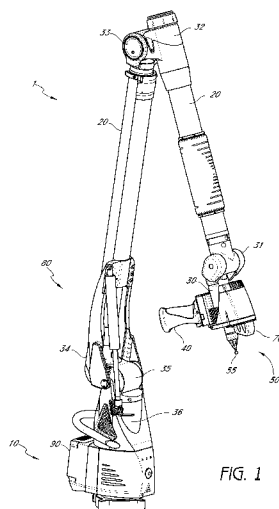


FIG. 1

(57) Abstract: An articulated arm CMM comprises a plurality of transfer members, a plurality of articulation members connecting at least two transfer members to each other, a coordinate acquisition member at a distal end, and a base at a proximal end. At least two of the articulation members can include at least one encoder and the at least two encoders can both be enclosed within a single monoblock housing.



WO 2011/057130 A2

Declarations under Rule 4.17:

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

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

IMPROVED ARTICULATED ARM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Patent Application Serial Nos. 12/748,169; 12/748,243; 12/748,278; 12/748,206; and 12/748,267 (all filed 26 March 2010), each of which claiming the priority benefit under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 61/259,105 (filed November 6, 2009), the entirety of which being hereby expressly incorporated by reference herein.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to articulated arms and coordinate measurement, and more particularly to coordinate measurement machines.

Description of the Related Art

[0003] Rectilinear measuring systems, also referred to as coordinate measuring machines (CMMs) and articulated arm measuring machines, are used to generate highly accurate geometry information. In general, these instruments capture the structural characteristics of an object for use in quality control, electronic rendering and/or duplication. One example of a conventional apparatus used for coordinate data acquisition is a portable coordinate measuring machine (PCMM), which is a portable device capable of taking highly accurate measurements within a measuring sphere of the device. Such devices often include a probe mounted on an end of an arm that includes a plurality of transfer members connected together by joints. The end of the arm opposite the probe is typically coupled to a moveable base. Typically, the joints are broken down into singular rotational degrees of freedom, each of which is measured using a dedicated rotational transducer. During a measurement, the probe of the arm is moved manually by an operator to various points in the measurement sphere. At each point, the position of each of the joints must be determined at a given instant in time. Accordingly, each transducer outputs an electrical signal that varies according to the movement of the joint in that degree of freedom. Typically, the probe also generates a signal. These position signals and the probe signal are transferred through the arm to a recorder/analyzer. The position signals are then used to determine the position of the probe within the

measurement sphere. *See e.g.*, U.S. Patent Nos. 5,829,148 and 7,174,651, which are incorporated herein by reference in their entireties.

[0004] Generally, there is a demand for such machines with a high degree of accuracy, high reliability and durability, substantial ease of use, and low cost, among other qualities. The disclosure herein provides improvements of at least some of these qualities.

SUMMARY OF THE INVENTIONS

[0005] In one embodiment, an articulated arm CMM comprises a plurality of transfer members, a plurality of articulation members connecting at least two transfer members to each other, a coordinate acquisition member at a distal end, and a base at a proximal end. At least two of the articulation members can include at least one encoder and the at least two encoders can both be enclosed within a single monoblock housing.

[0006] In an additional embodiment, an articulated arm CMM comprises an articulated arm and a gas spring counterbalance. The articulated arm can include a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end. The gas spring counterbalance can support the arm at a rotational point between adjacent articulated arm members. Further, the gas spring counterbalance can connect to an articulated arm member closer to the base at a point nearer to the rotation point than to the base.

[0007] In yet another embodiment, an articulated arm CMM comprises an articulated arm and a gas spring counterbalance. The articulated arm can comprise a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end. The gas spring counterbalance can support the arm at a rotational point between two adjacent articulated arm members. Further, rotation at the rotational point can bring one of the two adjacent articulated arm members to a substantially horizontal position when the gas spring counterbalance is also brought to a substantially horizontal position.

[0008] In a further embodiment, an articulated arm CMM comprises an articulated arm and a handle. The articulated arm can include a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end. The handle can include electronics and be removably connected to the coordinate acquisition member.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Further objects, features and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention, in which:

[0010] Figure 1 is a perspective view of an articulated arm;

[0011] Figures 1A is an exploded view of the articulated arm of Figure 1;

[0012] Figure 2 is a perspective view of a transfer member of the articulated arm of Figure 1 with its associated articulation members;

[0013] Figure 2A is a perspective view of the transfer member of Figure 2 with a cover portion removed;

[0014] Figure 2B is an enlarged perspective view of the transfer member of Figure 2A;

[0015] Figure 2C is an enlarged cross-sectional view of the articulation members of Figure 2

[0016] Figure 2D is an enlarged cross-sectional view of the transfer member of Figure 2B;

[0017] Figure 2E is a partially exploded side view of the transfer member and articulation members of Figure 2;

[0018] Figure 3 is a perspective view of a counterbalance system of the articulated arm of Figure 1;

[0019] Figure 3A is an exploded view of the counterbalance system of Figure 3;

[0020] Figure 3B is a side view of the counterbalance system of Figure 3 in a first position;

[0021] Figure 3C is a side view of the counterbalance system of Figure 3 in a second position;

[0022] Figure 4 is a perspective view of a handle of the articulated arm of Figure 1;

[0023] Figure 5 is a perspective view of a base and a feature pack of the articulated arm of Figure 1;

[0024] Figure 6 is a plan view of a demonstrative embodiment of an encoder;

[0025] Figure 7 is a screen shot from an embodiment of calibration software associated with an articulated arm;

[0026] Figure 7A is a perspective view of an articulated arm in wireless communication with a computer; and

[0027] Figure 8 is a flow diagram of a method of operating an articulated arm.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0028] Figures 1 and 1A illustrate one embodiment of a portable coordinate measuring machine (PCMM) 1 in accordance with the present invention. In the illustrated embodiment, the PCMM 1 comprises a base 10, a plurality of rigid transfer members 20, a coordinate acquisition member 50 and a plurality of articulation members 30-36 that form "joint assemblies" connecting the rigid transfer members 20 to one another. The articulation members 30-36 along with the transfer members 20 and hinges (described below) are configured to impart one or more rotational and/or angular degrees of freedom. Through the various members 30-36, 20, the PCMM 1 can be aligned in various spatial orientations thereby allowing fine positioning and orientating of the coordinate acquisition member 50 in three dimensional space.

[0029] The position of the rigid transfer members 20 and the coordinate acquisition member 50 may be adjusted using manual, robotic, semi-robotic and/or any other adjustment method. In one embodiment, the PCMM 1, through the various articulation members 30-36, is provided with seven rotary axes of movement. It will be appreciated, however, that there is no strict limitation to the number of axes of movement that may be used, and fewer or additional axes of movement may be incorporated into the PCMM design.

[0030] In the embodiment PCMM 1 illustrated in Figure 1, the articulation members 30-36 can be divided into two functional groupings based on their associated motion members operation, namely: 1) those articulation members 30, 32, 34, 36 which are associated with the swiveling motion associated with a specific and distinct transfer member (hereinafter, "swiveling joints"), and 2) those articulation members 31, 33, 35 which allow a change in the relative angle formed between two adjacent members or between the coordinate acquisition member 30 and its adjacent member (hereinafter, "hinge joints" or "hinges"). While the illustrated embodiment includes four swiveling joints and three hinge joints

positioned as to create seven axes of movement, it is contemplated that in other embodiments, the number of and location of hinge joints and swiveling joints can be varied to achieve different movement characteristics in a PCMM. For example, a substantially similar device with six axes of movement could simply lack the swivel joint 30 between the coordinate acquisition member 50 and the adjacent articulation member 20. In still other embodiments, the swiveling joints and hinge joints can be combined and/or used in different combinations.

[0031] As is known in the art (see e.g., U.S. Patent No. 5,829,148, which is hereby incorporated by reference herein) and depicted in Figure 2D, the transfer members 20 can comprise a pair of dual concentric tubular structures having an inner tubular shaft 20a rotatably mounted coaxially within an outer tubular sheath 20b through a first bearing mounted proximately to a first end of the member adjacent and a second bearing located at an opposite end of the member and which can be positioned within the dual axis housing 100. The transfer members 20 operate to transfer motion from one end of the transfer member to the other end of the transfer member. The transfer members 20 are, in turn, connected together with articulation members 30-36 to form joint assemblies.

[0032] The hinge joint, in turn, is formed, in part, by the combination of a yoke 28 extending from one end of a transfer member (see Figure 1A), the rotational shaft extending through the articulation members 31, 33, 35 and the articulation members 31, 33, 35 themselves, which rotate about the rotational shaft to form a hinge or hinge joint.

[0033] Each hinge or swiveling joint has its own dedicated motion transducer in the form of an encoder 37 which can be seen in Figure 2C. Advantageously, both the hinge and swiveling joint encoders are positioned at least partially, and more preferably, entirely within the dual axis housing 100 within the respective articulation members 30-36.

[0034] In various embodiments, the coordinate acquisition member 50 comprises a contact sensitive member 55 (depicted as a hard probe in Figure 1) configured to engage the surfaces of a selected object and generate coordinate data on the basis of probe contact. In the illustrated embodiment, the coordinate acquisition member 50 also comprises a non-contact scanning and detection component that does not necessarily require direct contact with the selected object to acquire geometry data. As depicted, the non-contact scanning device

comprises a non-contact coordinate detection device (shown as a laser coordinate detection device/laser scanner) that may be used to obtain geometry data without direct object contact. The non-contact scanning device can include a camera or other optical device 70, which functions in conjunction with a laser not depicted herein. It will be appreciated that various coordinate acquisition member configurations including: a contact-sensitive probe, a non-contact scanning device, a laser-scanning device, a probe that uses a strain gauge for contact detection, a probe that uses a pressure sensor for contact detection, a device that uses an infrared beam for positioning, and a probe configured to be electrostatically-responsive may be used for the purposes of coordinate acquisition. Further, in some embodiments, a coordinate acquisition member 50 can include one, two, three, or more than three coordinate acquisition mechanisms.

[0035] Further description of certain embodiments of a coordinate acquisition member that can be used with the embodiments described herein can be found in U.S. Patent Application No. 12/487,535, filed 18 June 2009 and entitled ARTICULATING MEASURING ARM WITH LASER SCANNER, which is incorporated by reference herein in its entirety. As depicted in said reference, the coordinate acquisition member can include a modular laser scanner that can attach to the main body of the coordinate acquisition member (which can also include a touch probe). The modular features can allow various other coordinate detection devices to be used with the coordinate acquisition member. Additionally, other coordinate acquisition members can be used, as is generally known by those of skill in the art.

[0036] Advantageously, as depicted in Figures 2-2C, the articulation members 30-36 form a dual-axis housing 100. The dual-axis housing 100 can be a single monoblock housing, a housing comprising multiple pieces bonded together (e.g. by welding, adhesive, etc.), or otherwise. As depicted, the dual-axis housing 100 can be coupled to the transfer members 20 and comprise part of hinge and swivel joints, corresponding to the second and third axes of rotation from the base 10. As noted above, separately functional rotational encoders 37 and associated electronics for measuring a position of the transfer members and hinge and swivel joints (as are generally known by those of skill in the art) can be positioned

in the articulation members 34 and 35 (as well as the articulation members 30-33 and 36, depicted in other figures).

[0037] To facilitate assembly of the dual-axis assembly, the dual-axis housing 100 can include a removable back cover 102, shown removed in Figure 2A. As depicted, the removable cover 102 can cover an opening in the housing 100 generally axially aligned with an adjacent transfer member 20 mounted to the housing. Further, in some embodiments the cover 102 can be configured so as not to bare any significant load of the CMM 1. Accordingly, it may be desirable to form the cover 102 of a less rigid material that can also serve as a shock absorber. As depicted, the cover 102 can be positioned at an “elbow” position of the arm 1. During some activities the “elbow” positions may be more likely to abruptly contact an external, hard surface that could damage the arm 1. Advantageously, a cover 102 formed of a shock absorbent material can protect the arm 1 from such damage. Even further, in some embodiments the material of the cover 102 can also serve to promote enhanced sealing with the material of the dual-axis housing 100. The dual-axis housing 100 can comprise a rigid material, and the cover 102 can comprise a more flexible material that can conform to the edges of the housing when mounted thereto, creating an enhanced seal.

[0038] The removable back cover 102 can provide a general sealing of the interior of the dual-axis housing 100 from the external elements, protecting the encoders 37 positioned within the housing. When the cover 102 is removed the separate encoder 37 associated with the articulation member 34 can be exposed and inserted/removed from the dual-axis housing 100 into a swivel-receiving portion 104 generally axially aligned with the depicted transfer member 20 (as depicted in Figure 2E). In the illustrated embodiment, the encoders associated with the articulation members 34 and 35 are separate components from the transfer members 20. That is, the encoder and transfer member are two separate and distinct components that are connected together but can rotatably operate apart from each other. The same principle can also be applied to the other articulation members 30-33 and 36. That is, the transfer members 20 can operate separately from the articulation members 30-36 that form a joint or joint assembly as described above and operate to measure rotation.

[0039] Additionally, additional electronics can be inserted/removed while the cover 102 is removed, as depicted in Figure 2B. As shown, the dual-axis housing 100 can

provide a receiving portion for a printed circuit board 38 that can hold additional electronics. In some embodiments, the additional electronics can perform additional signal processing such as digitizing an analog signal from the encoders. In some embodiments, such digitization can be performed prior to passing the signal to slip rings or other rotatable electronic connections. Further, in some embodiments the additional printed circuit board 38 can facilitate forming the physical electronic connection between both encoders within the dual-axis housing 100.

[0040] Further, in the depicted dual-axis housing 100 the separate encoder 37 associated with the articulation member 35 can be inserted/removed independent of the back cover 102. To facilitate this insertion/removal, the dual-axis housing 100 can have a hinge-receiving portion 106 oriented perpendicularly from a primary plane of the housing. The hinge-receiving portion 106 can have an open end 108, into which the encoder 37 can enter, and a substantially closed end 110 against which the encoder can abut to define a position for the encoder. Once the encoder 37 has been inserted, a cap piece 112 can then be inserted to secure the encoder within the hinge-receiving portion 106.

[0041] As depicted in Figure 2C, the encoder 37 can include an encoder disk 38a and a read head 38b. The encoder disk 38a can have a pattern on its surface that can be measured by the read head 38b. For example, in some embodiments the encoder disk 38a can have an optical pattern including varying colors, transparent and opaque portions, or other visible variations; and the read head 38b can include an optical measuring device such as a camera. In some embodiments the disk 38a can have a defined pattern of lines on the disk similar to a bar code such that any image of the disk by the read head can define an absolute rotational angle, as further discussed below. As another example, the encoder disk 38a can have varying magnetic portions and the read head 38b can measure a corresponding magnetic field. The varying patterns on the encoder disk 38a can be measured by the read head 38b to indicate a rotational position, or a change in rotational position of the encoder disk relative to the read head. In turn, as depicted, the read head 38b can be rotationally fixed with the housing 100 and the encoder disk 38a can be rotationally fixed to an encoder shaft 39 that is rotatably mounted within the housing. Thus, rotation of the shaft 39 relative to the housing 100 can cause a corresponding relative rotation between the disk 38a and read head

38b that can be measured. However, it will be clear from the description herein that the apparatus can vary. For example, in some embodiments the read head 38b can be rotatably mounted to the housing 100 and the encoder disk 38a can be rotatably fixed.

[0042] In the depicted embodiment, the encoder associated with the articulation member 35 can mount with an adjacent transfer member, not shown in Figure 2, via a fork joint on the transfer member and the encoder shaft 39. Said fork joint can be similar to that depicted at the end of the depicted transfer member 20 opposite the dual-axis housing 100, with a yoke 28 that can mount to the encoder shaft 39 rotatably mounted within the housing 100. The forks of the yoke 28 can mount about the ends of the dual-axis housing 100 and its contained encoder to form a hinge articulation member 35. Accordingly, both encoders in the dual-axis housing 100 can be inserted/removed independently of one another from the single housing. Notably, in other embodiments the form of the dual-axis housing 100 can vary. For example, in some embodiments the dual-axis housing 100 can form two swivel-receiving portions 104, or two hinge-receiving portions 106, as opposed to one of each.

[0043] Placing the encoders 37 into a single housing can provide numerous advantages over prior art assemblies with separate housings. For example, the combined housing can reduce the number of parts and joints required, and thus also reduce cost and assembly time. Further, the accuracy of the device can improve from the elimination of deflection, misalignment, or other problems with multiple components. Additionally, removal of the additional housing can allow a more compact combined joint assembly, allowing the arm to be better supported and have less weight. As shown Figure 1A, a yoke 28 of the next or proceeding transfer member 20 can be coupled to the bearing shaft extending through dual axis housing 100 to form the hinge joint.

[0044] Although depicted as enclosing the second and third axes from the base, a similar dual-axis housing 100 can be used with other combinations of articulation members, such as the fourth and fifth articulation members 32, 33. Further, the dual-axis housing can provide additional advantages not explicitly discussed herein. However, it should be noted that in other embodiments of the inventions described herein, the articulation members 30-36 can each have a separate housing.

[0045] It should be appreciated that the dual-axis housing or joint assembly described above can be used in other types of CMMs and need not be used in combination with the additional embodiments described below.

[0046] Figures 3 and 3A depict an improved counterbalance system 80. As depicted, the counter balance system 80 can include a piston assembly 84 forming a gas shock counterbalance. A nitrogen charged gas spring can connect between points separated by a pivot 88 aligned with an articulation member such as the second-closest-to-the-base articulation member 35. As depicted, the connection point nearer the base 10 can be closer to the pivot 88 than to the base. This results in a counterbalance design where the gas shock is in a predominantly horizontal position when the second linkage is in a horizontal position, as depicted in Figure 3C. The predominantly horizontal position of the gas shock can be further promoted by the position of the connection point further from the base. As depicted, the connection point further from the base can be positioned at approximately the mid-point of the transfer member 20 supported by the counterbalance system 80. Further, as depicted the piston assembly 84 can include a lock 86 that can increase the resistance against movement of the piston, thus preventing additional rotation of the aligned articulation member 35. In one embodiment the lock is implemented with a lever on the lock 86, pushing on a pin that opens and closes an aperture within the gas shock. The opening and closing of the aperture either allows or prevents the flow of gas within the piston.

[0047] This improved counterbalance system 80 can provide a number of advantages. For example, this design can allow the first axis of rotation from the base (associated with articulation member 36) to be shorter, reducing associated deflection. Additionally, this reduced length can be accomplished without a reduced angular span of rotation about the pivot 88. The improved counterbalance system 80 can also reduce the number of parts required, as the locking mechanism and the counterbalance mechanism can be integrally combined into a single system. Further, the piston assembly 84 can damp the motion about the pivot 88. This reduces the chance of damaging the CMM when a user tries to move the arm while it is still locked. However, it should be noted that in other embodiments of the inventions described herein, a different counterbalance system can be used, such as a weight provided on a back end of a transfer member 20. Further, in other

embodiments of the inventions described herein, a different locking mechanism can be used, such as a rigid physical stop. It should be appreciated the improved counterbalance system 80 described above can be used in other types of CMMs and need not be used in combination with the additional embodiments described above and below the preceding section.

[0048] Figure 4 depicts an improved handle 40. The handle 40 can include one or more integrated buttons 41. The handle can connect to the axis with bolts, snaps, or clamps. Additionally, the handle 40 can include electronics 44 included within its interior. Advantageously, providing the electronics 44 in the handle 40 can further separate the electronics from rotational encoders and other components that may lose accuracy when heated. In some embodiments the handle 40, or the electronics 44 therein, can be thermally isolated from the remainder of the arm. Additionally, when the handle 40 is removable and includes the electronics 44, it can form a modular component similar to the feature packs (described below). Thus, a user can change the functionality by changing the handle 40, and accordingly also changing the electronics 44 and the buttons 41 that control the electronics. A plurality of handles 40 with different functionalities can thus be provided in a CMM system to provide modular features to the CMM. Again, it should be noted that in other embodiments of the inventions described herein, a different handle can be used, or alternatively there can be no distinct handle. Additionally, the handle can contain a battery to power the arm, the scanner or both.

[0049] It should be appreciated the improved handle 40 described above can be used in other types of CMMs and need not be used in combination with the additional embodiments described above and below the preceding section

[0050] Additionally or alternatively, in some embodiments a CMM arm 1 can be at least partially controlled by motion of the arm itself, as depicted in Figure 8. For example, whereas some commands or instructions may be triggered by the pressing of a button, pulling a lever, turning a dial, or actuating some other traditional actuation device in some embodiments, in other embodiments the same or different instruction can be triggered by a specific motion or position of the CMM arm 1, which can be detected by the encoders 37. As a more specific example, in some embodiments the CMM arm 1 can be instructed to enter a sleep mode when the arm is placed in a generally folded or retracted position, such as that

depicted in Figure 1. The CMM arm 1 can then perform that instruction. Similarly, the CMM arm 1 can be reawakened by a rapid movement, or movement into a more extended position. Other combinations of instructions, motions, and positions are possible.

[0051] For example, in some embodiments the CMM arm 1 can enter into different data acquisition modes depending on its general orientation. Varying the data acquisition mode by position can be advantageous where the CMM arm 1 regularly measures products that require different data acquisition modes along different parts of a product.

[0052] Further, in some embodiments the arm can enter into different data acquisition modes depending on its speed of movement. For example, an operator of the CMM may move the CMM slowly when a critical point will soon be measured. Thus, the CMM can increase its measurement frequency, accuracy, or other characteristics when the arm is moving slowly. Additionally, the CMM can be toggled between a mode where the arm is used as a computer mouse and a measurement mode with a quick movement of one of the last axes (embodiments of an associated computer further described below).

[0053] As with the previous embodiments, it should be appreciated that these features related to control of the arm can be used in other types of CMMs and need not be used in combination with the additional embodiments described above and below the preceding section.

[0054] Figure 5 depicts a set of feature packs 90 that can connect with the base 10 via a docking portion 12. The docking portion 12 can form an electronic connection between the CMM arm 1 and the feature pack 90. In some embodiments the docking portion 12 can provide connectivity for high-speed data transfer, power transmission, mechanical support, and the like. Thus, when connected to a docking portion, a feature pack 90 can provide a modular electronic, mechanical, or thermal component to the CMM arm 1, allowing a variety of different features and functionality such as increased battery life, wireless capability, data storage, improved data processing, processing of scanner data signals, temperature control, mechanical support or ballast, or other features. In some embodiments this modular functionality can complement or replace some modular features of the handle 40. The modular feature packs can contain connectors for enhanced functionality, batteries, electronic circuit boards, switches, buttons, lights, wireless or wired communication electronics,

speakers, microphones, or any other type of extended functionality that might not be included on a base level product. Further, in some embodiments the feature packs 90 can be positioned at different portions of the CMM arm 1, such as along a transfer member, an articulation member, or as an add-on to the handle 40.

[0055] As one example, a feature pack 90 can include a battery, such as a primary battery or an auxiliary battery. Advantageously, in embodiments where the pack 90 is an auxiliary battery the CMM can include an internal, primary battery that can sustain operation of the CMM while the auxiliary battery is absent or being replaced. Thus, by circulating auxiliary batteries a CMM can be sustained indefinitely with no direct power connection.

[0056] As another example, a feature pack 90 can include a data storage device. The available data storage on the feature pack 90 can be arbitrarily large, such that the CMM can measure and retain a large amount of data without requiring a connection to a larger and/or less convenient data storage device such as a desktop computer. Further, in some embodiments the data storage device can transfer data to the arm, including instructions for arm operation such as a path of movement for a motorized arm, new commands for the arm upon pressing of particular buttons or upon particular motions or positions of the arm, or other customizable settings.

[0057] In examples where the feature pack includes wireless capability, similar functionality can be provided as with a data storage device. With wireless capability, data can be transferred between the CMM and an external device, such as a desktop computer, continuously without a wired connection. In some embodiments, the CMM can continuously receive commands from the auxiliary device. Further, in some embodiments the auxiliary device can continuously display data from the arm, such as the arm's position or data points that have been acquired. In some embodiments the device can be a personal computer ("PC") and the feature pack can transmit arm coordinate data and scanner data wirelessly to the PC. Said feature pack can combine the arm data and scanner data in the feature pack before wireless transmission or transmit them as separate data streams.

[0058] In further embodiments, the feature packs can also include data processing devices. These can advantageously perform various operations that can improve the operation of the arm, data storage, or other functionalities. For example, in some

embodiments commands to the arm based on arm position can be processed through the feature pack. In additional embodiments, the feature pack can compress data from the arm prior to storage or transmission.

[0059] In another example, the feature pack can also provide mechanical support to the CMM. For example, the feature pack can connect to the base 10 and have a substantial weight, thus stabilizing the CMM. In other embodiments, the feature pack may provide for a mechanical connection between the CMM and a support on which the CMM is mounted.

[0060] In yet another example, the feature pack can include thermal functionality. For example, the feature pack can include a heat sink, cooling fans, or the like. A connection between the docking portion and the feature pack can also connect by thermally conductive members to electronics in the base 10 and the remainder of the CMM, allowing substantial heat transfer between the CMM arm and the feature pack.

[0061] Further, as depicted in Figure 1, in some embodiments the feature packs 90 can have a size and shape substantially matching a side of the base 10 to which they connect. Thus, the feature pack 90 can be used without substantially increasing the size of the CMM, reducing its possible portability, or limiting its location relative to other devices.

[0062] Again, the feature packs 90 can be used in combination with each other and the other features described herein and/or can be used independently in other types of CMMs.

[0063] Additionally, in some embodiments the CMM arm 1 can include an absolute encoder disk 95, a demonstrative embodiment depicted in Figure 6. The absolute encoder disk 95 can include a generally circular, serialized pattern that can be embodied in reflective and non-reflective materials, translucent and non-translucent materials, alternating magnetic properties, or the like. The serialized pattern can allow a read head to determine a unique position on the encoder by only reading a limited portion of the encoder's coded surface. In some embodiments, the serialized pattern can resemble a bar code, as depicted in Figure 6. The pattern can be non-repetitive along a viewing range of an associated read-head. Thus, an image or other data collected by the read-head from the encoder disk 95 can yield a pattern unique from any other position on the encoder, and therefore be associated with a unique angular position. Each encoder can consist of a single serialized disk that is read by

one or more read-heads that can be, e.g., CCD imagers. The use of two or preferably four CCD imagers can improve the accuracy of the encoder by measuring the eccentricity of the axis and subtracting out the eccentricity from the angle measurement. Further, the angle accuracy can be improved by averaging the measurements of the multiple CCD imagers.

[0064] In prior art encoders an incremental and repetitive surface was often used, in which the coded surface only indicates incremental steps and not an absolute position. Thus, incremental encoders would require a return to a uniquely identified home position to re-index and determine the incremental positions away from the home position. Advantageously, some embodiments of an absolute encoder disk 95 can eliminate the required return to a home position. This feature of a CMM can also be used in combination with the other features described herein and/or can be used independently in other types of CMMs.

[0065] Advantageously, the absolute encoder disk 95 can improve functionality of a CMM arm 1 that enters a sleep mode. Entering sleep mode can reduce the power consumption of a CMM arm 1. However, if enough systems are shut down during sleep mode then incremental encoders may “forget” their position. Thus, upon exiting sleep mode incremental encoders may need to be brought back to the home position prior to use. Alternatively, incremental encoders can be kept partially powered-on during sleep mode to maintain their incremental position. Advantageously, with an absolute encoder disk 95 the encoders can be completely powered off during sleep mode and instantly output their position when power is returned. In other modes, the absolute encoder can read its position at a lower frequency without concern that it may miss an incremental movement and thus lose track of its incremental position. Thus, the CMM arm 1 can be powered-on or awakened and can immediately begin data acquisition, from any starting position, without requiring an intermediary resetting to the “home” position. In some embodiments absolute encoders can be used with every measured axis of rotation of the CMM. This feature of a CMM can also be used in combination with the other features described herein and/or can be used independently in other types of CMMs. For example, as described above, this sleep mode can be induced by movement into a particular position. As a further example, the encoder disk 38a can be an absolute encoder disk 95.

[0066] Additionally, in some embodiments the CMM arm 1 can be associated with calibration software. Generally, calibration of a CMM arm can be performed by positioning the distal end of the CMM arm (e.g. the probe) at certain predefined and known positions, and then measuring the angular position of the arm. However, these calibration points often do not define a unique arm orientation, but instead can be reached with a plurality of arm positions. To improve the effectiveness of the calibration procedure, software can be included that indicates a preferred or desired CMM arm calibration position 1a, including the distal point as well as the orientation of the rest of the arm. Further, in some embodiments the software can also show the arm's current position 1b in real time as compared to the desired position 1a, as depicted in Figure 7. Even further, in some embodiments the software can highlight portions of the arm that are out of alignment with the desired position 1a.

[0067] As depicted in Figure 7A, the calibration software can be included on a separate, auxiliary device such as a computer 210 coupled to a display 220 and one or more input devices 230. An operator 240 may plan a calibration procedure using system the computer 210 by manipulating the one or more input devices 230, which may be a keyboard and / or a mouse. The display 220 may include one or more display regions or portions, each of which displays a different view of the CMM arm 1 in its current position, and optionally a desired calibration position (as described above). Each of these displays may be linked internally within a program and data on computer 210. For example, a program running on a computer 210 may have a single internal representation of the CMM arm's current position in memory and the internal representation may be displayed in two or more abstract or semi-realistic manners on display 220.

[0068] In various embodiments, the computer 210 may include one or more processors, one or more memories, and one or more communication mechanisms. In some embodiments, more than one computer may be used to execute the modules, methods, and processes discussed herein. Additionally, the modules and processes herein may each run on one or multiple processors, on one or more computers; or the modules herein may run on dedicated hardware. The input devices 230 may include one or more keyboards (one-handed or two-handed), mice, touch screens, voice commands and associated hardware, gesture

recognition, or any other means of providing communication between the operator 240 and the computer 210. The display 220 may be a 2D or 3D display and may be based on any technology, such as LCD, CRT, plasma, projection, et cetera.

[0069] The communication among the various components of system 200 may be accomplished via any appropriate coupling, including USB, VGA cables, coaxial cables, FireWire, serial cables, parallel cables, SCSI cables, IDE cables, SATA cables, wireless based on 802.11 or Bluetooth, or any other wired or wireless connection(s). One or more of the components in system 200 may also be combined into a single unit or module. In some embodiments, all of the electronic components of system 200 are included in a single physical unit or module.

[0070] The enhanced capabilities of the calibration software can allow the operator to refer simply to the live images on the display and position the live image over the desired image which reduces the need for manuals or additional training documentation which slows down the calibration process. Additionally, new calibration technicians can be trained accurately and quickly with the aid of the aforementioned display. The data acquired from these methods of calibration can be more repeatable and more accurate due to, e.g., increased consistency of articulations. In addition to positioning of the CMM in the correct pose, the calibration artifact 120 should be positioned in the correct location within the arm's volume of reach. When the display shows a true 3 dimensional image, the position of the calibration artifact in 3D space can also be correctly displayed, further ensuring that the correct volume of measurement is measured.

[0071] These calibration features of a CMM can also be used in combination with the other features described herein and/or can be used independently in other types of CMMs. For example, in some embodiments the calibration process can utilize commands based on the position and motion of the CMM (as discussed above). In some embodiments, during calibration holding the arm still for an extended period of time can indicate to the calibration software that the arm is in the desired position. The software can then acknowledge its processing of this command with a change in display, sound, color, etc. This result can then be confirmed by the operator with a rapid motion of the arm out of said position. The calibration software can then indicate a next calibration point, or indicate that calibration is

complete. In addition this functionality can be extended to the operator as well. One example is during the calibration of the probe the software can display the required articulation pose that the CMM should be in as well as the actual pose that it is in. The operator can then move the CMM until it is in the correct position and record a position or it can be recorded automatically. This simplifies the process for the user and improves the accuracy of the data taken. Different methods can be presented depending on the type of probe that is sensed to be present such as laser line scanner, touch trigger probe, etc.

[0072] Even further, in some embodiments the CMM arm 1 can include a tilt sensor. In some embodiments the tilt sensor can have an accuracy of at least approximately 1 arc-second. The tilt sensor can be included in the base 10, a feature pack 90, or in other parts of the CMM arm 1. When placed in the base 10 or the feature pack 90, the tilt sensor can detect movement of the CMM arm's support structure, such as a table or tripod on which the arm sits. This data can then be transferred to processing modules elsewhere in the arm or to an external device such as a computer. The CMM arm 1 or the external device can then warn the user of the movement in the base and/or attempt to compensate for the movement, for example when the tilt changes beyond a threshold amount. Warnings to the user can come in a variety of forms, such as sounds, LED lights on the handle 40 or generally near the end of the arm 1, or on a monitor connected to the arm 1. Alternatively or additionally, the warning can be in the form of a flag on the data collected by the arm 1 when tilting has occurred. This data can then be considered less accurate when analyzed later. When attempting to compensate for the movement, in some embodiments the tilting and its effects on position can be partially measured and accounted for in the calibration process. In further embodiments, the tilting can be compensated by adjusting the angular positions of the articulation members accordingly. This feature of a CMM can also be used in combination with the other features described herein and/or can be used independently in other types of CMMs.

[0073] In further embodiments, a trigger signal is sent from the arm to the scanner upon each measurement of the arm position. Coincident with the arm trigger the arm can latch the arm position and orientation. The scanner can also record the time of receipt of the signal (e.g. as a time stamp), relative to the stream of scanner images being captured

(also, e.g., recorded as a time stamp). This time signal data from the arm can be included with the image data. Dependent on the relative frequency of the two systems (arm and scanner) there may be more than one arm trigger signal per scanner image. It might not be desirable to have the arm running at a lower frequency than the scanner, and this usually results in the arm and scanner frequencies being at least partially non-synchronized. Post-processing of the arm and scanner data can thus combine the arm positions by interpolation with the scanner frames to estimate the arm position at the time of a scanner image. In some embodiments, the interpolation can be a simple, linear interpolation between the two adjacent points. However, in other embodiments higher-order polynomial interpolations can be used to account for accelerations, jerks, etc. This feature of a CMM can also be used in combination with the other features described herein and/or can be used independently in other types of CMMs.

[0074] The various devices, methods, procedures, and techniques described above provide a number of ways to carry out the invention. Of course, it is to be understood that not necessarily all objectives or advantages described may be achieved in accordance with any particular embodiment described herein. Also, although the invention has been disclosed in the context of certain embodiments and examples, it will be understood by those skilled in the art that the invention extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses and obvious modifications and equivalents thereof. Accordingly, the invention is not intended to be limited by the specific disclosures of preferred embodiments herein.

WHAT IS CLAIMED IS:

1. An articulated arm CMM comprising:
an articulated arm comprising a plurality of transfer members, a plurality of articulation members connecting at least two transfer members to each other, a coordinate acquisition member at a distal end, and a base at a proximal end;
wherein at least two of the articulation members each comprise at least one encoder and the at least two encoders are both enclosed within a single monoblock housing.
2. The articulated arm CMM of Claim 1 wherein the monoblock housing comprises a removable cover portion.
3. The articulated arm CMM of Claim 2 wherein the removable cover portion occludes an opening of the housing through which an encoder can be inserted into the housing.
4. The articulated arm CMM of any of the preceding claims wherein the housing comprises a hinge-receiving portion and a swivel receiving portion.
5. The articulated arm CMM of any of the preceding claims wherein the at least two encoders are configured to detect rotation about at least two axes that are perpendicular to each other.
6. The articulated arm CMM of any of the preceding claims wherein the at least two encoders can be inserted and removed independently.
7. An articulated arm CMM comprising:
an articulated arm comprising a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end; and
a gas spring counterbalance supporting the arm at a rotational point between adjacent articulated arm members;
wherein the gas spring counterbalance connects to an articulated arm member closer to the base at a point nearer to the rotational point than to the base.
8. The articulated arm CMM of Claim 7, wherein the gas spring counterbalance comprises an integral locking mechanism.

9. The articulated arm CMM of either of Claims 7 and 8, wherein the gas spring counterbalance comprises nitrogen gas.

10. The articulated arm CMM of any of Claims 7-9, wherein the gas spring counterbalance comprises a lock that can increase a resistance against movement of the gas spring counterbalance.

11. The articulated arm CMM of Claim 10, wherein the lock comprises a lever and a pushing pin that can open and close an aperture within the gas spring counterbalance, controlling gas flow.

12. An articulated arm CMM comprising:

an articulated arm comprising a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end; and

a gas spring counterbalance supporting the arm at a rotational point between two adjacent articulated arm members;

wherein rotation at the rotational point brings one of the two adjacent articulated arm members to a substantially horizontal position when the gas spring counterbalance is also brought to a substantially horizontal position.

13. The articulated arm CMM of Claim 12, wherein the gas spring counterbalance comprises an integral locking mechanism.

14. The articulated arm CMM of either of Claims 12 and 13, wherein the gas spring counterbalance comprises nitrogen gas.

15. The articulated arm CMM of any of Claims 12-14, wherein the gas spring counterbalance comprises a lock that can increase a resistance against movement of the gas spring counterbalance.

16. The articulated arm CMM of Claim 15, wherein the lock comprises a lever and a pushing pin that can open and close an aperture within the gas spring counterbalance, controlling gas flow.

17. An articulated arm CMM comprising:

an articulated arm comprising a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end; and

a handle comprising electronics and removably connected to the coordinate acquisition member.

18. The articulated CMM of Claim 17, wherein the handle provides modular functionality.

19. The articulated CMM of either of Claims 17 and 18, wherein the electronics are thermally isolated from the articulated arm.

20. The articulated CMM of any of Claims 17-19, the handle is thermally isolated from the articulated arm.

21. A method of operating an articulated arm CMM comprising inputting an instruction to the CMM arm by an action chosen from the group consisting of placing the arm in a predefined position and moving the arm in a predefined manner.

22. The method of Claim 21, wherein the step of inputting is performed without actuating any buttons, levers, dials, or other traditional actuation devices.

23. The method of either of Claims 21 and 22, further comprising the steps of:
placing the articulated arm into a retracted position; and
the arm entering a sleep mode automatically after the step of placing the articulated arm into a retracted position.

24. The method of any of Claims 21-23, further comprising the step of awakening the articulated arm from a sleep mode by rapidly moving the arm.

25. The method of any of Claims 21-23, further comprising the step of awakening the articulated arm from a sleep mode by moving the arm into an extended position.

26. The method of any of Claims 21-25, further comprising the step of changing the arm's data acquisition mode automatically when the arm is moved slowly.

27. The method of Claim 26, wherein the arm's data acquisition mode is changed to a higher frequency or higher accuracy mode upon slow movement of the arm.

28. The method of any of Claims 21-27, further comprising the steps of:
indicating that a desired calibration position has been reached by holding the arm still for an extended period of time; and
confirming that the calibration position with a rapid movement of the arm.

29. The method of Claim 28, wherein the step of confirming is performed after the indication that a desired calibration position has been reached is acknowledged by the arm or an auxiliary device in communication with the arm.

30. An articulated arm CMM configured to receive instructions from actions chosen from the group consisting of placing the arm in a predefined position and moving the arm in a predefined manner.

31. A method for calibrating an articulated arm CMM comprising:
indicating a calibration point and an associated arm calibration position to a user;

moving a distal end of an articulated arm to the calibration point; and
moving the articulated arm to the calibration position.

32. The method of Claim 31, wherein the step of indicating a calibration point and associated arm calibration position comprises displaying the arm calibration position.

33. The method of either of Claims 31 and 32, further comprising the step of displaying the current position of the articulated arm during the moving steps.

34. The method of any of Claims 31-33, further comprising the step of displaying a calibration artifact representative of one or more calibration positions.

35. The method of any of Claims 31-34, further comprising the step of highlighting a portion out of alignment from the calibration position.

36. The method of any of Claims 31-35, further comprising the step of indicating that a calibration position has been reached.

37. The method of Claim 36, wherein the step of indicating that a calibration position has been reached comprises holding the arm still for an extended period of time.

38. The method of either of Claims 36 and 37, wherein the step of indicating that a calibration position has been reached comprises a change in display, sound, or color.

39. The method of any of Claims 36-38, further comprising confirming that a calibration position has been reached by rapidly moving the arm.

40. An articulated arm CMM system comprising an articulated arm CMM and a display in communication with the CMM, the display indicating a calibration point, an

associated calibration position, and a current position of the CMM simultaneously and in real-time.

41. An articulated arm CMM system comprising an articulated arm and a display, wherein the display illustrates a current position of the CMM and a desired position of the CMM

42. The system of claim 41 wherein the desired position of the CMM is one of a sequence of positions used for a probe calibration.

43. The system of claim 42 wherein the probe is a touch probe.

44. The system of claim 42 wherein the probe is a laser scanning probe.

45. A method of operating an articulated arm CMM comprising:

measuring one or more coordinates on an object with an articulated arm CMM;

at least partially powering off at least one encoder in the articulated arm CMM;

powering on said at least one encoder; and

measuring one or more coordinates on said object after powering on said encoder without re-indexing said encoder.

46. The method of Claim 45, wherein the step of powering off comprises fully powering off said encoder.

47. The method of either of Claims 45 and 46, further comprising the step of putting the CMM in a sleep mode.

48. The method of any of Claims 45-47, further comprising the step of combining the measured coordinates from before and after the powering off step into a single data set representing the measured object.

49. An articulated arm CMM comprising:

an articulated arm comprising a plurality of articulated arm members, a coordinate acquisition member at a distal end, and a base at a proximal end;

wherein at least one of the articulation members comprises an absolute encoder.

50. The articulated arm CMM of Claim 49, wherein the at least one absolute encoder is configured to enter a sleep mode during which it does not measure its position.

51. The articulated arm CMM of Claim 50, wherein the at least one absolute encoder is powered off during said sleep mode.

52. The articulated arm CMM of any of Claims 49-51, wherein the at least one absolute encoder is configured to enter a mode in which it reads position at a lower frequency.

53. The articulated arm CMM of any of Claim 49-52, wherein the absolute encoder comprises a non-repeating pattern.

54. The articulated arm CMM of Claim 53, wherein the pattern comprises varying reflective properties.

55. The articulated arm CMM of either of Claims 53 and 54, wherein the pattern comprises varying translucent properties.

56. The articulated arm CMM of any of Claims 53-55, wherein the pattern comprises varying magnetic properties.

57. The articulated arm CMM of any of Claims 49-56, wherein the arm comprises a plurality of measured axes of rotation and at least one absolute encoder for each measured axis of rotation.

58. The articulated arm CMM of any of Claims 49-57, wherein the absolute encoder consists of more than one readhead.

59. An articulated arm CMM comprising:

an articulated arm comprising a plurality of articulated arm members, a measuring probe, at a distal end, and a base at a proximal end:

a tilt sensor rigidly connected to the base such that the tilt sensor can detect a tilting angle of the base.

60. The articulate arm CMM of Claim 59, wherein the arm provides a signal to a user when the tilt of the base changes beyond a threshold amount.

61. The articulated arm CMM of either of Claims 59 and 60, wherein the arm or an external device compensates the data for tilting sensed by the tilt sensor.

62. The articulated arm CMM of any of Claims 59-61, wherein the arm or an external device flags data taken while the tilt of the base has changed beyond a threshold amount.

63. A method of operating an articulated arm CMM comprising:
measuring one or more coordinates with an articulated arm CMM;
continuously measuring the tilt of the articulated arm CMM; and
when the measured tilt exceeds a threshold value, performing an action in response to the tilt.

64. The method of Claim 63, wherein the action comprises compensating the measured coordinates for the tilt.

65. The method of either of Claims 63 and 64, wherein the action comprises providing a signal regarding the tilt to a user.

66. The method of any of Claims 63-65, wherein the action comprises flagging the measured coordinates taken during the tilt.

67. An articulated arm CMM comprising:
an articulated arm comprising a plurality of articulated arm members, a measuring probe at a distal end, and a base at a proximal end; and
a docking portion on the base, the docking portion configured to form a connection with a modular feature pack.

68. The articulated arm CMM of Claim 67, wherein the docking portion comprises an electronic connector configured to form an electronic connection with the feature pack.

69. The articulated arm CMM of Claim 68, wherein the electronic connection comprises a data transfer connection.

70. The articulated arm CMM of either of Claims 68 and 69, wherein the electronic connection comprises a power transmission connection.

71. The articulated arm CMM of any of Claims 67-70, wherein the docking portion comprises a mechanical connection.

72. The articulated arm CMM of any of Claims 67-71, wherein the docking portion comprises a thermal connection.

73. The articulated arm CMM of Claim 72, wherein the docking portion connects to electronics in the arm by thermally conductive members, allowing substantial heat transfer between the arm and the feature pack.

74. An articulated arm CMM system comprising:

an articulated arm comprising a plurality of articulated arm members, a measuring probe at a distal end, and a base at a proximal end, the base comprising a docking portion; and

a plurality of feature packs configured to electronically connect to the articulated arm via the docking portion and provide additional electronic functionality.

75. The articulated arm CMM system of Claim 74, wherein at least one feature pack comprises a tilt sensor.

76. The articulated arm CMM system of either of Claims 74 and 75, wherein at least one feature pack comprises a data storage device.

77. The articulated arm CMM system of Claim 76, wherein the at least one feature pack comprising a data storage device comprises instructions for arm operation

78. The articulated arm CMM system of any of Claims 74-77, wherein at least one feature pack comprises a wireless capability for data transfer.

79. The articulated arm CMM system of any of Claims 74-78, wherein at least one feature pack includes a heat sink or cooling fan.

80. The articulated arm CMM system of any of Claims 74-79, wherein at least one feature pack comprises a battery.

81. A feature pack for an articulated arm portable CMM system comprising a modular design with a shape substantially matching the shape of the base of the portable CMM, the feature pack further comprising at least one electronic device providing additional functionality to the CMM.

82. The feature pack of Claim 81, wherein said functionality comprises data storage.

83. The feature pack of either of Claims 81 and 82, wherein said functionality comprises wireless data transfer capability

84. The feature pack of any of Claims 81-83, wherein said functionality comprises thermal heat transfer.

85. A coordinate measurement device comprising:

an articulated arm having a first end, a second end, and a plurality of jointed arm segments therebetween, each arm segment defining at least one axis of rotation, a last axis of rotation being defined by bearings near a distal end of the arm; and

a laser scanner assembly coupled to the distal end of the arm wherein the arm continuously generates trigger signals which are received by the laser scanner and indicate a time at which the arm's position is measured.

86. The CMM of Claim 85 wherein an arm measurement frequency is higher than a scanner measurement frequency.

87. The CMM of either of Claims 85 and 86 wherein the arm position at the time of a scanner image is calculated by interpolating between two arm positions based on times associated with the trigger signals and the time of the scanner image.

88. The CMM of any of Claims 85-87 wherein the trigger signal is created by a function generator in electronics in the arm.

89. A method of operating a coordinate measurement device comprising:

continuously measuring the position of an articulated arm;

generating a plurality of trigger signals upon each measurement of the position of the articulated arm;

transmitting the trigger signals to a scanner at an end of the articulated arm;

acquiring a scanner measurement from the scanner; and

associating the scanner measurement with a plurality of trigger signals.

90. The method of Claim 89, further comprising the step of associating an interpolated arm position with the scanner measurement.

91. The method of Claim 90, wherein the interpolation is a linear interpolation.

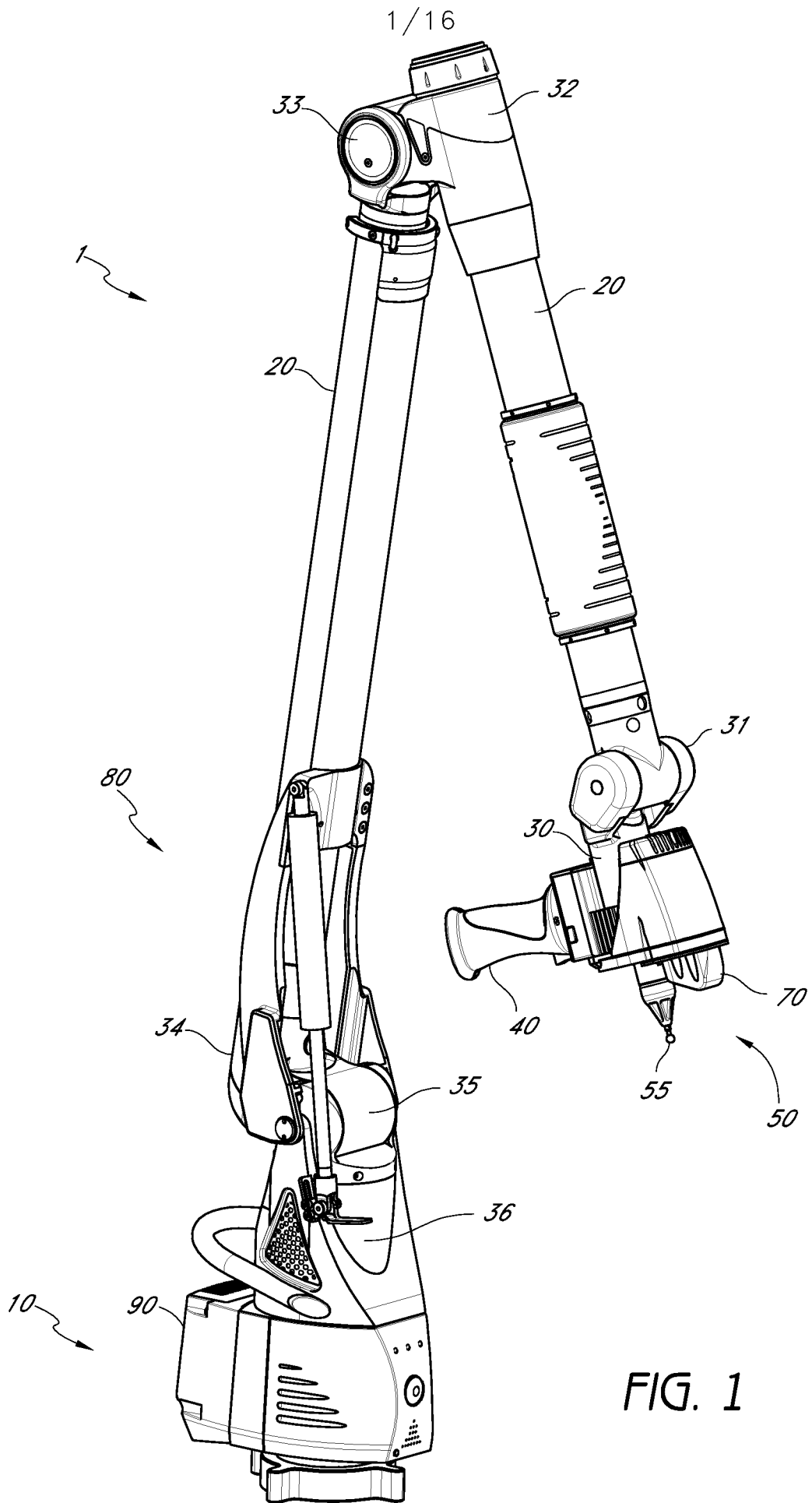
92. The method of Claim 90, wherein the interpolation is a higher order polynomial interpolation.

93. The method of any of Claims 89-92, wherein the step of continuously measuring comprises continuously outputting the angular position of a plurality of rotatable joints.

94. The method of any of Claims 89-93, wherein the scanner is a laser scanner.

95. The method of Claim 94, wherein the scanner measurement comprises coordinate measurements.

96. The method of any of Claims 89-95, wherein a frequency of measurement of the position of the articulated arm is higher than a frequency of measurement of the scanner.



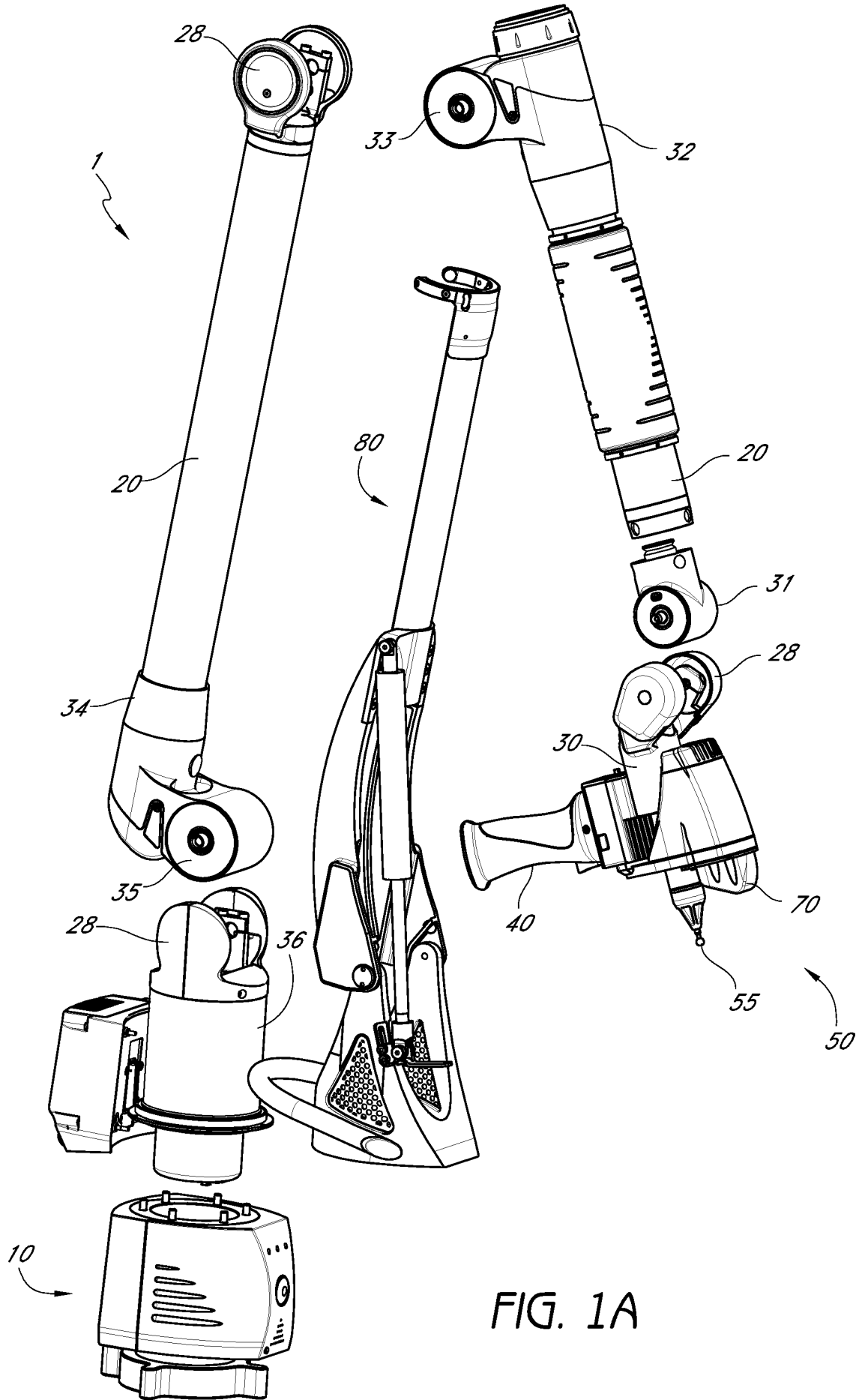


FIG. 1A

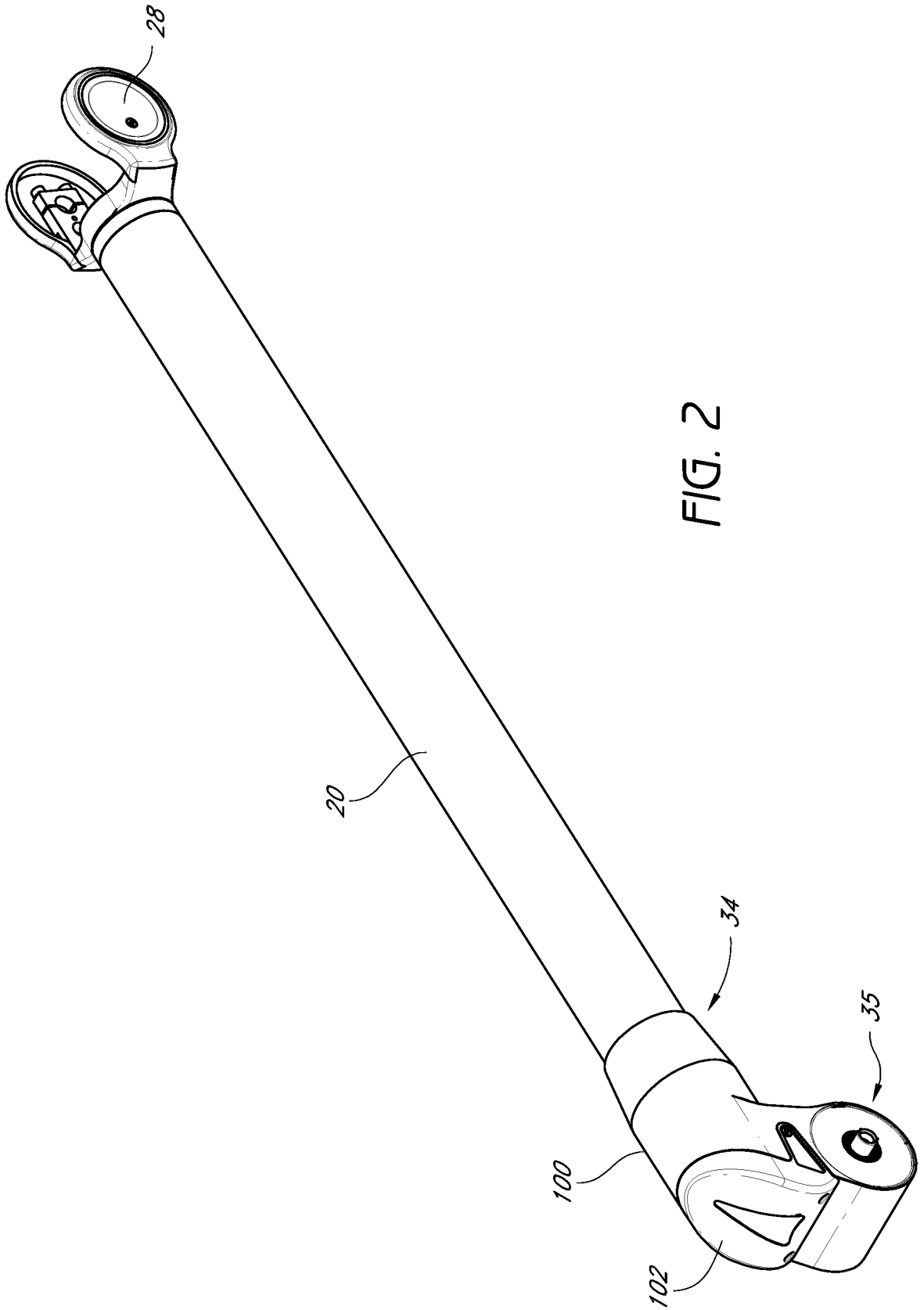


FIG. 2

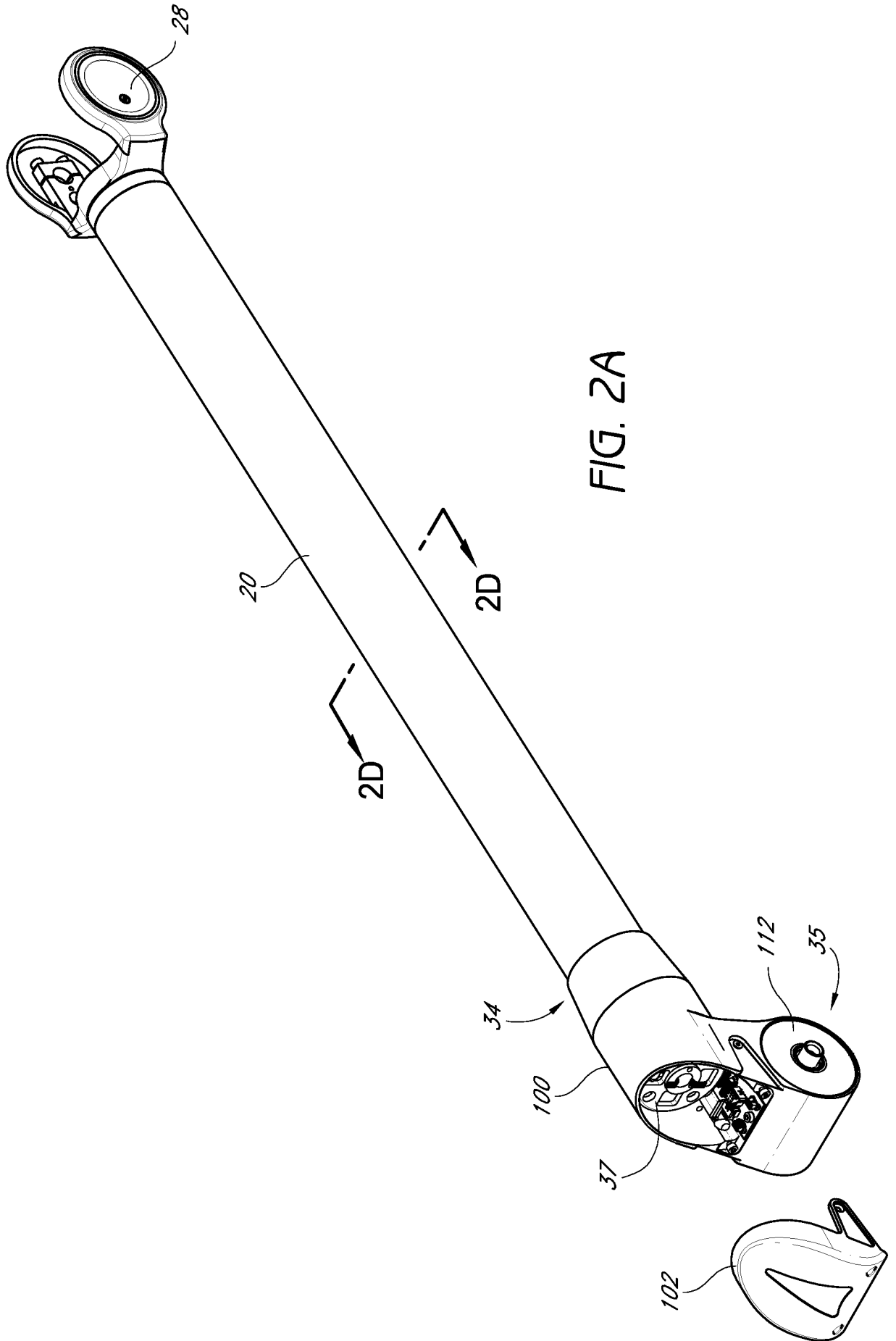
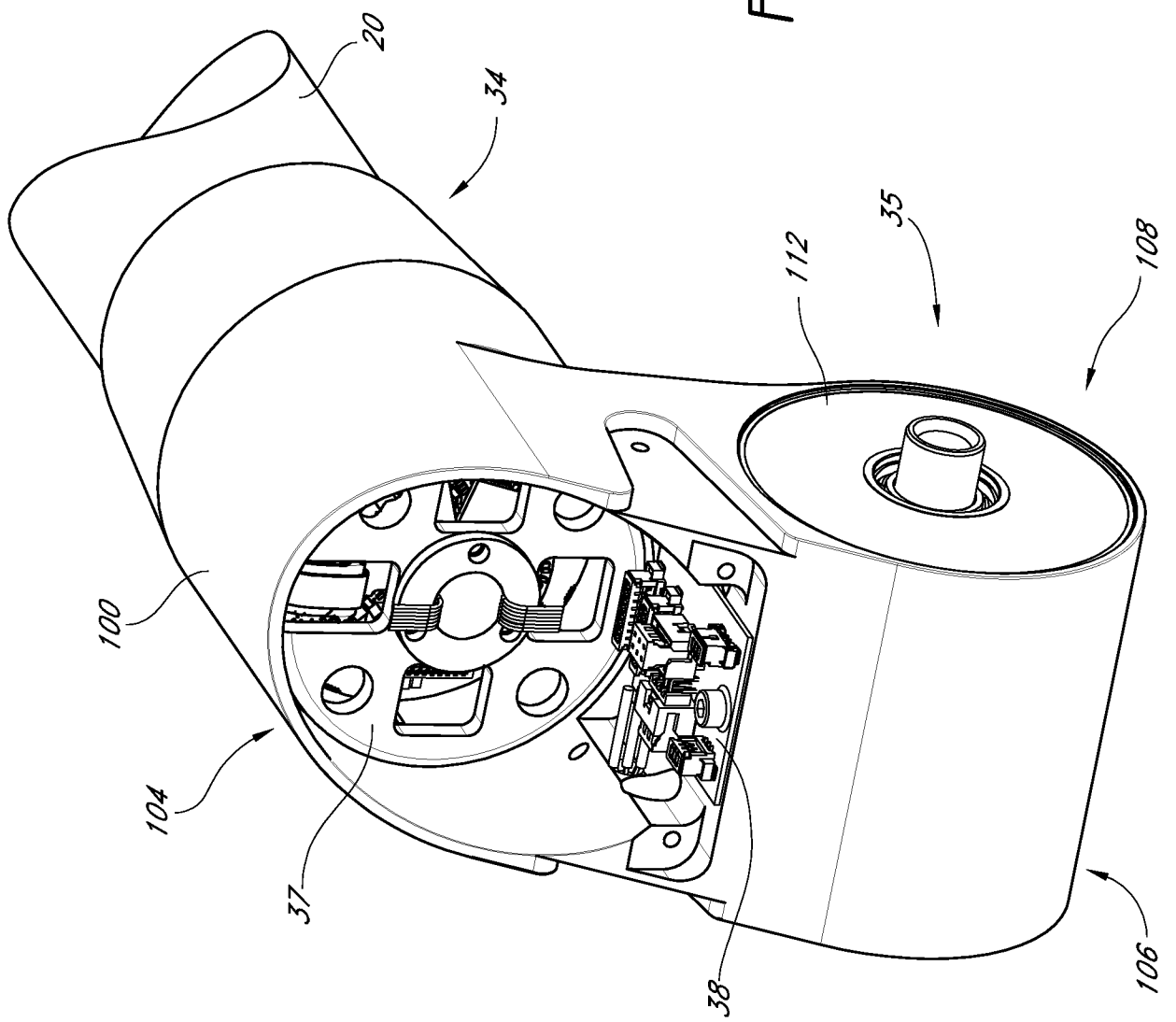


FIG. 2B



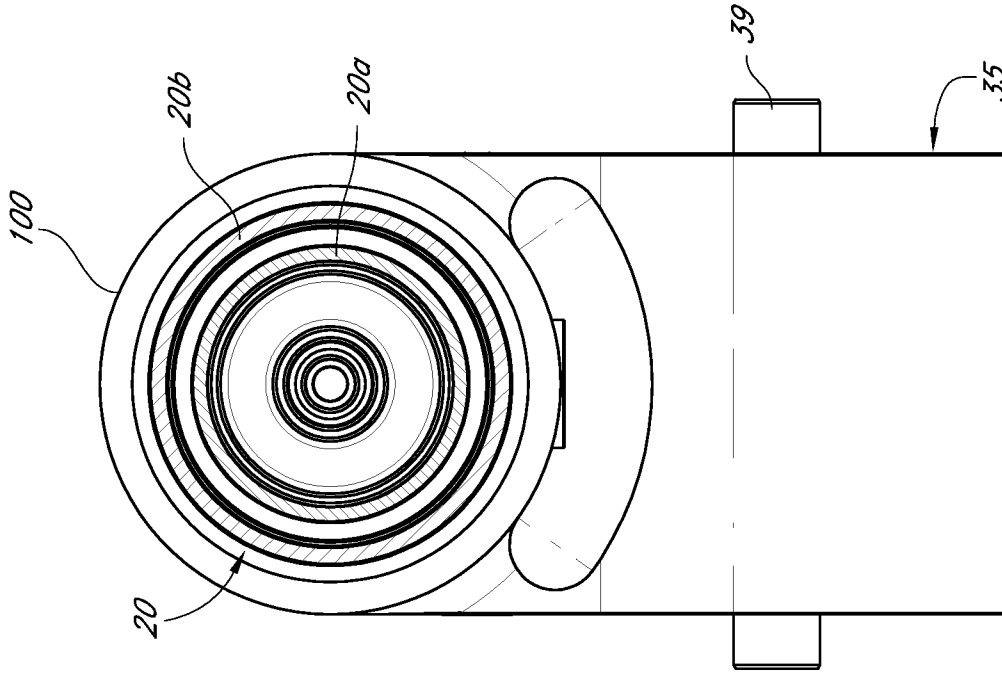


FIG. 2D

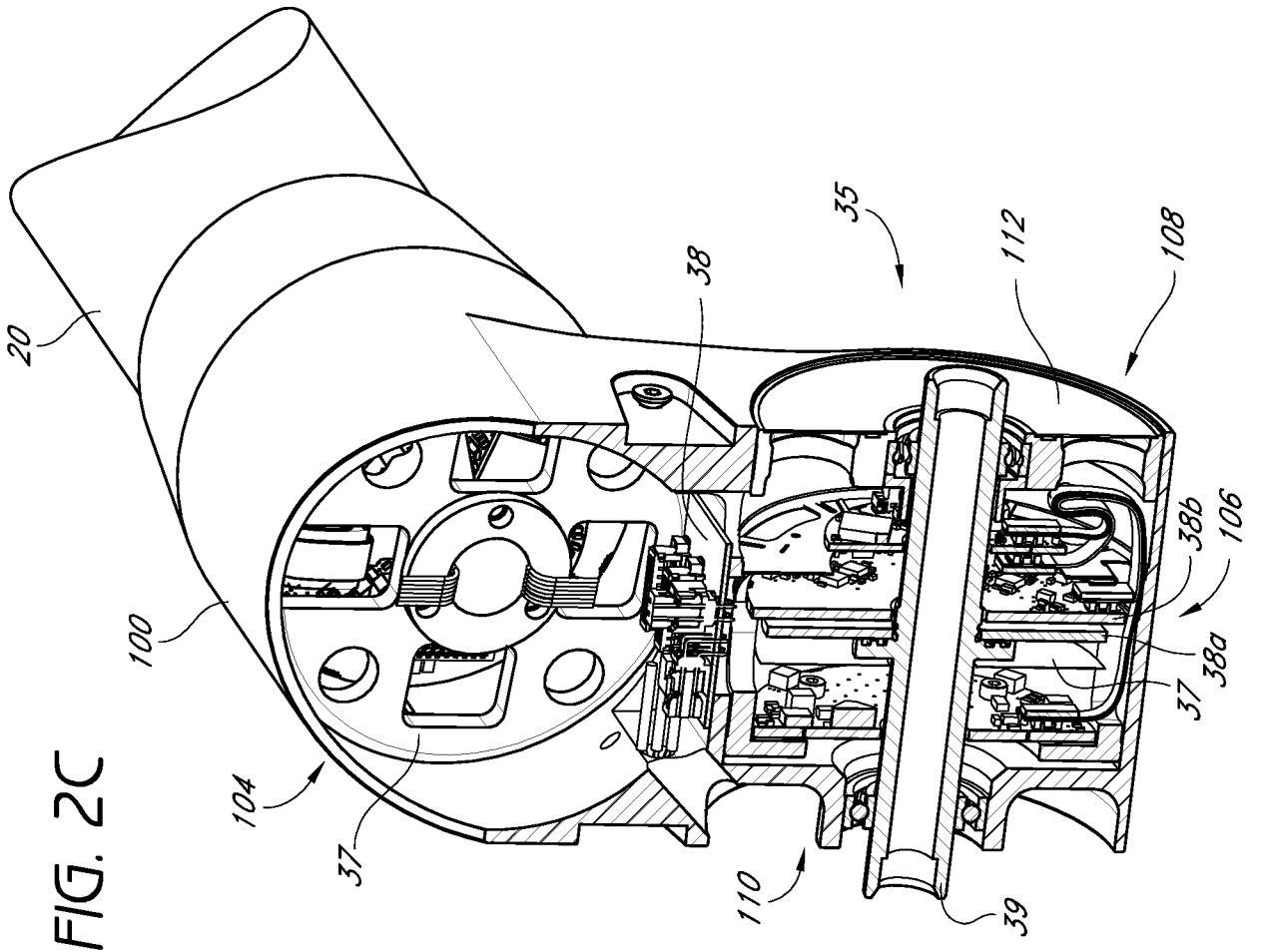


FIG. 2C

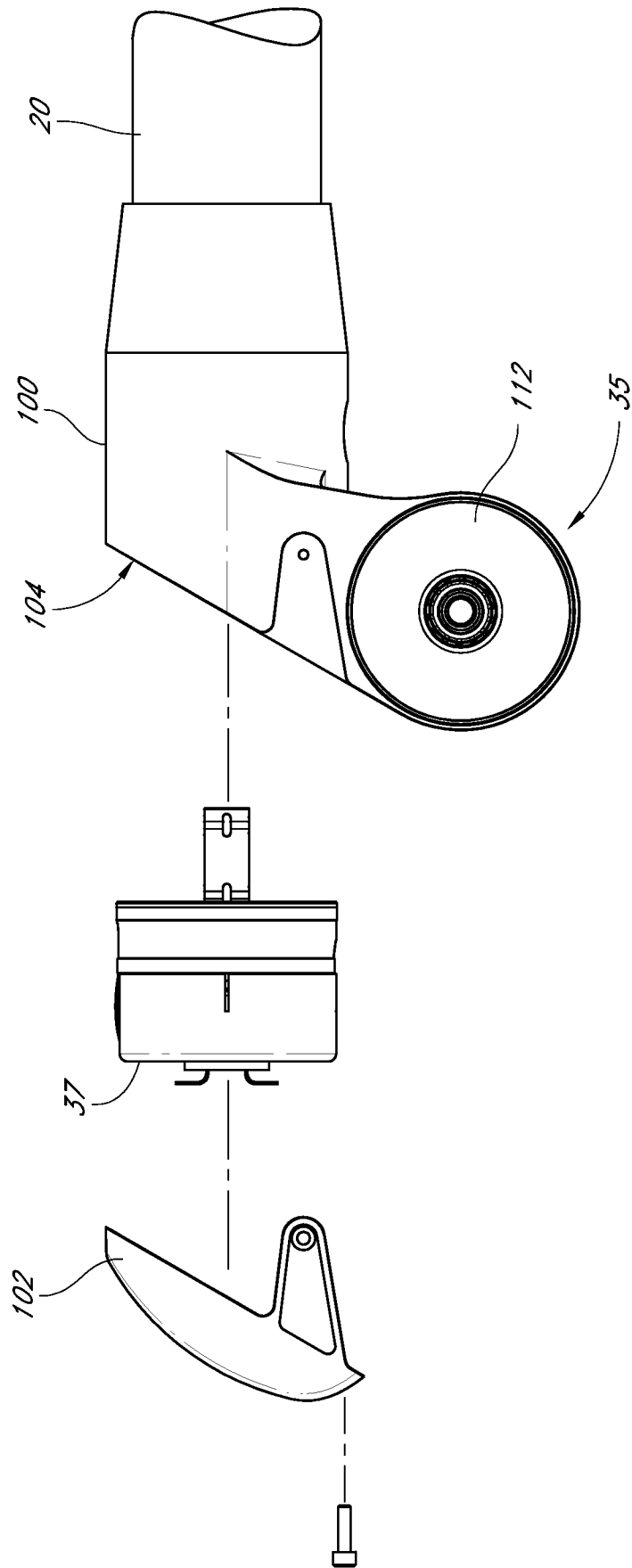


FIG. 2E

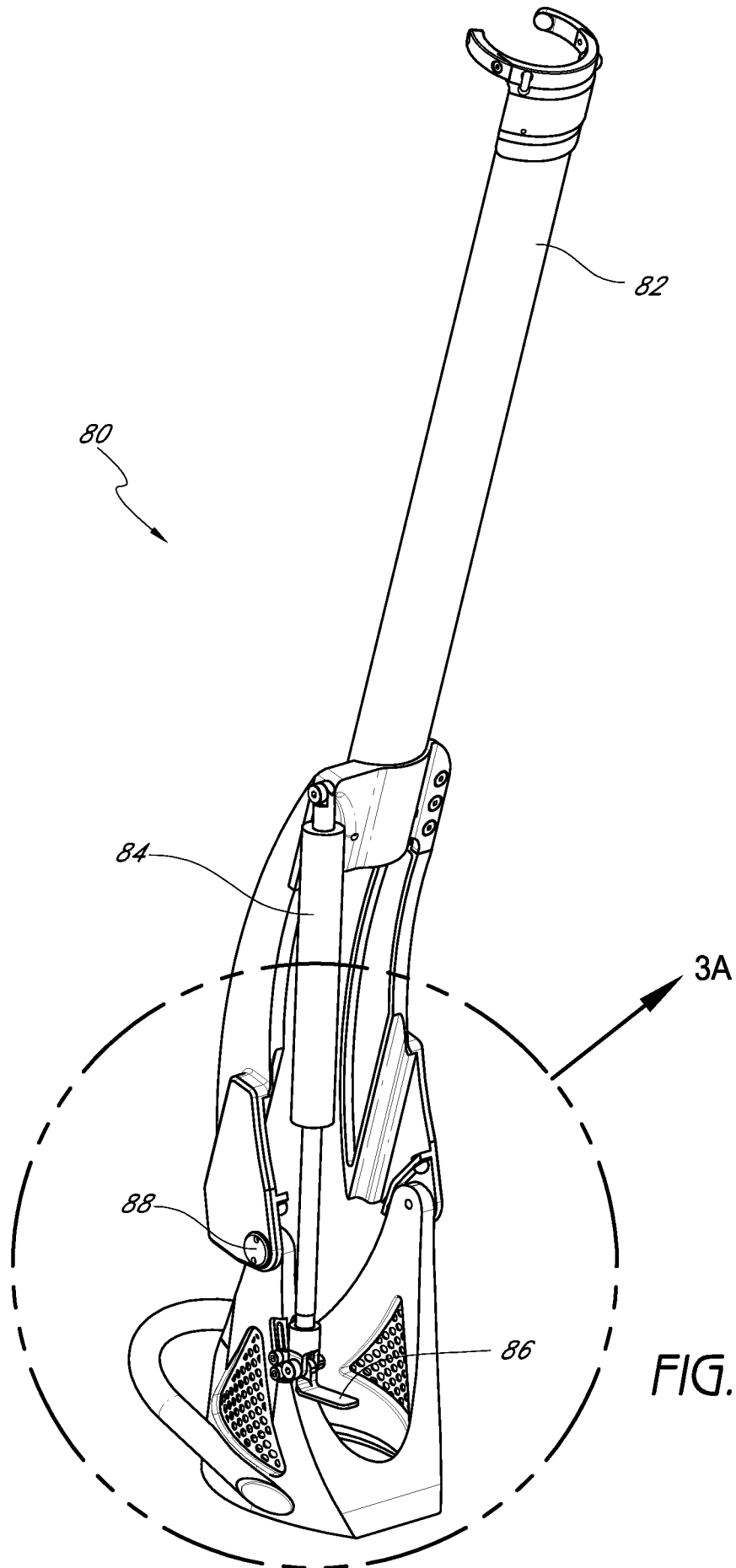


FIG. 3

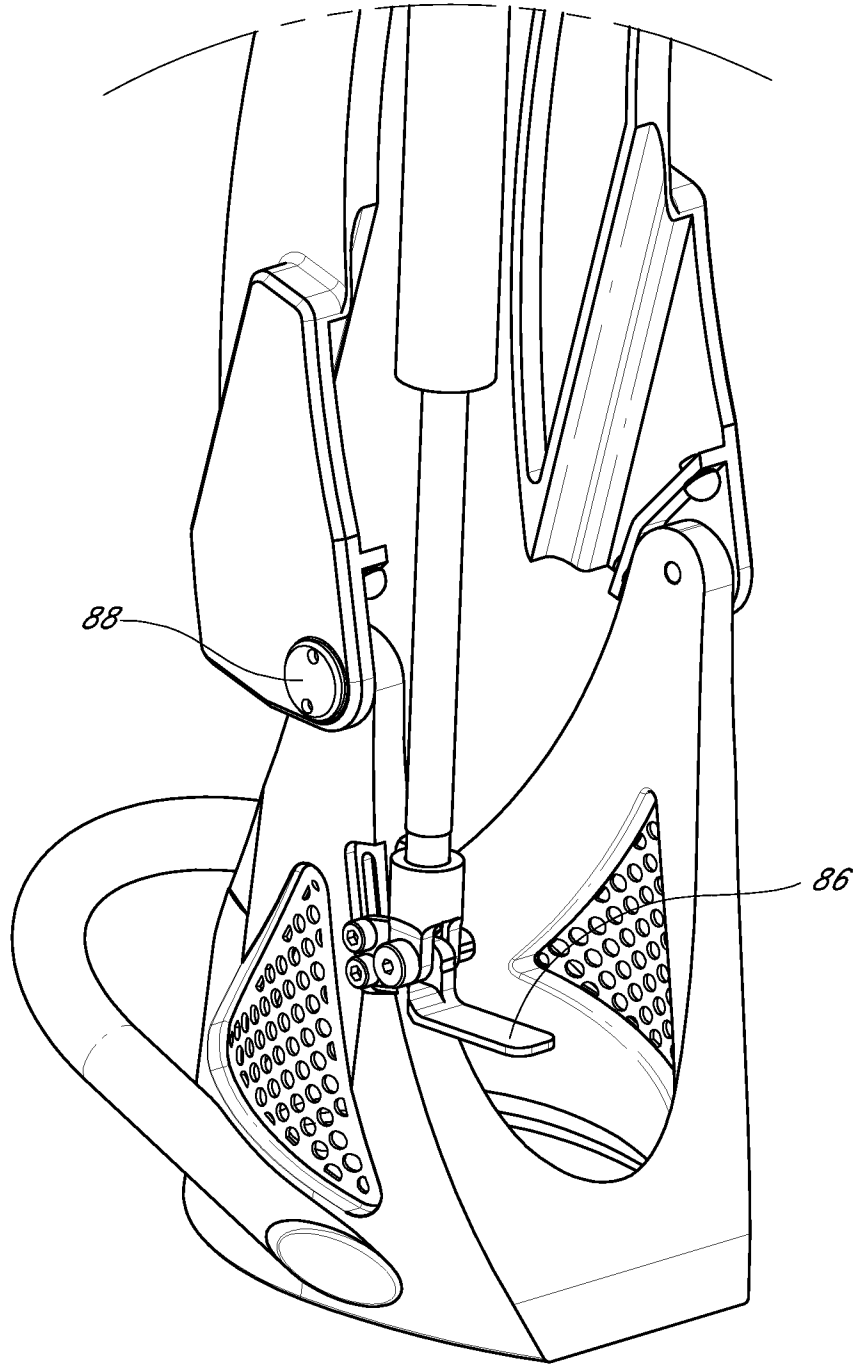


FIG. 3A

FIG. 3B

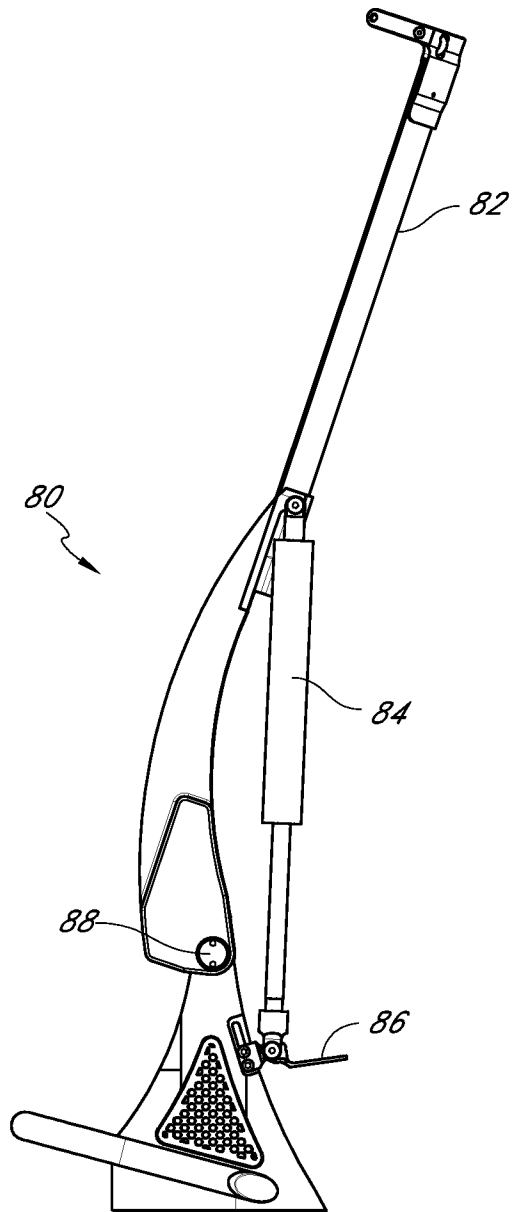
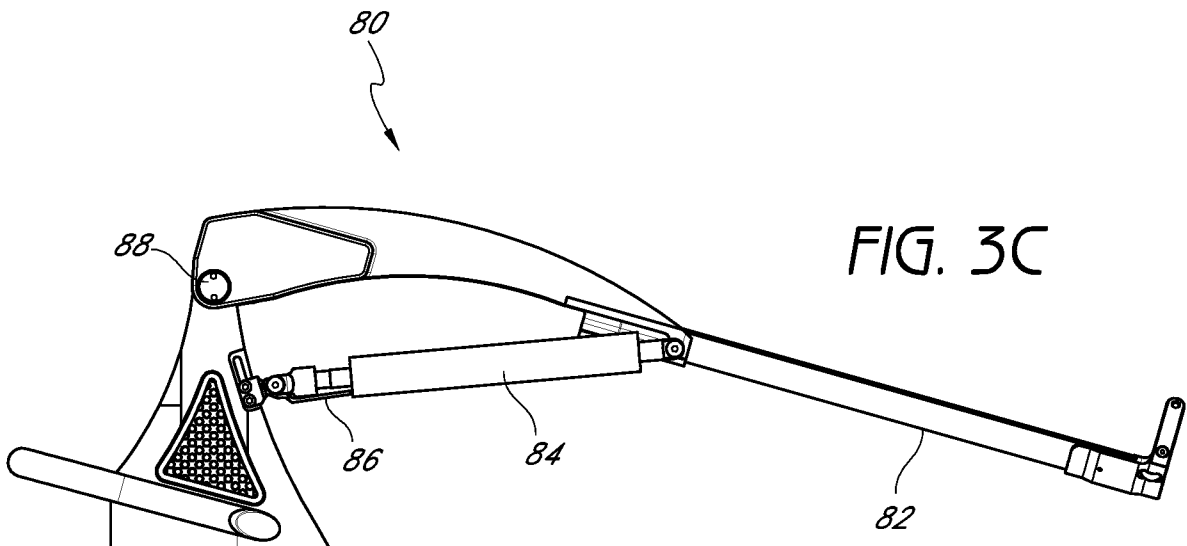


FIG. 3C



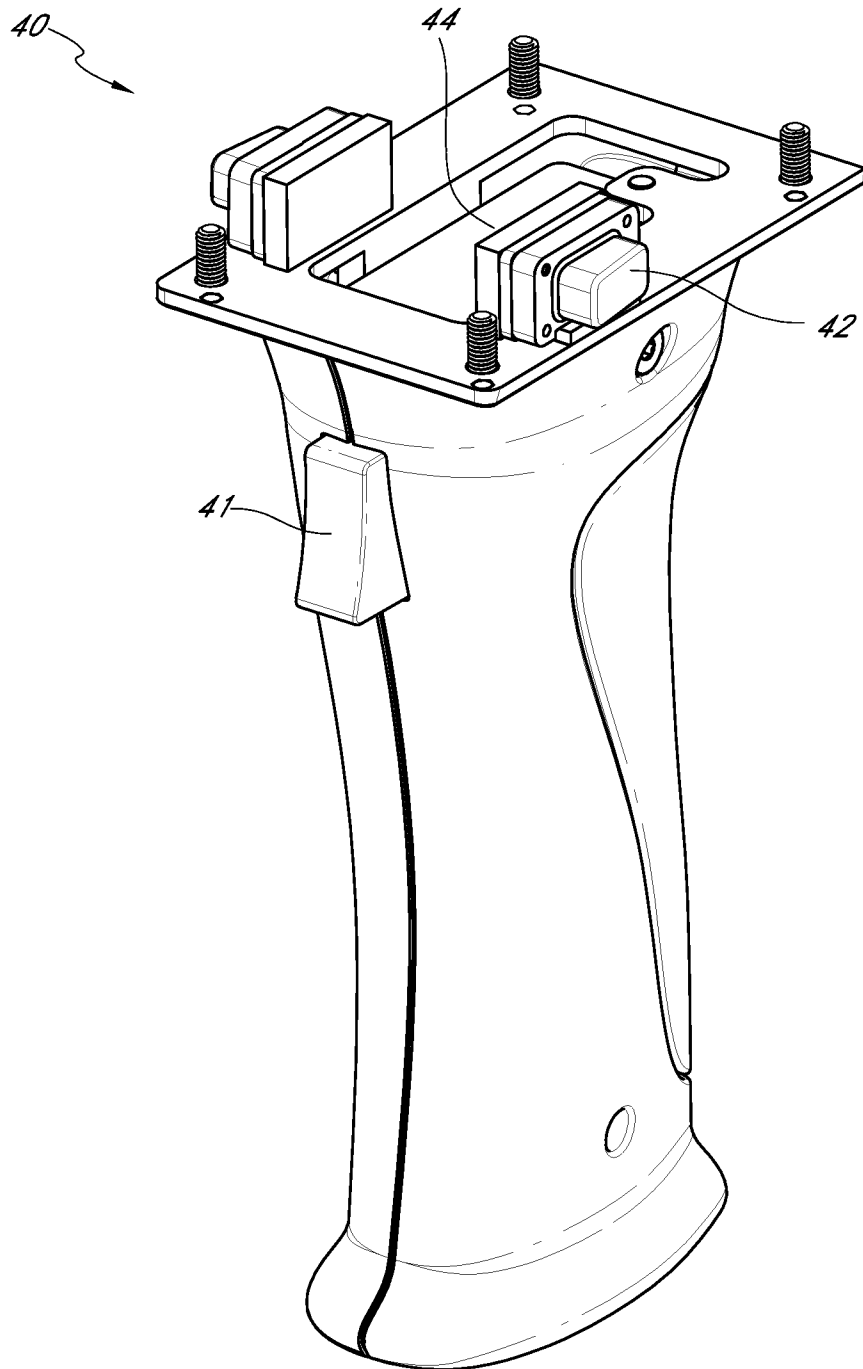


FIG. 4

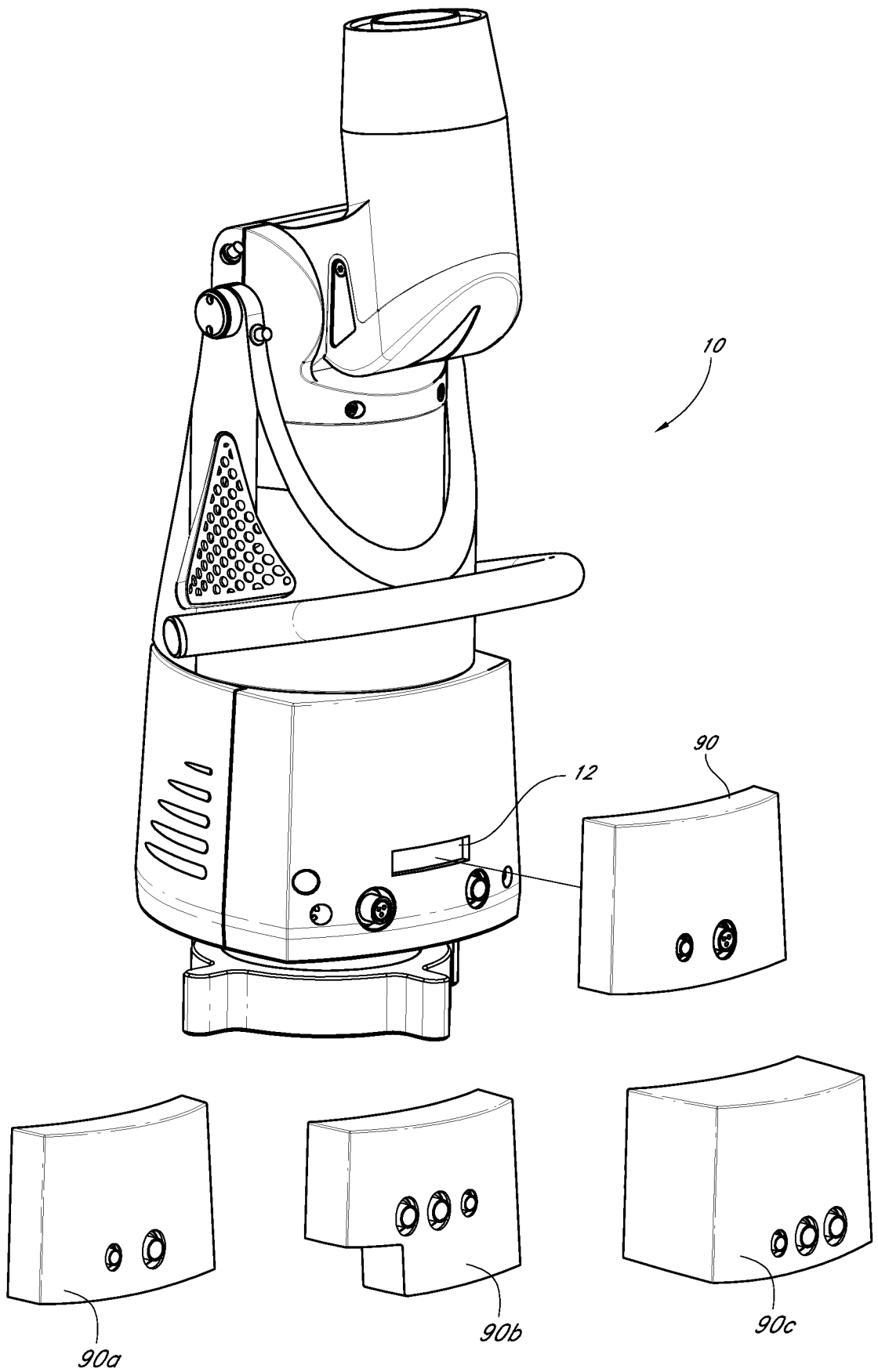


FIG. 5

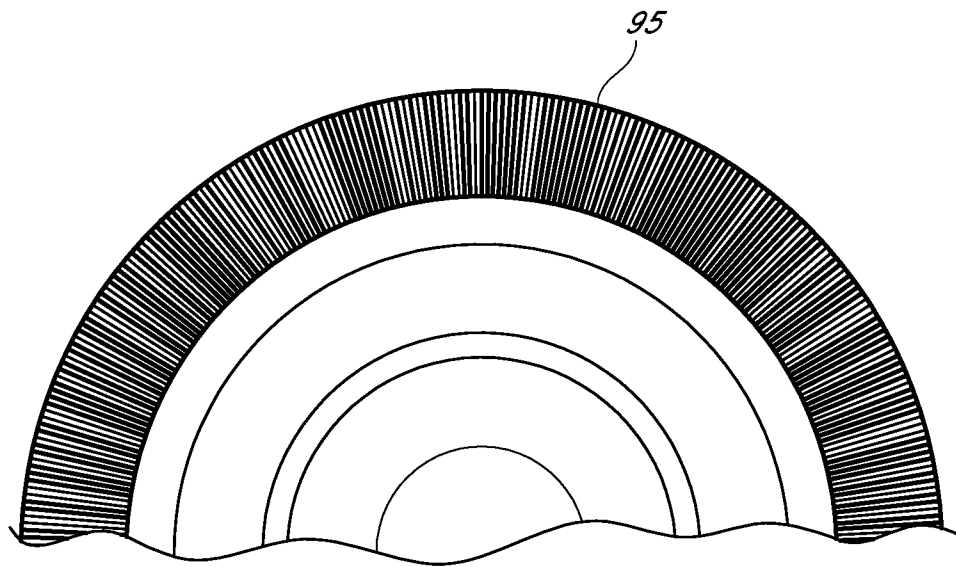


FIG. 6

120

1a

1b

Sub step

Point 1/6

Connected

15:16:36:203 - File 'shlbow38' already exists ...
15:16:36:265 - File 'shlbow38' contains 48 rows

Stop

#	Step
53	shlbow37
▷ 54	shlbow38
55	shlbow39
56	shlbow40
57	shlbow41
58	shlbow42
59	shlbow43
60	shlbow44
61	shlbow45
62	shlbow46
63	shlbow47
64	shlbow48
65	shlbow49
66	shlbow50
67	shlbow51
68	shlbow52
69	shlbow53
70	shlbow54
71	shlbow55
72	shlbow56
73	shlbow57
74	shlbow58
75	shlbow59
76	shlbow60
77	shlbow61
78	shlbow62

FIG. 7

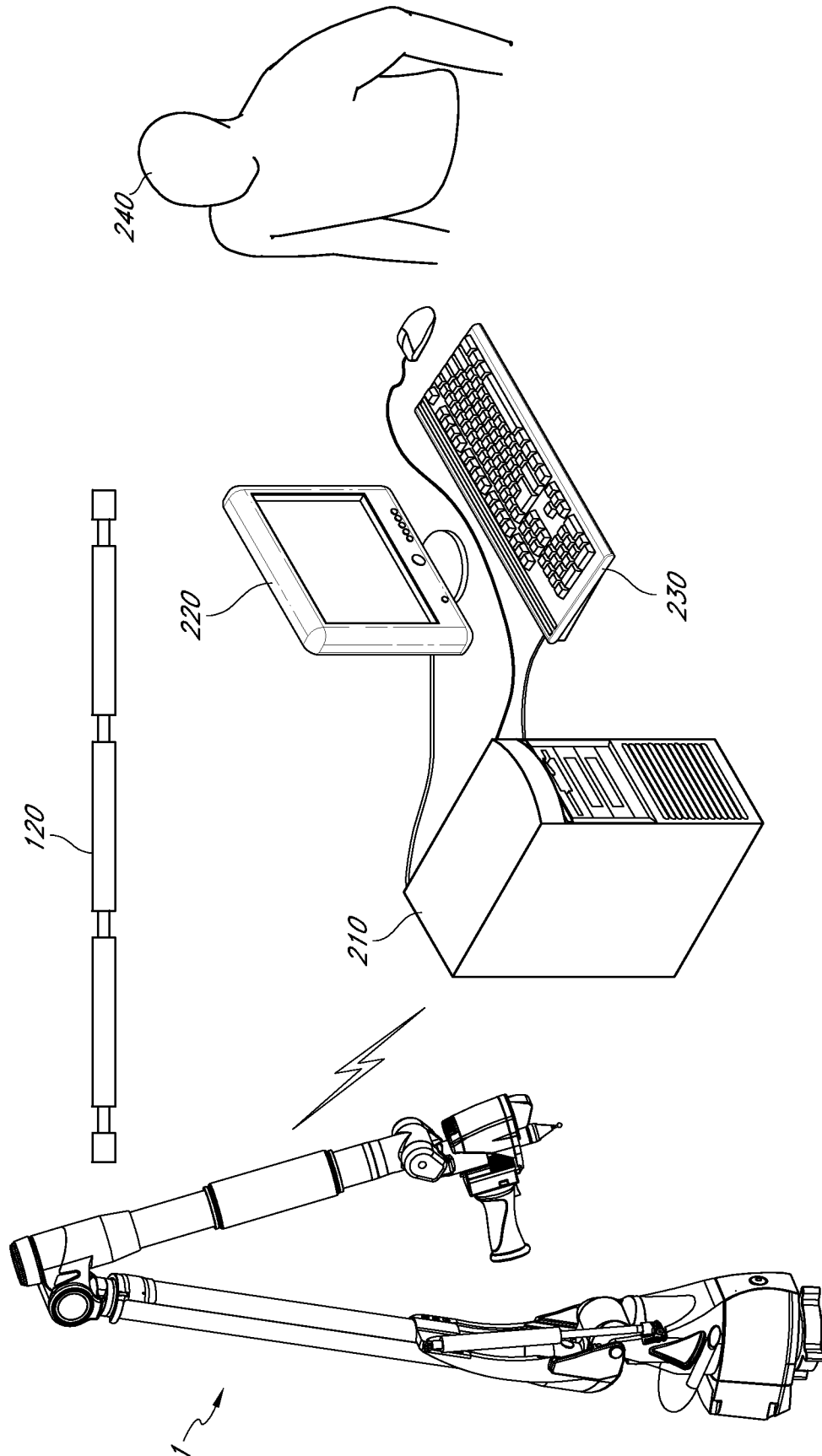


FIG. 7A

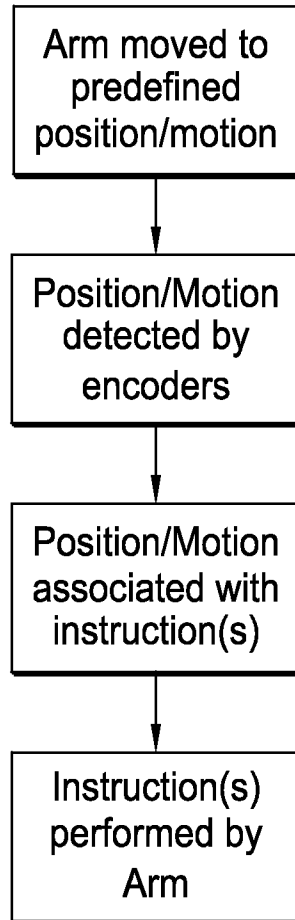


FIG. 8