(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
16 April 2026 (16.04.2026)

WIPO | PCT

(10) **International Publication Number**
WO 2026/080691 A1

(51) **International Patent Classification:**
B25J 15/12 (2006.01) ***B25J 15/00*** (2006.01)
B25J 15/02 (2006.01) ***B25J 9/00*** (2006.01)
B25J 17/02 (2006.01) *A61F 2/58* (2006.01)
B25J 18/00 (2006.01)

(21) **International Application Number:**
PCT/US2025/050215

(22) **International Filing Date:**
09 October 2025 (09.10.2025)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
63/706,004 10 October 2024 (10.10.2024) US

(71) **Applicant: TESLA, INC.** [US/US]; 1 Tesla Road, Austin, Texas 78725 (US).

(72) **Inventors: OLIVE, Harry Edward**; 1 Tesla Road, Austin, Texas 78725 (US). **LASKARIS, Konstantinos**; 1 Tesla Road, Austin, Texas 78725 (US). **SIZOV, Gennadi**; 1 Tesla Road, Austin, Texas 78725 (US). **GADDALA, Lalith Chandra**; 1 Tesla Road, Austin, Texas 78725 (US). **SOTIRIOU, Maria Ioanna**; 1 Tesla Road, Austin, Texas 78725 (US). **GUDGEL, Garrett**; 1 Tesla Road, Austin, Texas 78725 (US). **JUN, Hyungbin**; 1 Tesla Road, Austin, Texas 78725 (US). **AKTAR, Berat**; 1 Tesla Road, Austin, Texas 78725 (US). **BLATCHER, James Anthony**; 1 Tesla Road, Austin, Texas 78725 (US). **VAMVAKAS, Georgios**; 1 Tesla Road, Austin, Texas 78725 (US). **SARLI, Christopher William**; 1 Tesla Road, Austin, Texas 78725 (US). **REELIE, Douglas Dane**; 1 Tesla Road, Austin, Texas 78725 (US). **NORDMAN, Douglas**; 1 Tesla Road, Austin, Texas 78725 (US). **JASPERSON, Huntington Shin**; 1 Tesla Road, Austin, Texas 78725 (US).

(74) **Agent: SOPHIR, Eric** et al.; Foley & Lardner LLP, 3000 K Street N.W., Washington, District of Columbia 20007 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM,

(54) **Title:** ROBOTIC FOREARM ASSEMBLY

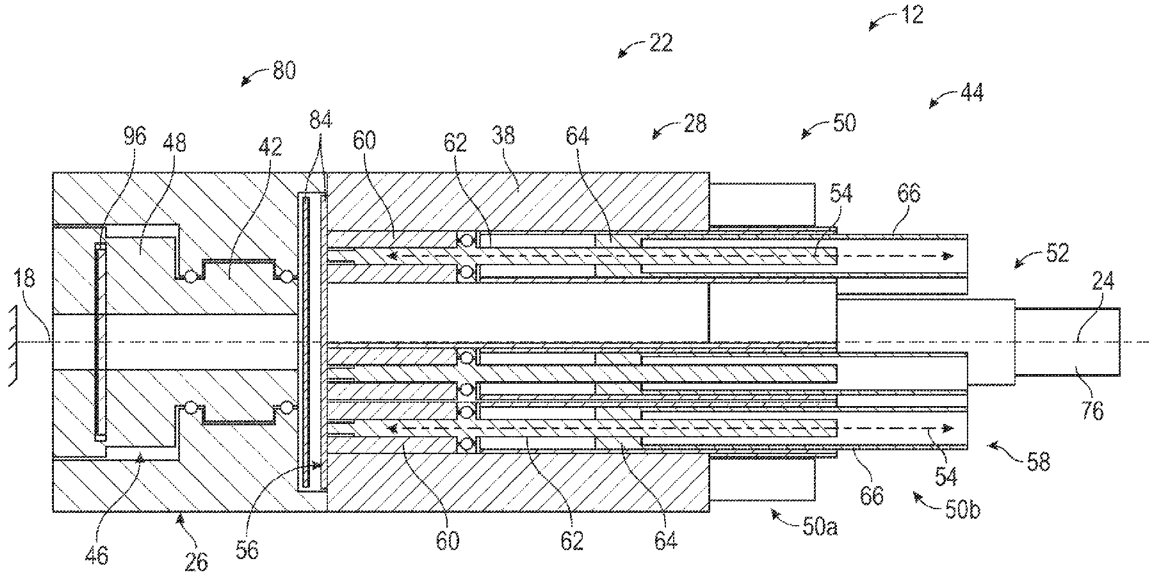

FIG. 5

(57) **Abstract:** A robotic forearm assembly includes a housing defining a central axis that extends along a first housing section and a second housing section, a rotary actuator arranged within the first housing section, a plurality of hand linear actuators, and a wrist linear actuator at least partially received within the second housing section and extending outwardly from the second housing section. Each of the plurality of hand linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section. The rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis. The plurality of hand linear actuators and the wrist linear actuator each extend along a longitudinal direction that is approximately parallel to the central axis.

WO 2026/080691 A1

[Continued on next page]

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UY, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MU, MW, MZ, NA, RW, SC, SD, SL, ST, 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, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

ROBOTIC FOREARM ASSEMBLY

CROSS-REFERENCE TO RELATED PATENT APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/706,004, filed October 10, 2024, the entire disclosure of which is incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure relates generally to robotics. More specifically, the present disclosure relates to a robotic forearm assembly for controlling a robotic hand.

BACKGROUND

[0003] Robotic appendages are used by robots to interact with objects in the surrounding environment. By way of example, an appendage may be used to push or grasp an object or to propel the robot. To accomplish this, some appendages utilize joints that permit relative motion between different components. It may be desirable for such an appendage to provide multiple points of articulation that can be independently controlled to facilitate performance of complex tasks that require grasping objects of different shapes and/or in different orientations.

SUMMARY

[0004] In at least one embodiment, the present disclosure relates to a robotic forearm assembly including: a housing defining a central axis that extends along a first housing section and a second housing section; a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis; a plurality of hand linear actuators, each of the plurality of hand linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section; and a wrist linear actuator at least partially received within the second housing section and extending outwardly from the second housing section, wherein the plurality of hand linear actuators and the wrist linear actuator each extend along a longitudinal direction that is approximately parallel to the central axis.

[0005] In some embodiments, the first housing section extends axially from a first end to a second end, and the second housing section extends axially from a first end to a second end, and wherein a second end of the first housing section abuts the first end of the second housing section.

[0006] In some embodiments, the plurality of hand linear actuators includes a first subset of hand actuators and a second subset of hand actuators, wherein the first subset of hand actuators is arranged radially outwardly relative to the second subset of hand actuators.

[0007] In some embodiments, the first subset of hand actuators is arranged in a circumferential pattern with each actuator in the first subset of hand actuators being circumferentially spaced from one another.

[0008] In some embodiments, the wrist linear actuator is arranged radially inwardly relative to the first subset of hand actuators.

[0009] In some embodiments, the second housing section includes an outer portion and an inner portion that is arranged radially inwardly relative to the outer portion.

[0010] In some embodiments, the first subset of hand actuators are at least partially received within the outer portion, the second subset of hand actuators are at least partially received within the inner portion, and the wrist linear actuator is at least partially received within the inner portion.

[0011] In some embodiments, the inner portion extends axially away from a first end of the second housing section a greater distance than the outer portion.

[0012] In some embodiments, the wrist linear actuator is a first wrist linear actuator and the robotic forearm assembly further includes a second wrist linear actuator.

[0013] In some embodiments, a number of linear actuators, including the plurality of hand linear actuators and the wrist linear actuator, at least partially received within the second housing section is greater than or equal to 17.

[0014] In some embodiments, a number of linear actuators, including the plurality of hand linear actuators and the wrist linear actuator, at least partially received within the second housing section is greater than or equal to 23.

[0015] In some embodiments, each of the plurality of hand linear actuators and the wrist linear actuator defines a diameter that is between about 10 millimeters and about 30 millimeters.

[0016] In some embodiments, each of the plurality of hand linear actuators and the wrist linear actuator extends along the longitudinal direction from a first actuator end to a second actuator end, and wherein the first actuator ends are coplanar.

[0017] In some embodiments, the robotic forearm assembly further includes a rotary printed circuit board assembly electrically coupled to the rotary actuator and a linear printed circuit board assembly electrically coupled to the plurality of hand linear actuators or the wrist linear actuator.

[0018] In some embodiments, the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

[0019] In at least one embodiment, the present disclosure relates to a robotic forearm assembly including: a housing defining a central axis that extends along a first housing section and a second housing section, wherein the first housing section extends axially from a first end to an interface between the first housing section and the second housing section, and the second housing section extends axially from the interface to a second end; a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis; and a plurality of linear actuators, each of the plurality of linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section, and the plurality of linear actuators includes greater than or equal to 17 linear actuators.

[0020] In some embodiments, the plurality of linear actuators includes a plurality of hand linear actuators and a pair of wrist linear actuators, and wherein each of the plurality of hand linear actuators and the pair of wrist linear actuators extends along a longitudinal direction that is approximately parallel to the central axis.

[0021] In some embodiments, the plurality of hand linear actuators includes a first subset of hand actuators and a second subset of hand actuators, wherein the first subset of hand actuators is arranged radially outwardly relative to the second subset of hand actuators, where the first subset of hand actuators is arranged in a circumferential pattern with each actuator in the first subset of hand actuators being circumferentially spaced from one another.

[0022] In some embodiments, the robotic forearm assembly further includes a rotary printed circuit board assembly electrically coupled to the rotary actuator and a linear printed circuit board assembly electrically coupled to the plurality of linear actuators, wherein the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

[0023] In some aspects, the present disclosure relates to a robotic forearm assembly including: a housing defining a central axis that extends along a first housing section and a second housing section; a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis; a plurality of linear actuators, each of the plurality of linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section; a rotary printed circuit board assembly electrically coupled to the rotary actuator; and a linear printed circuit board assembly electrically coupled to the plurality of linear actuators, wherein the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

[0024] This summary is illustrative only and is not intended to be in any way limiting. Other aspects, inventive features, and advantages of the devices or processes described herein will become apparent in the detailed description set forth herein, taken in conjunction with the accompanying figures, wherein like reference numerals refer to like elements.

BRIEF DESCRIPTION OF THE FIGURES

[0025] FIG. 1 is a bottom view of a robotic appendage, according to at least one embodiment.

[0026] FIG. 2 is a top, front, right isometric view of a robotic forearm assembly of the robotic appendage of FIG. 1, according to at least one embodiment.

[0027] FIG. 3 is a right side view of the robotic forearm assembly of FIG. 2.

[0028] FIG. 4 is a front view of the robotic forearm assembly of FIG. 2.

[0029] FIG. 5 is a cross-sectional view of the robotic forearm assembly of FIG. 4 taken along line 5-5.

[0030] FIG. 6 is a cross-sectional view of the robotic forearm assembly of FIG. 4 taken along line 6-6.

[0031] FIG. 7 is a schematic illustration of a control system of the robotic forearm assembly of FIG. 2.

[0032] FIG. 8 is a is a top, front, right isometric view of a robotic forearm assembly of the robotic appendage of FIG. 1, according to at least one embodiment.

[0033] FIG. 9 is a right side view of the robotic forearm assembly of FIG. 8.

[0034] FIG. 10 is a front view of the robotic forearm assembly of FIG. 8.

[0035] FIG. 11 is a cross-sectional view of the robotic forearm assembly of FIG. 10 taken along line 11-11.

[0036] FIG. 12 is a cross-sectional view of the robotic forearm assembly of FIG. 10 taken along line 12-12.

DETAILED DESCRIPTION

[0037] Before turning to the figures, which illustrate certain exemplary embodiments in detail, it should be understood that the present disclosure is not limited to the details or methodology set forth in the description or illustrated in the figures. It should also be understood that the terminology used herein is for the purpose of description only and should not be regarded as limiting.

[0038] The use herein of the term “axial” and variations thereof refers to a direction that extends generally along an axis of symmetry, a central axis, or an elongate direction of a particular component or system. For example, axially extending features of a component may be features that extend generally along a direction that is parallel to an axis of symmetry or an elongate direction of that component. Similarly, the use herein of the term “radial” and variations thereof refers to directions that are generally perpendicular to a corresponding axial direction. For example, a radially extending structure of a component may generally extend at least partly along a direction that is perpendicular to a longitudinal or central axis of that component. The use herein of the term “circumferential” and variations thereof refers to a direction that extends generally around a circumference or periphery of an object, around an axis of symmetry, around a central axis, or around an elongate direction of a particular component or system.

[0039] Referring generally to the figures, a robotic arm assembly (e.g., a lower arm assembly) includes a robotic forearm assembly, a wrist assembly, and a robotic hand. The robotic hand includes a human-like anatomy with five fingers (e.g., a thumb, three forefingers, and a pinky), and the robotic hand is coupled to the forearm assembly by the wrist assembly. Movement of the wrist assembly and each of the fingers in the robotic hand are controlled by a plurality of actuators arranged within the robotic forearm assembly. Specifically, the robotic forearm assembly includes both linear actuators that control the movement of the fingers in the hand and movement of the wrist assembly, and a rotary actuator that controls rotation of the forearm assembly (and the wrist assembly and the fingers).

[0040] In some embodiments, the robotic forearm assembly includes a housing that is axially divided into a first housing section and a second housing section. The rotary actuator is arranged within the first housing section and the plurality of linear actuators are at least partially arranged within the second housing section. In other words, the rotary actuator is mounted in series with the plurality of linear actuators, which simplifies the assembly and manufacture of the robotic forearm assembly. The plurality of linear actuators are each at least partially received within extend along a longitudinal direction that is parallel to a center axis defined along the first housing section and the second housing section. At least a portion or a subset of the plurality of linear actuators are arranged in a circumferential pattern, with a first subset of linear actuators being arranged radially outwardly relative to a second subset of linear actuators. The orientation, longitudinal extension, and pattern arrangement of the plurality of linear actuators provides a compact packaging, reduces the envelope defined by the robotic forearm assembly (e.g., fits within a representative human form), maximizes heat transfer (e.g., cooling), and minimizes electromagnetic interference between the electromagnetic components within the robotic forearm assembly.

[0041] In some embodiments, the robotic forearm assembly operates as a stand-alone unit that does not require any components external to or separate from the housing (except power) for operation. For example, the robotic forearm assembly includes printed circuit board assemblies, inverters, and sensors arranged within the housing, in addition to the rotary actuator and the plurality of linear actuators.

[0042] Referring to FIG. 1, a humanoid appendage, a robotic appendage, a limb, a jointed assembly, a posable assembly, or a digit, is shown as robotic arm assembly 10. The robotic arm assembly 10 includes a robotic forearm assembly 12 (e.g., a first member, a forearm member, an upper member, etc.), a wrist assembly 14 (e.g., a linkage, a joint assembly, etc.), and a hand assembly 16 (e.g., a third member, a hand member, a lower member, an articulatable member, etc.). The hand assembly 16 is coupled to the robotic forearm assembly 12 by the wrist assembly 14. The robotic forearm assembly 12 is also coupled to an arm base 18 at an end of the robotic forearm assembly 12 opposite to the wrist assembly 14.

[0043] Movement of both the wrist assembly 14 and the hand assembly 16 is controlled by the robotic forearm assembly 12. The robotic forearm assembly 12 includes a plurality of actuators or motors that are independently moveable or rotatable to control movement of the wrist assembly 14 and a plurality of fingers 20 (e.g., a thumb, three forefingers, and a pinky) of the hand assembly 16. Referring to FIGS. 1-4, the robotic forearm assembly 12 includes a housing 22 that defines a central axis 24 that extends along a first housing section 26 and a second housing section 28. In some embodiments, the first housing section 26 is rigidly or fixedly coupled to the second housing section 28 via welding, an adhesive, one or more fastening elements (e.g., screws, bolts, rivets), etc. The first housing section 26 and the second housing section 28 extend axially along the central axis 24 and abut one another. Specifically, the first housing section 26 extends axially from a first end 30 to a second end 32, and the second housing section 28 extends axially from a first end 34 to a second end 36. The second end 32 of the first housing section 26 abuts the first end 34 of the second housing section 28. In other words, an interface between the first housing section 26 and the second housing section 28 is formed between the first end 30 of the first housing section 26 and the second end 36 of the second housing section 28.

[0044] The first housing section 26 defines a generally cylindrical shape and the second housing section 28 defines a generally cylindrical shape with an outer portion 38 and an inner portion 40 that is arranged radially inwardly relative to the outer portion 38. The inner portion 40 extends axially away from a distal end of the outer portion 38 so that the inner portion 40 protrudes axially outwardly from the distal end of the outer portion 38 (see, e.g., FIGS. 2 and 3). In other words, the inner portion 40 extends axially away from the first end 34 of the second housing section 28 a greater distance than the outer portion 38.

[0045] The first housing section 26 and the second housing section 28 house or support different components of the robotic forearm assembly 12. In some embodiments, the first housing section 26 houses or supports rotary movement components, and the second housing section 28 houses or supports linear movement components. Referring to FIGS. 1-6, a rotary actuator 42 (e.g., a rotary motor, a stepper motor, a servo motor, etc.) is arranged or housed within the first housing section 26, and a plurality of linear actuators 44 are at least partially received within and extend outwardly from the second housing section 28. The mounting of the rotary actuator 42 and the plurality of linear actuators 44 within the first housing section 26 and the second housing section 28, respectively, arranges the rotary actuator 42 and the 44 in series. In other words, the rotary actuator 42 and the plurality of linear actuators 44 are arranged axially back-to-back without axial overlap between the components (see, e.g., FIG. 5), which simplifies the assembly and manufacture of the robotic forearm assembly 12.

[0046] Referring to FIG. 5, the rotary actuator 42 is arranged within an internal cavity 46 (e.g., an internal bore, an internal cutout, an internal recess, etc.) of the first housing section 26 and is coupled to the first housing section 26 (e.g., to an internal surface of the first housing section 26). The rotary actuator 42 is also coupled to a gear train 48 that includes one or more gears. The gear train 48 is configured to change an output speed and/or torque provided by a rotary output (e.g., a shaft coupled to a rotor) of the rotary actuator 42. The rotary actuator 42 is coupled to the arm base 18 through the gear train 48, and the arm base 18 is rotationally fixed (i.e., does not rotate). With the rotary actuator 42 being coupled to the first housing section 26 and the arm base 18, which is rotationally fixed, a rotational output provided by the rotary actuator 42 on the first housing section 26 results in the first housing section 26 and the second housing section 28, which is rigidly coupled to the first housing section 26, rotating relative to the arm base 18 about the central axis 24. Accordingly, selective rotation provided by the rotary actuator 42 is configured to rotate the housing 22 of the robotic forearm assembly 12, and provide a wrist roll movement to the wrist assembly 14 and the hand assembly 16.

[0047] Referring to FIGS. 1-6, the plurality of linear actuators 44 are each configured to provide a linear output (e.g., push/pull or extend/retract) to the wrist assembly 14 or the hand assembly 16 to control the movement of the wrist assembly 14 and the hand assembly 16. In some embodiments, each of the plurality of linear actuators 44 is coupled to a respective joint formed in the wrist assembly 14 or the hand assembly 16 via a cable or linkage to control movement of the joint about a particular degree of freedom. The plurality of linear actuators 44 includes a plurality of hand linear actuators 50 and a wrist linear actuator 52. In the illustrated embodiment, the wrist linear actuator 52 includes a pair of wrist linear actuators 52 (e.g., a first wrist linear actuator and a second wrist linear actuator). Each of the plurality of hand linear actuators 50 is configured to control movement of a joint in the hand assembly 16, and the wrist linear actuators 52 control movement of one or more joints within the wrist assembly 14. In some embodiments, each of the plurality of linear actuators 44 defines a generally cylindrical shape with an outer diameter (see, e.g., FIGS. 3, 5, and 6). In some embodiments, each of the plurality of linear actuators 44, including the plurality of hand linear actuators 50 and the wrist linear actuators 52, defines a diameter that is between about 10 millimeters (mm) and about 30 mm. In the illustrated embodiment, the plurality of hand linear actuators 50 each define a diameter that is about 12 mm, and the wrist linear actuators 52 define a diameter that is about 20 mm. The diameters defined by the plurality of linear actuators 44 are smaller than conventionally used in robotic appendages, which allows the robotic forearm assembly 12 to include an increased number of linear actuators.

[0048] The plurality of hand linear actuators 50 are each at least partially received within the second housing section 28 and extend outwardly from the second housing section 28. The wrist linear actuators 52 are both at least partially received within the second housing section 28 and extend outwardly from the second housing section 28. In some embodiments, a number of the plurality of linear actuators 44, including the plurality of hand linear actuators 50 and the wrist linear actuators 52, at least partially received within the second housing section is greater than or equal to 17, greater than or equal to 18, greater than or equal to 19, greater than or equal to 20, greater than or equal to 21, greater than or equal to 22, greater than or equal to 23, greater than or equal to 24, or greater than or equal to 25. In general, by including greater than or equal to 17 linear actuators in the robotic forearm assembly 12, the robotic forearm assembly 12 is capable of controlling the movement of the wrist assembly 14 and the hand assembly 16 about at least 24 degrees of freedom (25 degrees of freedom including the wrist roll provided by the rotary actuator 42) and enables dexterous operation of the hand assembly 16. In the illustrated embodiment, the robotic forearm assembly 12 includes 25 linear actuators (23 of the plurality of hand linear actuators 50 and two of the wrist linear actuators 52) and provides dexterous operation of the wrist assembly 14 and the hand assembly 16.

[0049] Referring to FIGS. 2-4, the plurality of linear actuators 44 are arranged within the second housing section 28 in a pattern that provides compact packaging and reduces the overall envelope defined by the robotic forearm assembly 12 (e.g., fits within a representative human form). In the illustrated embodiment, the plurality of hand linear actuators 50 includes a first subset of hand actuators 50a and a second subset of hand actuators 50b, both arranged within the second housing section 28. The first subset of hand actuators 50a is arranged radially outwardly relative to the second subset of hand actuators 50b, and the wrist linear actuators 52 are arranged radially inwardly relative to the first subset of hand actuators 50a. The first subset of hand actuators 50a are at least partially received within the outer portion 38 of the second housing section 28, and the second subset of hand actuators 50b are at least partially received within the inner portion 40 of the second housing section 28.

[0050] The first subset of hand actuators 50a is arranged in a circumferential pattern about the central axis 24, with each actuator in the first subset of hand actuators 50a being arranged at a particular radial distance from the central axis 24 and being circumferentially spaced from one another (see, e.g., FIG. 3). In the illustrated embodiment, the circumferential pattern defined by the first subset of hand actuators 50a is an elliptical pattern, where each actuator of the first subset of hand actuators 50a is circumferentially offset or spaced from a circumferentially adjacent actuator, and a radial distance from the central axis 24 for each of the first subset of hand actuators 50a varies according to the geometric properties of an ellipse. In some embodiments, each actuator of the first subset of hand actuators 50a is arranged within the outer portion 38 at a common radial distance from the central axis 24 (e.g., a circular pattern) and each actuator of the first subset of hand actuators 50a is circumferential offset or spaced from a circumferentially adjacent actuator. In the illustrated embodiment, the first subset of hand actuators 50a includes 16 actuators that are circumferentially spaced about the outer portion 38 in a predetermined circumferential offset.

[0051] A portion of the second subset of hand actuators 50b are arranged in a circumferential pattern about the central axis 24, with each actuator in the portion of the second subset of hand actuators 50b being arranged at a common radial distance from the central axis 24 and being circumferentially spaced from one another (see, e.g., FIG. 3). Unlike the first subset of hand actuators 50a, the portion of the second subset of hand actuators 50b are not continuously spaced about the inner portion 40, because the wrist linear actuators 52 are arranged circumferentially between two groups of the second subset of hand actuators 50b. The wrist linear actuators 52 are arranged on radially-opposing sides of the central axis 24 (or on opposing sides of a vertical midplane V that intersects the central axis 24) and are aligned along a horizontal midplane H that intersects the central axis 24. In the illustrated embodiment, the portion of the second subset of hand actuators 50b arranged in the circumferential pattern includes 6 actuators, with 3 actuators being arranged in a first circumferential gap formed between the wrist linear actuators 52 (e.g., an upper gap formed above the horizontal midplane H from the perspective of FIG. 3) and 3 actuators being arranged in a second circumferential gap formed between the wrist linear actuators 52 (e.g., a lower gap formed below the horizontal midplane H from the perspective of FIG. 3). In some embodiments, the second subset of hand actuators 50b and the wrist linear actuators 52 may be arranged in a different pattern. For example, the wrist linear actuators 52 may be arranged below the horizontal midplane H (e.g., from the perspective of FIG. 3) and each of the actuators in the second subset of hand actuators 50b may be arranged above (e.g., from the perspective of FIG. 3) the wrist linear actuators 52.

[0052] In the illustrated embodiment, the second subset of hand actuators 50b includes 7 actuators, with 6 actuators being arranged in the circumferential pattern around an outer periphery of the inner portion 40 and a single actuator being arranged radially inwardly relative to the actuators in the circumferential pattern. The single actuator in the second subset of hand actuators 50b is arranged below the horizontal midplane H and is laterally between (e.g., in a direction parallel to the horizontal midplane) the wrist linear actuators 52. In general, the arrangement and mounting pattern defined by the first subset of hand actuators 50a in the outer portion 38 and both the second subset of hand actuators 50b and the wrist linear actuators 52 in the inner portion 40 maximize the amount of linear actuators mounted within the available space defined by the second housing section 28. Additionally, the arrangement and mounting pattern defined by the first subset of hand actuators 50a in the outer portion 38 and both the second subset of hand actuators 50b and the wrist linear actuators 52 in the inner portion 40 aids in facilitating efficient heat transfer to the environment and reduce heat generated by the plurality of linear actuators 44, as well as reduce the effects of electromagnetic interference within the robotic forearm assembly 12.

[0053] Still referring to FIGS. 2-4, a distal end of each of the plurality of linear actuators 44 terminates at a different axial position, when each of the plurality of linear actuators 44 are in a fully retracted position (as shown in FIGS. 2 and 3). Specifically, when each of the first subset of hand actuators 50a, the second subset of hand actuators 50b, and the wrist linear actuators 52 is in the fully retracted position, the distal ends of the second subset of hand actuators 50b are arranged axially between the distal ends of the first subset of hand actuators 50a and the distal ends of the wrist linear actuators 52, with the distal ends of the wrist linear actuators 52 being arranged axially further from the first end 34 of the second housing section 28 than the distal ends of the first subset of hand actuators 50a. This axially-staggered arrangement of the plurality of linear actuators 44 further aids in packaging more linear actuators within of the robotic forearm assembly 12 and facilitates access between the plurality of linear actuators 44 and the corresponding joints in the wrist assembly 14 and the hand assembly 16.

[0054] Referring to FIGS. 5 and 6, each of the plurality of linear actuators 44 are arranged within the second housing section 28, the plurality of linear actuators 44, including the plurality of hand linear actuators 50 and the wrist linear actuators 52, each extend along a longitudinal direction 54 that is parallel to the central axis 24. In some embodiments, the longitudinal direction 54 is arranged approximately parallel to the central axis 24 (e.g., plus or minus about 5 degrees, plus or minus about 10 degrees, plus or minus about 15 degrees, plus or minus about 20 degrees, plus or minus about 25 degrees, or plus or minus about 30 degrees). In other words, the longitudinal direction 54 defined by one or more of the plurality of linear actuators 44 may be tilted or rotated (e.g., clockwise or counterclockwise from the perspective of FIGS. 5 and 6 along a rotation direction that is coplanar with the central axis 24) to be plus or minus about 5 degrees, plus or minus about 10 degrees, plus or minus about 15 degrees, plus or minus about 20 degrees, plus or minus about 25 degrees, or plus or minus about 30 degrees relative to parallel to the central axis 24. In some embodiments, a group of the plurality of linear actuators 44 may be tilted or rotated relative to the central axis 24, while a remaining group of the plurality of linear actuators 44 may be parallel to the central axis 24. For example, the wrist linear actuators 52 may be tilted or rotated relative to the central axis 24 and the plurality of hand linear actuators 50 may be parallel to the central axis 24, or the wrist linear actuators 52 and a portion of the plurality of hand linear actuators 50 may be tilted or rotated relative to the central axis 24 and a remaining portion of the plurality of hand linear actuators 50 may be parallel to the central axis 24. In some embodiments, one or more of the plurality of linear actuators 44 may be tilted about 2 axes relative to the central axis 24 (e.g., rotated or tiled about a direction that is coplanar with the central axis 24 and an axis that is perpendicular to the central axis 24) to define a generally cone-like or conical shape). For example, the wrist linear actuators 52 may be tilted or rotated about two directions, one that is coplanar with the central axis 24 and one that is perpendicular to the central axis 24. Alternatively or additionally, one or more of the plurality of hand linear actuators 50 may be tilted or rotated about two directions, one that is coplanar with the central axis 24 and one that is perpendicular to the central axis 24. In the illustrated embodiment, each of the plurality of linear actuators 44 extend along the longitudinal direction 54 from a first actuator end 56 to a second actuator end 58. The first actuator ends 56 are coplanar about a plane that intersects a surface at the first end 34 of the second housing section 28, which aids in facilitating the series arrangement between the rotary actuator 42 and the plurality of linear actuators 44.

[0055] Each of the plurality of hand linear actuators 50 includes a hand motor 60, an internal rod 62 (e.g., a ball screw, a screw rod, a lead screw, a roller screw, etc.), a hand gear train 64, and an output rod 66 (e.g., a push tube, a plunger, a shaft, a piston rod, etc.), as shown in FIG. 5. The hand motor 60, the internal rod 62, the hand gear train 64, and the output rod 66 each extend along the longitudinal direction 54 co-axially. The longitudinal extension of the plurality of hand linear actuators 50 and parallel orientation relative to the central axis 24 differs from conventional actuators used in robotic appendages that define a ninety degree relationship (right angle) between the input mechanism (e.g., a motor) and the output (e.g., output rod). In addition to the circumferential mounting pattern and axial offset of the plurality of hand linear actuators 50, the longitudinal orientation of the plurality of hand linear actuators 50 reduces the overall envelope defined by the robotic forearm assembly 12, and aids in packaging more linear actuators into the robotic forearm assembly 12 to control movement about additional degrees of freedom without increasing a size of the overall envelope or packaging size of the robotic forearm assembly 12.

[0056] During operation, each of the plurality of hand linear actuators 50 is independently movable to control movement of one of the joints in the hand assembly 16. In some embodiments, the hand motor 60 selectively rotates in a particular direction and rotates the internal rod 62, which is coupled to the hand motor 60 (e.g., to a rotor of the hand motor 60). The internal rod 62 is coupled to the hand gear train 64 and the hand gear train 64 is coupled to the output rod 66. The hand gear train 64 is configured to convert rotational motion of the internal rod 62 into linear motion of the output rod 66, with the rotation direction of the hand motor 60 governing whether the output rod 66 extends outwardly from the second housing section 28 or retracts inwardly toward the second housing section 28. In some embodiments, each of the plurality of hand linear actuators 50 may be in the form of a ball screw actuator, a lead screw actuator, or a roller screw actuator. In some embodiments, each of the plurality of hand linear actuators 50 may be in the form of a direct drive linear motor, where the internal rod 62 and the output rod 66 are driven linearly by the hand motor 60, and the hand gear train 64 is omitted.

[0057] Each of the wrist linear actuators 52 includes a wrist motor 70, an internal rod 72 (e.g., a ball screw, a screw rod, a lead screw, a roller screw, etc.), a wrist gear train 74, and an output rod 76 (e.g., a push tube, a plunger, a shaft, a piston rod, etc.), as shown in FIG. 6. The wrist motor 70, the internal rod 72, the wrist gear train 74, and the output rod 76 each extend along the longitudinal direction 54 co-axially. During operation, each of the 52 is independently movable to control movement of one of the joints in the wrist assembly 14. In some embodiments, the wrist motor 70 selectively rotates in a particular direction and rotates the internal rod 72, which is coupled to the wrist motor 70 (e.g., to a rotor of the wrist motor 70). The internal rod 72 is coupled to the wrist gear train 74 and the wrist gear train 74 is coupled to the output rod 76. The wrist gear train 74 is configured to convert rotational motion of the internal rod 72 into linear motion of the output rod 76, with the rotation direction of the wrist motor 70 governing whether the output rod 76 extends or retracts. In some embodiments, each of wrist linear actuators 52 may be in the form of a ball screw actuator, a lead screw actuator, or a roller screw actuator. In some embodiments, each of the wrist linear actuators 52 may be in the form of a direct drive linear motor, where the internal rod 72 and the output rod 76 are driven linearly by the wrist motor 70, and the wrist gear train 74 is omitted.

[0058] Referring to FIGS. 5-7, the robotic forearm assembly 12 a control system 80 that controls operation of the rotary actuator 42 and the plurality of linear actuators 44. Specifically, the control system 80 includes a linear control group 82 that includes one or more linear printed circuit board assemblies 84. The linear printed circuit board assemblies 84 each include one or more controllers 86, each having a processor 88 and memory 90, and one or more inverters 92. The memory 90 may store instructions thereon that, when executed by the processor 88, cause the controller(s) 86 to perform the various processes described herein. For example, the one or more linear printed circuit board assemblies 84 and the controller(s) 86 are electrically coupled to and in communication with the plurality of linear actuators 44, and the controller(s) 86 receive instructions that result in one or more of the hand motors 60 rotating a predetermined magnitude in a particular direction to extend/retract one or more of the plurality of linear actuators 44. The inverters 92 are in electrical communication with the plurality of linear actuators 44 and are configured to supply electrical power to the plurality of linear actuators 44.

[0059] In some embodiments, the linear control group 82 includes one of the linear printed circuit board assemblies 84 that includes the control components (e.g., the controller(s) 86, the inverters 92, etc.) for operating all of the plurality of linear actuators 44. In some embodiments, the linear control group 82 includes two or more of the one or more linear printed circuit board assemblies 84 (e.g., one for the plurality of hand linear actuators 50 and one for the wrist linear actuators 52). In some embodiments, the linear control group 82 includes three or more of the one or more linear printed circuit board assemblies 84 (e.g., one for the first subset of hand actuators 50a, one for the second subset of hand actuators 50b, and one for the wrist linear actuators 52).

[0060] The control system 80 includes a rotary control group 94 that includes a rotary printed circuit board assembly 96. The rotary printed circuit board assembly 96 includes a controller 98, having a processor 100 and memory 102, and one or more inverters 104. The memory 102 may store instructions thereon that, when executed by the processor 100, cause the controller 98 to perform the various processes described herein. For example, the rotary printed circuit board assembly 96 and the controller 98 are electrically coupled to and in communication with the rotary actuator 42, and the controller 98 receives instructions that result in the rotary actuator 42 rotating a predetermined magnitude in a particular direction to rotate the housing 22 of the robotic forearm assembly 12. The inverter 104 is in electrical communication with the rotary actuator 42 and is configured to supply electrical power to the rotary actuator 42.

[0061] The control system 80 includes one or more sensors 106 that measure one or more operating parameters of the robotic forearm assembly 12. In some embodiments, the sensors 106 include a plurality of position sensors, each being configured to measure a position of the plurality of linear actuators 44 (e.g., a linear position of the output rods 66 of the plurality of hand linear actuators 50 and the output rods 76 of the wrist linear actuators 52). In some embodiments, the sensors 106 include a rotary position sensor (e.g., an encoder) that is configured to measure a rotational position of the rotary actuator 42 and/or the housing 22. In some embodiments, the sensors 106 include one or more temperature sensors that are configured to measure various operating temperatures within the robotic forearm assembly 12. Regardless of the particular configuration of the sensors 106, each of the components of the control system 80 are arranged internal to the housing 22, as shown in FIGS. 5-7. All of components of the control system 80 being arranged internal to the housing 22 facilitates the robotic forearm assembly 12 operating as a stand-alone unit that does not require any components external to or separate from the housing 22 (except power) for operation. In other words, the robotic forearm assembly 12 is able to be efficiently installed and in the robotic arm assembly 10 with minimal mechanical/electrical connections.

[0062] The robotic forearm assembly 12 described herein may be designed to include an alternative number of linear actuators and may include alternative arrangements of the linear/rotary actuators within the housing 22. Referring to FIGS. 8-12, the robotic forearm assembly 12 is shown to include an alternative arrangement of the housing, the rotary actuator 42, and the plurality of linear actuators 44. It should be appreciated that the robotic forearm assembly 12 shown in FIGS. 8-12 includes similar components as the robotic forearm assembly 12 shown in FIGS. 1-7, except as described herein or as apparent from the figures. The robotic forearm assembly 12 of FIGS. 8-12 includes a housing 150 that defines a central axis 152 that extends along a first housing section 154, a second housing section 156, and a third housing section 158. The first housing section 154 is rigidly or fixedly coupled to both the second housing section 156 and the third housing section 158 via welding, an adhesive, one or more fastening elements (e.g., screws, bolts, rivets), etc. The first housing section 154, the second housing section 156, and the third housing section 158 each extend axially along the central axis 152 and abut one another. In the illustrated embodiment, a portion of the first housing section 154 is nested within the first housing section 154. The first housing section 154 includes a flange 160 and a central hub 162 that extends axially away from the flange 160. The central hub 162 is received within and extends through an inner bore formed through the second housing section 156. The second housing section 156 is arranged radially outwardly relative to the central hub 162 and extends circumferentially around the central hub 162. The third housing section 158 abuts an axial end (e.g., an end opposite from the flange 160) of the central hub 162, and is axially spaced from the second housing section 156.

[0063] In some embodiments, the first housing section 154 houses or supports rotary movement components, and both the second housing section 156 and the third housing section 158 house or support linear movement components. The rotary actuator 42 is arranged or housed within the first housing section 154, a portion of the plurality of linear actuators 44 are at least partially received within and extend outwardly from the second housing section 156, and another portion of the plurality of linear actuators 44 are at least partially received within and extend outwardly from the third housing section 158. In the illustrated embodiment, the rotary actuator 42 is mounted within an internal cavity 164 that extends through the first housing section 154 and arranges the rotary actuator 42 in a nested configuration with the plurality of linear actuators 44 that are mounted within the second housing section 156. In other words, the rotary actuator 42 and the plurality of linear actuators 44 mounted within the second housing section 156 at least partially overlap axially and the rotary actuator 42 is arranged radially inwardly relative to the plurality of linear actuators 44 mounted within the second housing section 156 (see, e.g., FIG. 11).

[0064] Referring to FIG. 11, the rotary actuator 42 is coupled to the first housing section 154 (e.g., to an internal surface of the first housing section 154). The rotary actuator 42 is also coupled to the gear train 48 and to the arm base 18 through the gear train 48. With the rotary actuator 42 being coupled to the first housing section 154 and the arm base 18, which is rotationally fixed, a rotational output provided by the rotary actuator 42 on the first housing section 154 results in the first housing section 154, the second housing section 156, and the third housing section 158 rotating relative to the arm base 18 about the central axis 152. Accordingly, selective rotation provided by the rotary actuator 42 is configured to rotate the housing 150 of the robotic forearm assembly 12, and provide a wrist roll movement to the wrist assembly 14 and the hand assembly 16.

[0065] Referring to FIGS. 8-12, a portion of the plurality of hand linear actuators 50 are at least partially received within and extend outwardly from the second housing section 156, and another portion of the plurality of hand linear actuators 50 are at least partially received within and extend outwardly from the third housing section 158. The wrist linear actuators 52 are at least partially received within and extend outwardly from the third housing section 158. In the illustrated embodiment, the plurality of hand linear actuators 50 each define a diameter that is about 15 mm, and the wrist linear actuators 52 define a diameter that is about 30 mm. The diameters defined by the plurality of linear actuators 44 are smaller than conventionally used in robotic appendages, which allows the robotic forearm assembly 12 to include an increased number of linear actuators.

[0066] In the illustrated embodiment, a number of the plurality of linear actuators 44, including the plurality of hand linear actuators 50 and the wrist linear actuators 52, is greater than or equal to 17, which enables the robotic forearm assembly 12 to control movement of the wrist assembly 14 and the hand assembly 16 about at least 24 degrees of freedom (25 degrees of freedom including the wrist roll provided by the rotary actuator 42) and enables dexterous operation of the hand assembly 16. In the illustrated embodiment, the robotic forearm assembly 12 includes nineteen linear actuators (nineteen of the plurality of hand linear actuators 50 and two of the wrist linear actuators 52).

[0067] In the illustrated embodiment, the plurality of hand linear actuators 50 includes a first subset of hand actuators 50c mounted within the second housing section 156 and a second subset of hand actuators 50d mounted within the third housing section 158. The first subset of hand actuators 50c is arranged radially outwardly relative to the second subset of hand actuators 50d (see, e.g., FIG. 10), and the wrist linear actuators 52 are arranged radially inwardly relative to the first subset of hand actuators 50c. The first subset of hand actuators 50c is arranged in a circumferential pattern about the central axis 152, with each actuator in the first subset of hand actuators 50c being arranged at a common radial distance from the central axis 152 and being circumferentially spaced from one another (see, e.g., FIG. 10). In other words, each actuator of the first subset of hand actuators 50c is arranged within the second housing section 156 at a common radial distance from the central axis 152 and each actuator of the first subset of hand actuators 50c is circumferential offset or spaced from a circumferentially adjacent actuator. In the illustrated embodiment, the first subset of hand actuators 50c includes 12 actuators that are circumferentially spaced about the second housing section 156 in a predetermined circumferential offset.

[0068] The second subset of hand actuators 50d are arranged below a horizontal midplane H that intersects the central axis 152, with 5 total actuators being arranged in the second subset of hand actuators 50d. The wrist linear actuators 52 are arranged on radially-opposing sides of the central axis 24 (or on opposing sides of a vertical midplane V that intersects the central axis 152) and are above the second subset of hand actuators 50d relative to the horizontal midplane H. In general, the arrangement and mounting pattern defined by the first subset of hand actuators 50c in the second housing section 156 and both the second subset of hand actuators 50d and the wrist linear actuators 52 in the third housing section 158 maximize the amount of linear actuators mounted within the available space defined by the housing 150. Additionally, the arrangement and mounting pattern defined by the first subset of hand actuators 50c in the second housing section 156 and both the second subset of hand actuators 50d and the wrist linear actuators 52 in the third housing section 158 aids in facilitating efficient heat transfer to the environment and reduce heat generated by the plurality of linear actuators 44, as well as reduce the effects of electromagnetic interference within the robotic forearm assembly 12.

[0069] Still referring to FIGS. 8-12, a distal end of each of the plurality of hand linear actuators 50 terminates at a different axial position, when each of the plurality of hand linear actuators 50 are in a fully retracted position (as shown in FIGS. 8 and 9). Specifically, when each of the first subset of hand actuators 50c and the second subset of hand actuators 50d is in the fully retracted position, the distal ends of the second subset of hand actuators 50d are arranged axially further from the flange 160 of the first housing section 154 than the distal ends of the first subset of hand actuators 50c. This axially-staggered arrangement of the plurality of hand linear actuators 50 further aids in packaging more linear actuators within of the robotic forearm assembly 12 and facilitates access between the plurality of hand linear actuators 50 and the corresponding joints in the wrist assembly 14 and the hand assembly 16.

[0070] The operation and control components of the robotic forearm assembly 12 of FIGS. 8-12 is similar to that of the robotic forearm assembly 12 of FIGS. 1-7 described herein. For example, the robotic forearm assembly 12 shown in FIGS. 8-12 includes the one or more linear printed circuit board assemblies 84 and the rotary printed circuit board assembly 96 that are both arranged internal to the housing 150. The rotary actuator 42, the plurality of hand linear actuators 50, and the wrist linear actuators 52 are each independent controlled by a respective one of the linear printed circuit board assemblies 84 or the rotary printed circuit board assembly 96 to selectively move one or more of the joints in the wrist assembly 14 or the hand assembly 16.

[0071] As utilized herein with respect to numerical ranges, the terms “approximately,” “about,” “substantially,” and similar terms generally mean +/- 10% of the disclosed values. When the terms “approximately,” “about,” “substantially,” and similar terms are applied to a structural feature (e.g., to describe its shape, size, orientation, direction, etc.), these terms are meant to cover minor variations in structure that may result from, for example, the manufacturing or assembly process and are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. Accordingly, these terms should be interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and claimed are considered to be within the scope of the disclosure as recited in the appended claims.

[0072] It should be noted that the term “exemplary” and variations thereof, as used herein to describe various embodiments, are intended to indicate that such embodiments are possible examples, representations, or illustrations of possible embodiments (and such terms are not intended to connote that such embodiments are necessarily extraordinary or superlative examples).

[0073] The term “coupled” and variations thereof, as used herein, means the joining of two members directly or indirectly to one another. Such joining may be stationary (e.g., permanent or fixed) or moveable (e.g., removable or releasable). Such joining may be achieved with the two members coupled directly to each other, with the two members coupled to each other using a separate intervening member and any additional intermediate members coupled with one another, or with the two members coupled to each other using an intervening member that is integrally formed as a single unitary body with one of the two members. If “coupled” or variations thereof are modified by an additional term (e.g., directly coupled), the generic definition of “coupled” provided above is modified by the plain language meaning of the additional term (e.g., “directly coupled” means the joining of two members without any separate intervening member), resulting in a narrower definition than the generic definition of “coupled” provided above. Such coupling may be mechanical, electrical, or fluidic.

[0074] References herein to the positions of elements (e.g., “top,” “bottom,” “above,” “below”) are merely used to describe the orientation of various elements in the FIGURES. It should be noted that the orientation of various elements may differ according to other exemplary embodiments, and that such variations are intended to be encompassed by the present disclosure.

[0075] The hardware and data processing components used to implement the various processes, operations, illustrative logics, logical blocks, modules and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general purpose single- or multi-chip processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, or, any conventional processor, controller, microcontroller, or state machine. A processor also may be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. In some embodiments, particular processes and methods may be performed by circuitry that is specific to a given function. The memory (e.g., memory, memory unit, storage device) may include one or more devices (e.g., RAM, ROM, Flash memory, hard disk storage) for storing data and/or computer code for completing or facilitating the various processes, layers and modules described in the present disclosure. The memory may be or include volatile memory or non-volatile memory, and may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. According to an exemplary embodiment, the memory is communicably connected to the processor via a processing circuit and includes computer code for executing (e.g., by the processing circuit or the processor) the one or more processes described herein.

[0076] The present disclosure contemplates methods, systems and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure may be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0077] Although the figures and description may illustrate a specific order of method steps, the order of such steps may differ from what is depicted and described, unless specified differently above. Also, two or more steps may be performed concurrently or with partial concurrence, unless specified differently above. Such variation may depend, for example, on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations of the described methods could be accomplished with standard programming techniques with rule-based logic and other logic to accomplish the various connection steps, processing steps, comparison steps, and decision steps.

[0078] It is important to note that the construction and arrangement of the robotic forearm assembly 12 as shown in the various exemplary embodiments is illustrative only. Additionally, any element disclosed in one embodiment may be incorporated or utilized with any other embodiment disclosed herein.

CLAIMS

What is claimed is:

1. A robotic forearm assembly comprising:

a housing defining a central axis that extends along a first housing section and a second housing section;

a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis;

a plurality of hand linear actuators, each of the plurality of hand linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section; and

a wrist linear actuator at least partially received within the second housing section and extending outwardly from the second housing section, wherein the plurality of hand linear actuators and the wrist linear actuator each extend along a longitudinal direction that is approximately parallel to the central axis.

2. The robotic forearm assembly of claim 1, wherein the first housing section extends axially from a first end to a second end, and the second housing section extends axially from a first end to a second end, and wherein a second end of the first housing section abuts the first end of the second housing section.

3. The robotic forearm assembly of claim 1, wherein the plurality of hand linear actuators includes a first subset of hand actuators and a second subset of hand actuators, wherein the first subset of hand actuators is arranged radially outwardly relative to the second subset of hand actuators.

4. The robotic forearm assembly of claim 3, wherein the first subset of hand actuators is arranged in a circumferential pattern, with each actuator in the first subset of hand actuators being circumferentially spaced from one another.

5. The robotic forearm assembly of claim 3, wherein the wrist linear actuator is arranged radially inwardly relative to the first subset of hand actuators.

6. The robotic forearm assembly of claim 3, wherein the second housing section includes an outer portion and an inner portion that is arranged radially inwardly relative to the outer portion.

7. The robotic forearm assembly of claim 6, wherein the first subset of hand actuators is at least partially received within the outer portion, the second subset of hand actuators is at least partially received within the inner portion, and the wrist linear actuator is at least partially received within the inner portion.

8. The robotic forearm assembly of claim 7, wherein the inner portion extends axially away from a first end of the second housing section a greater distance than the outer portion.

9. The robotic forearm assembly of claim 1, wherein the wrist linear actuator is a first wrist linear actuator and the robotic forearm assembly further comprises a second wrist linear actuator.

10. The robotic forearm assembly of claim 1, wherein a number of linear actuators, including the plurality of hand linear actuators and the wrist linear actuator, at least partially received within the second housing section is greater than or equal to 17.

11. The robotic forearm assembly of claim 1, wherein a number of linear actuators, including the plurality of hand linear actuators and the wrist linear actuator, at least partially received within the second housing section is greater than or equal to 23.

12. The robotic forearm assembly of claim 1, wherein each of the plurality of hand linear actuators and the wrist linear actuator defines a diameter that is between about 10 millimeters and about 30 millimeters.

13. The robotic forearm assembly of claim 1, wherein each of the plurality of hand linear actuators and the wrist linear actuator extends along the longitudinal direction from a first actuator end to a second actuator end, and wherein the first actuator ends are coplanar.

14. The robotic forearm assembly of claim 1, further comprising a rotary printed circuit board assembly electrically coupled to the rotary actuator and a linear printed circuit

board assembly electrically coupled to the plurality of hand linear actuators or the wrist linear actuator.

15. The robotic forearm assembly of claim 14, wherein the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

16. A robotic forearm assembly comprising:

a housing defining a central axis that extends along a first housing section and a second housing section, wherein the first housing section extends axially from a first end to an interface between the first housing section and the second housing section, and the second housing section extends axially from the interface to a second end;

a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis; and

a plurality of linear actuators, each of the plurality of linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section, and the plurality of linear actuators includes greater than or equal to 17 linear actuators.

17. The robotic forearm assembly of claim 16, wherein the plurality of linear actuators includes a plurality of hand linear actuators and a pair of wrist linear actuators, and wherein each of the plurality of hand linear actuators and the pair of wrist linear actuators extends along a longitudinal direction that is approximately parallel to the central axis.

18. The robotic forearm assembly of claim 17, wherein the plurality of hand linear actuators includes a first subset of hand actuators and a second subset of hand actuators, wherein the first subset of hand actuators is arranged radially outwardly relative to the second subset of hand actuators, wherein the first subset of hand actuators is arranged in a circumferential pattern with each actuator in the first subset of hand actuators being circumferentially spaced from one another.

19. The robotic forearm assembly of claim 16, further comprising a rotary printed circuit board assembly electrically coupled to the rotary actuator and a linear printed circuit

board assembly electrically coupled to the plurality of linear actuators, wherein the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

20. A robotic forearm assembly comprising:

a housing defining a central axis that extends along a first housing section and a second housing section;

a rotary actuator arranged within the first housing section, wherein the rotary actuator is coupled to the first housing section and configured to rotate the first housing section and the second housing section about the central axis;

a plurality of linear actuators, each of the plurality of linear actuators is at least partially received within the second housing section and extends outwardly from the second housing section;

a rotary printed circuit board assembly electrically coupled to the rotary actuator; and

a linear printed circuit board assembly electrically coupled to the plurality of linear actuators, wherein the rotary printed circuit board assembly and the linear printed circuit board assembly are both arranged internal to the housing.

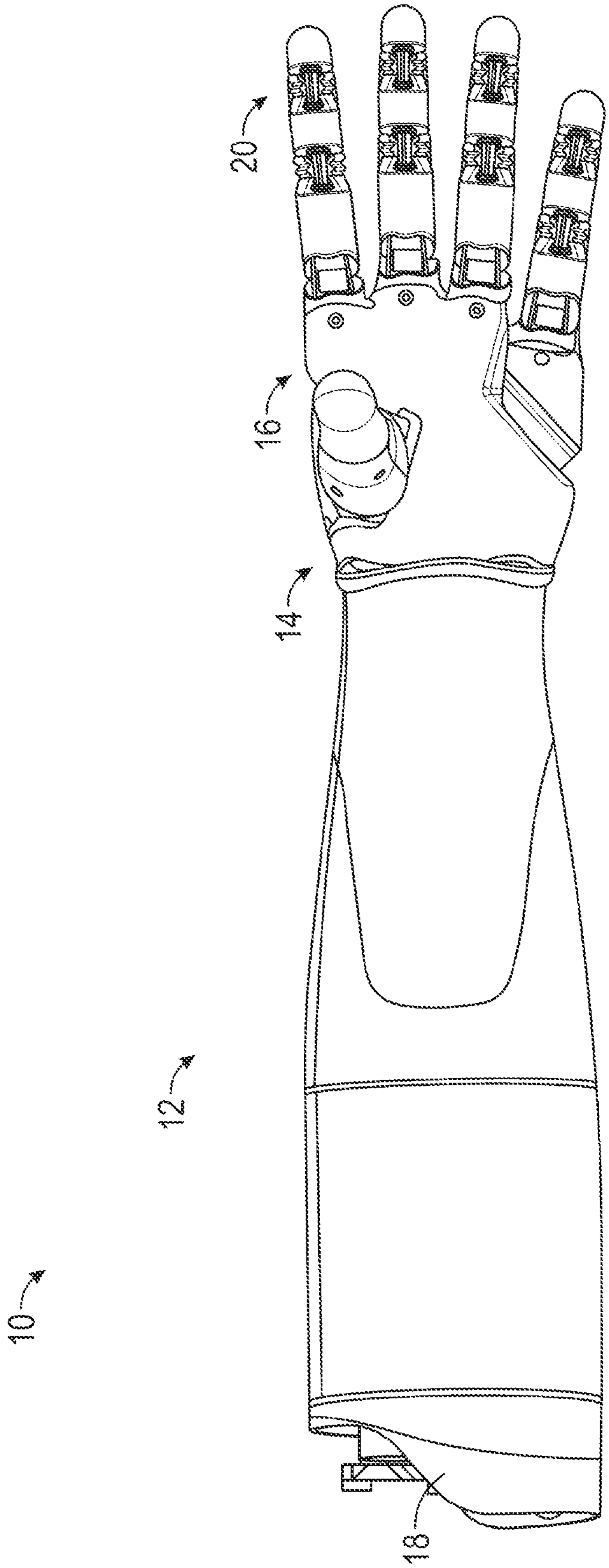

FIG. 1

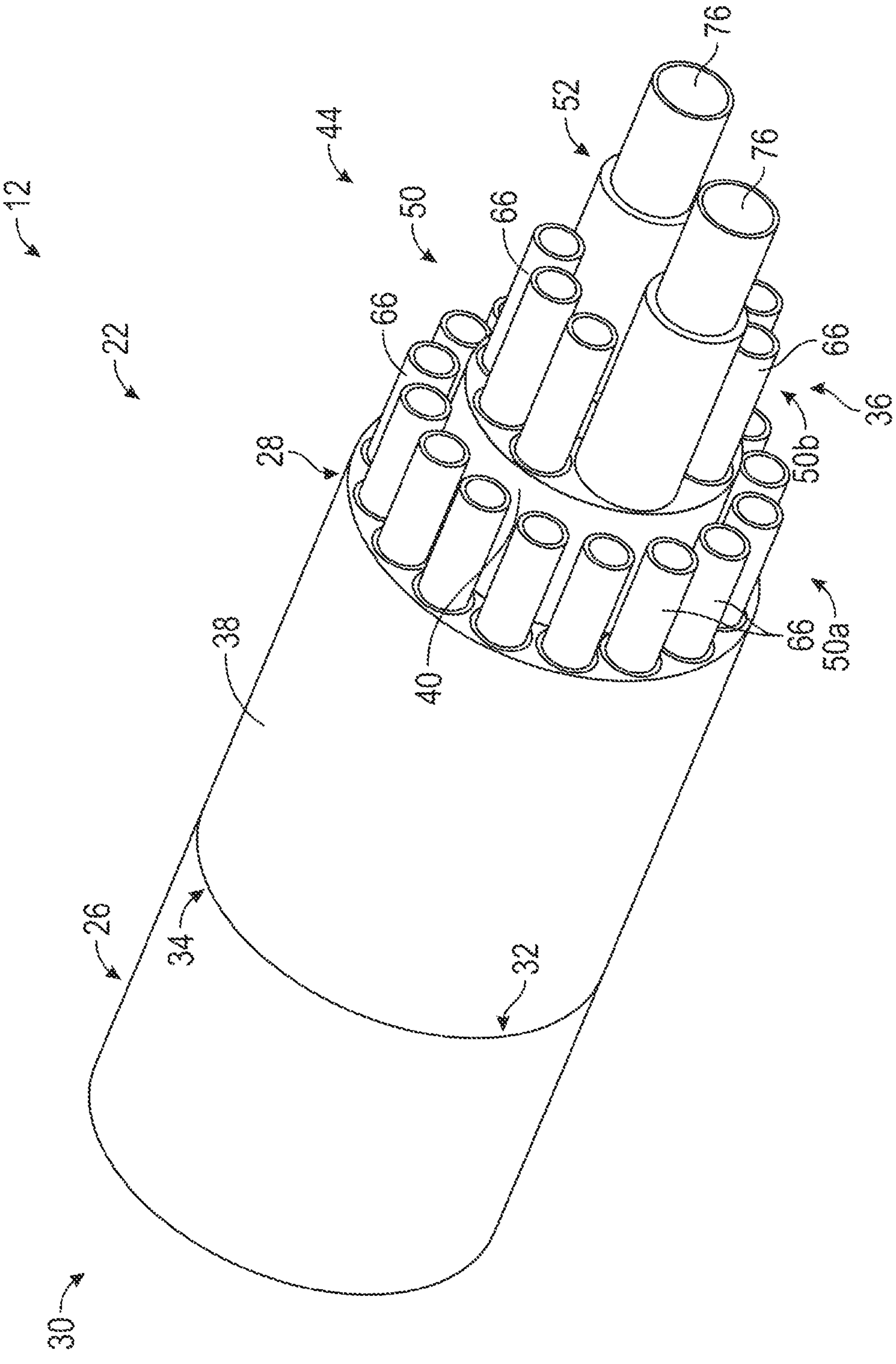

FIG. 2

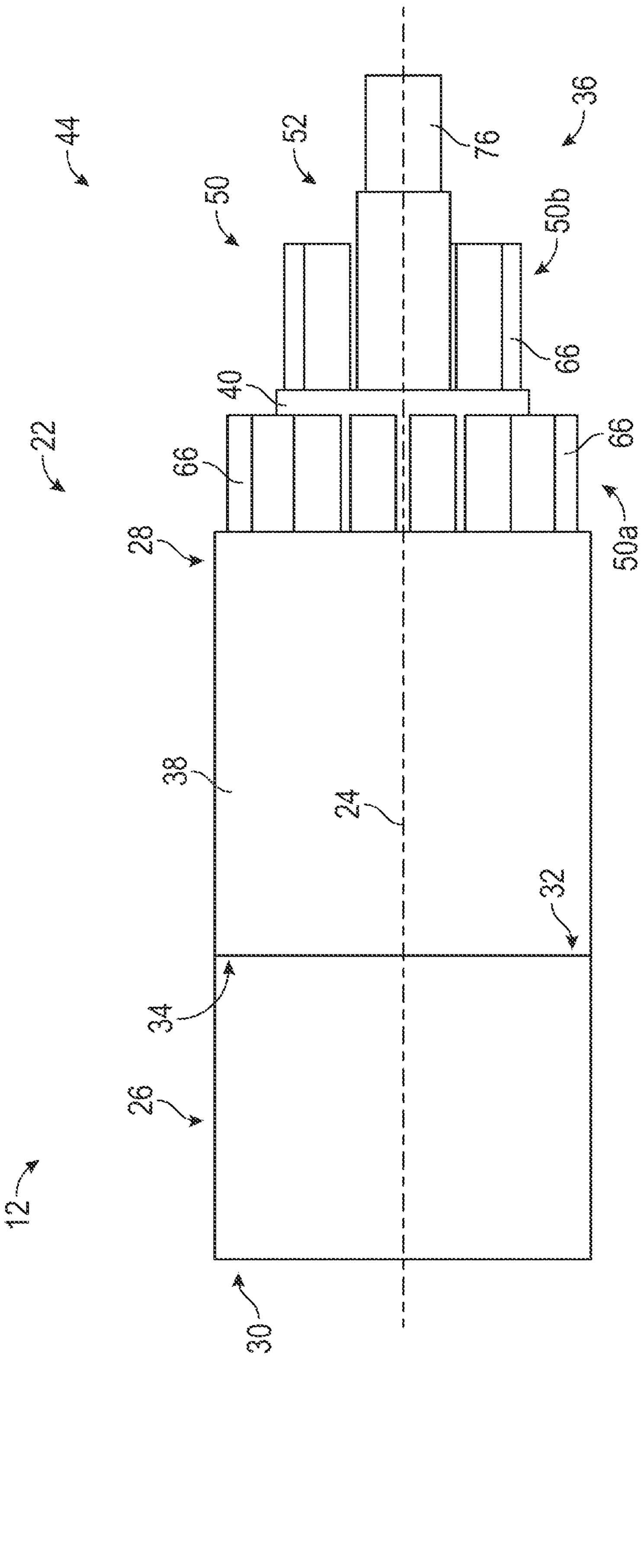

FIG. 3

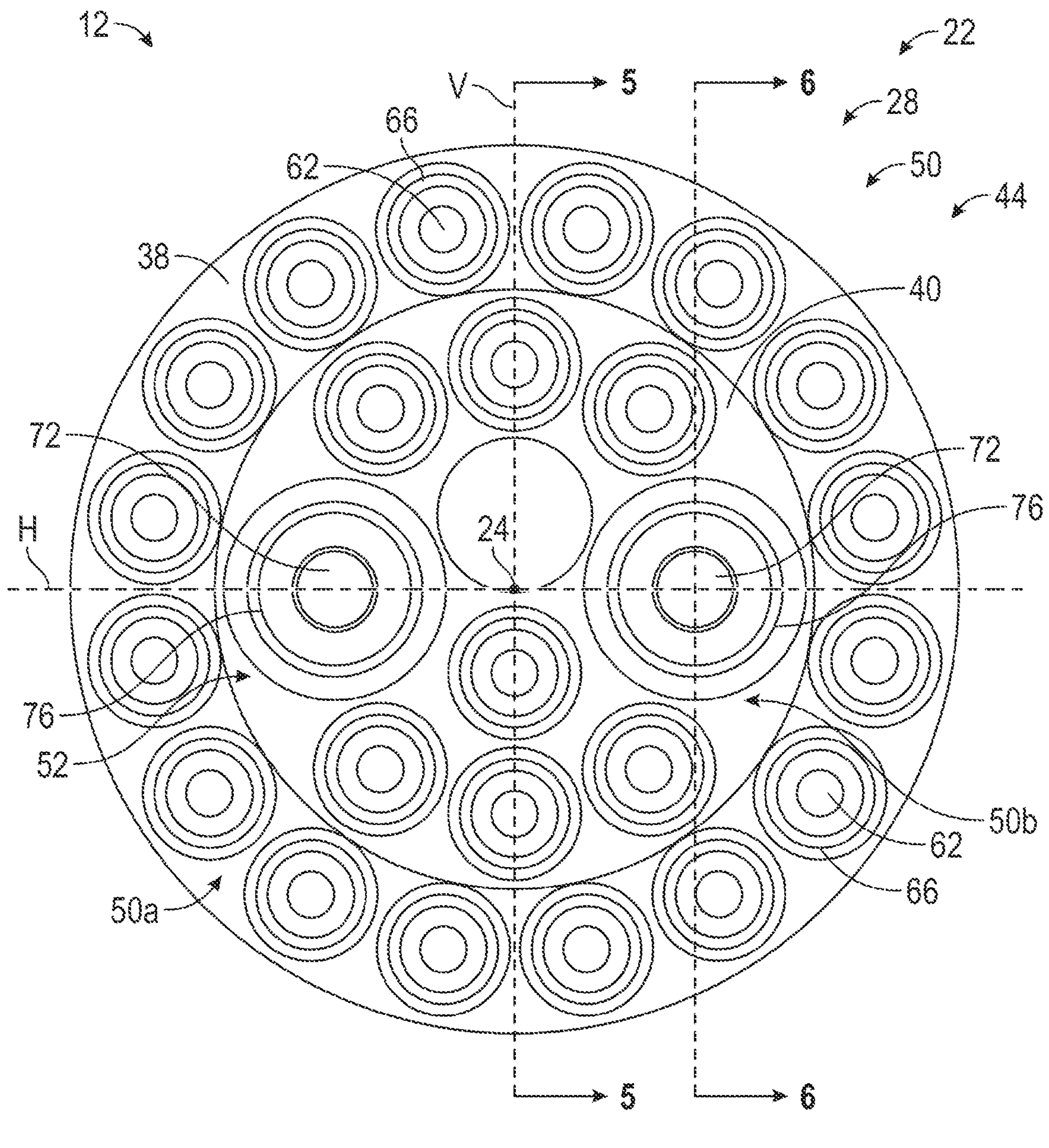

FIG. 4

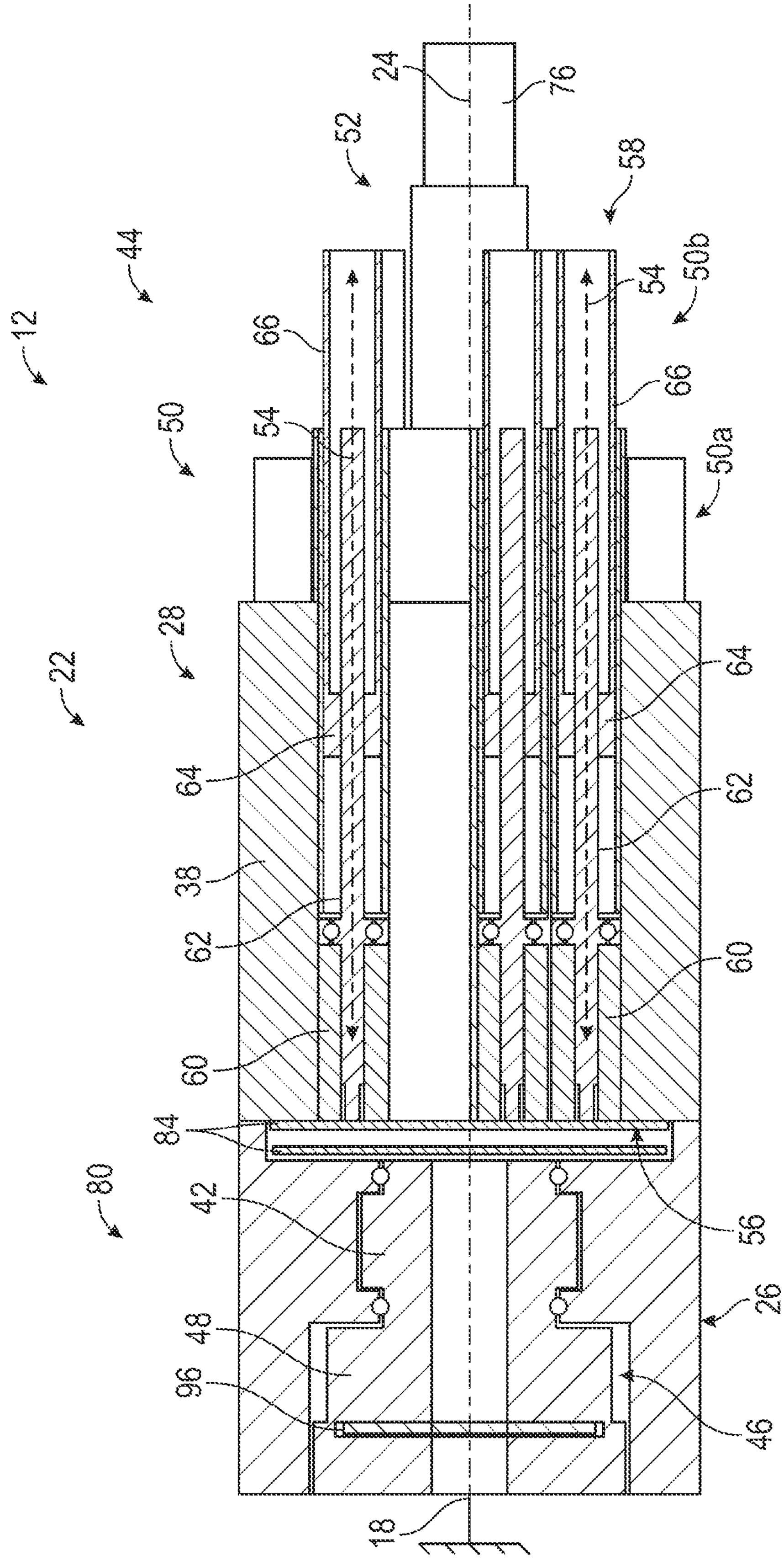
24
76
52
58
44
50b
54
66
12
66
54
50
50a
28
22
64
64
62
38
62
60
60
84
80
42
56
26
48
96
46
18

FIG. 5

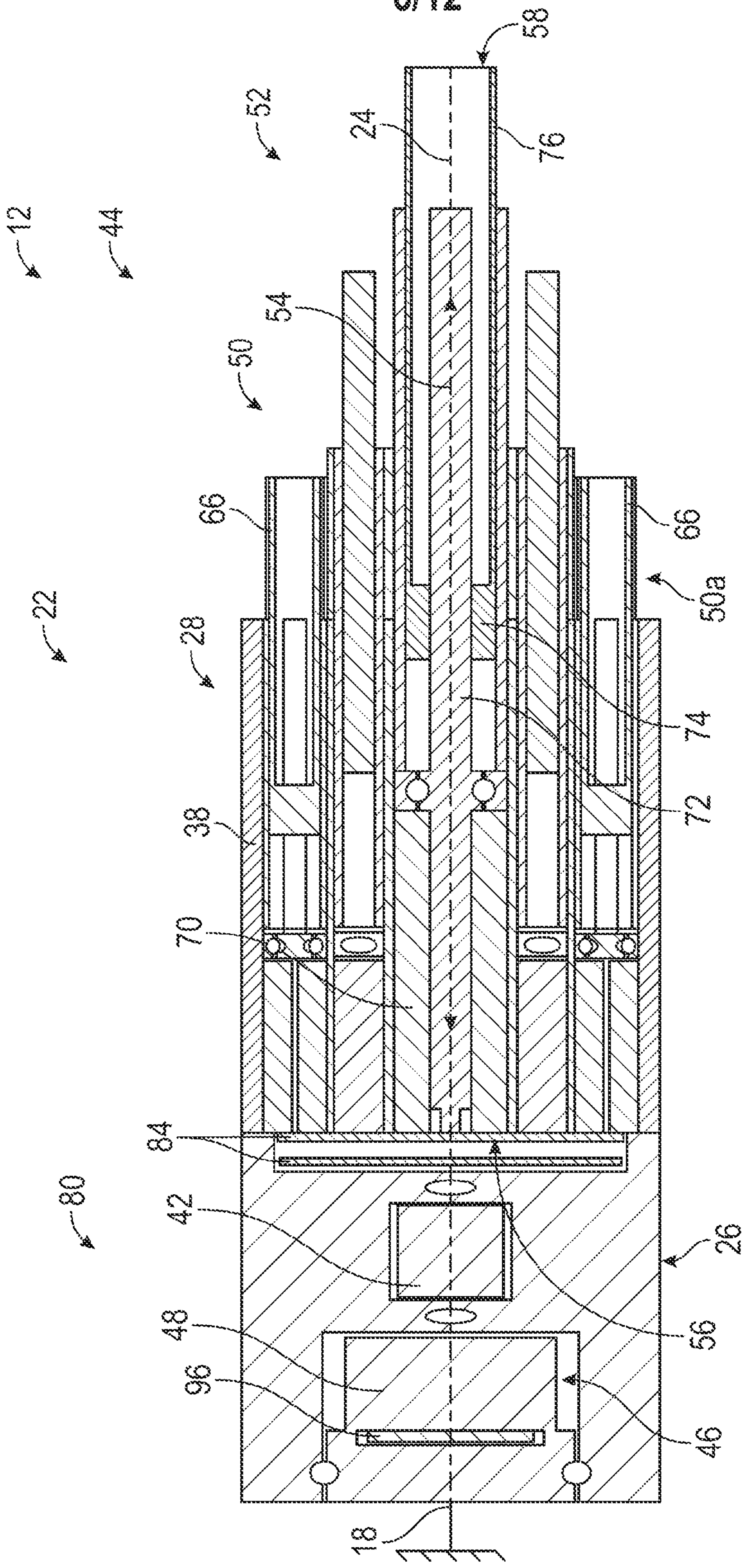
58
52
24
76
12
44
54
50
66
66
50a
22
28
74
38
72
70
84
80
42
26
48
56
96
46
18

FIG. 6

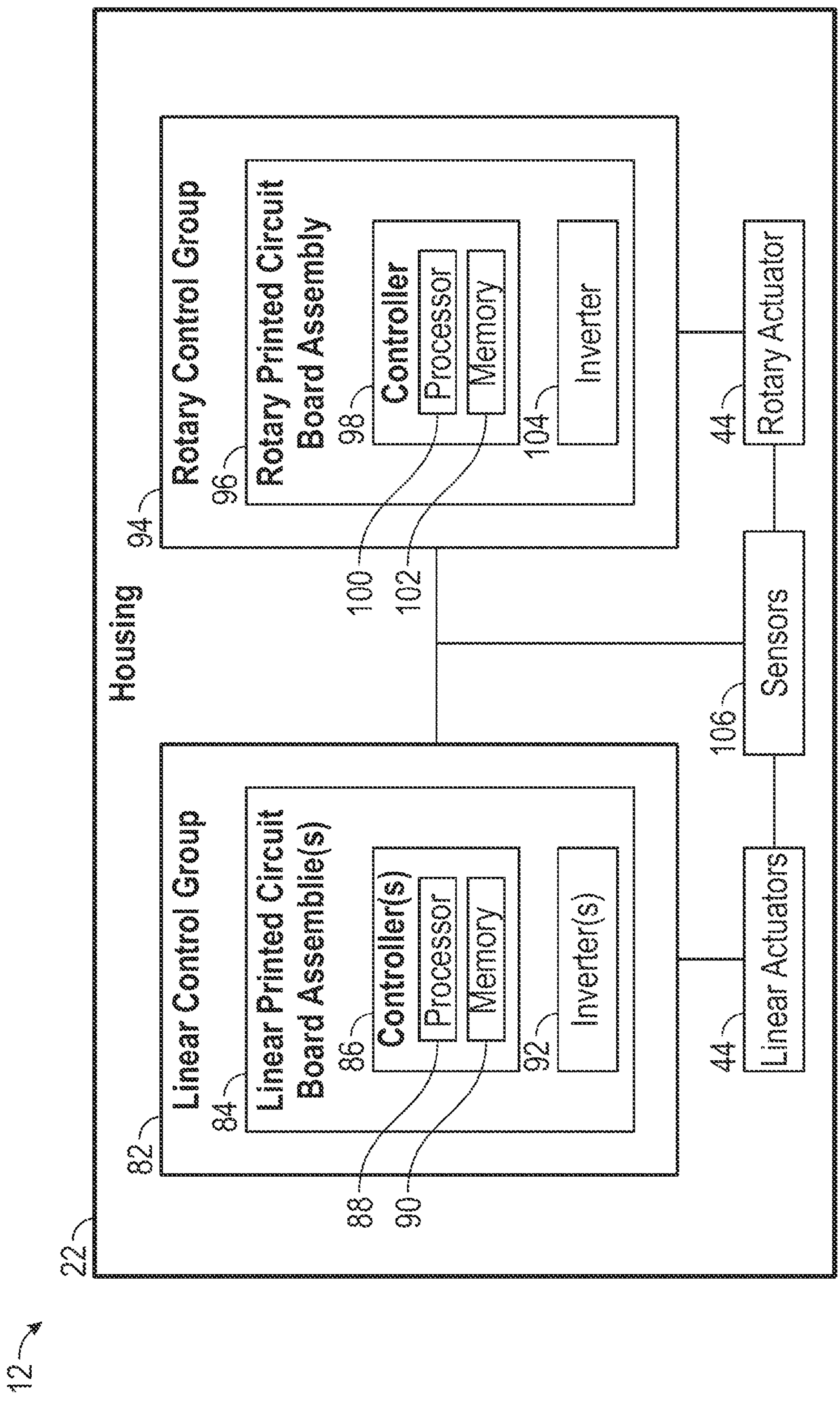
Housing
Rotary Control Group
Rotary Printed Circuit Board Assembly
Controller
Processor
Memory
Inverter
Rotary Actuator
Sensors
Linear Control Group
Linear Printed Circuit Board Assemblie(s)
Controller(s)
Processor
Memory
Inverter(s)
Linear Actuators
12
22
44
44
82
84
86
88
90
92
94
96
98
100
102
104
106

FIG. 7

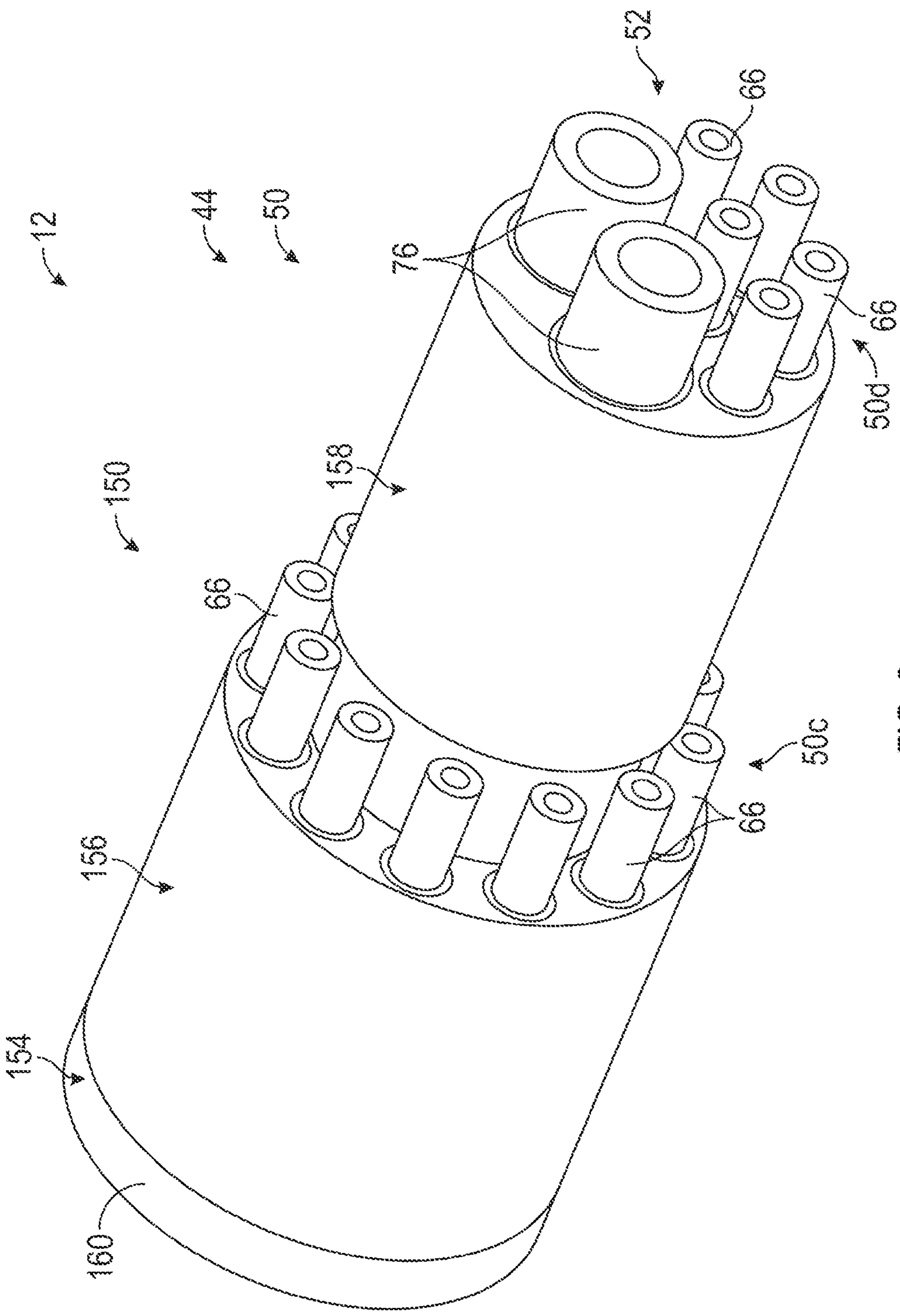

FIG. 8

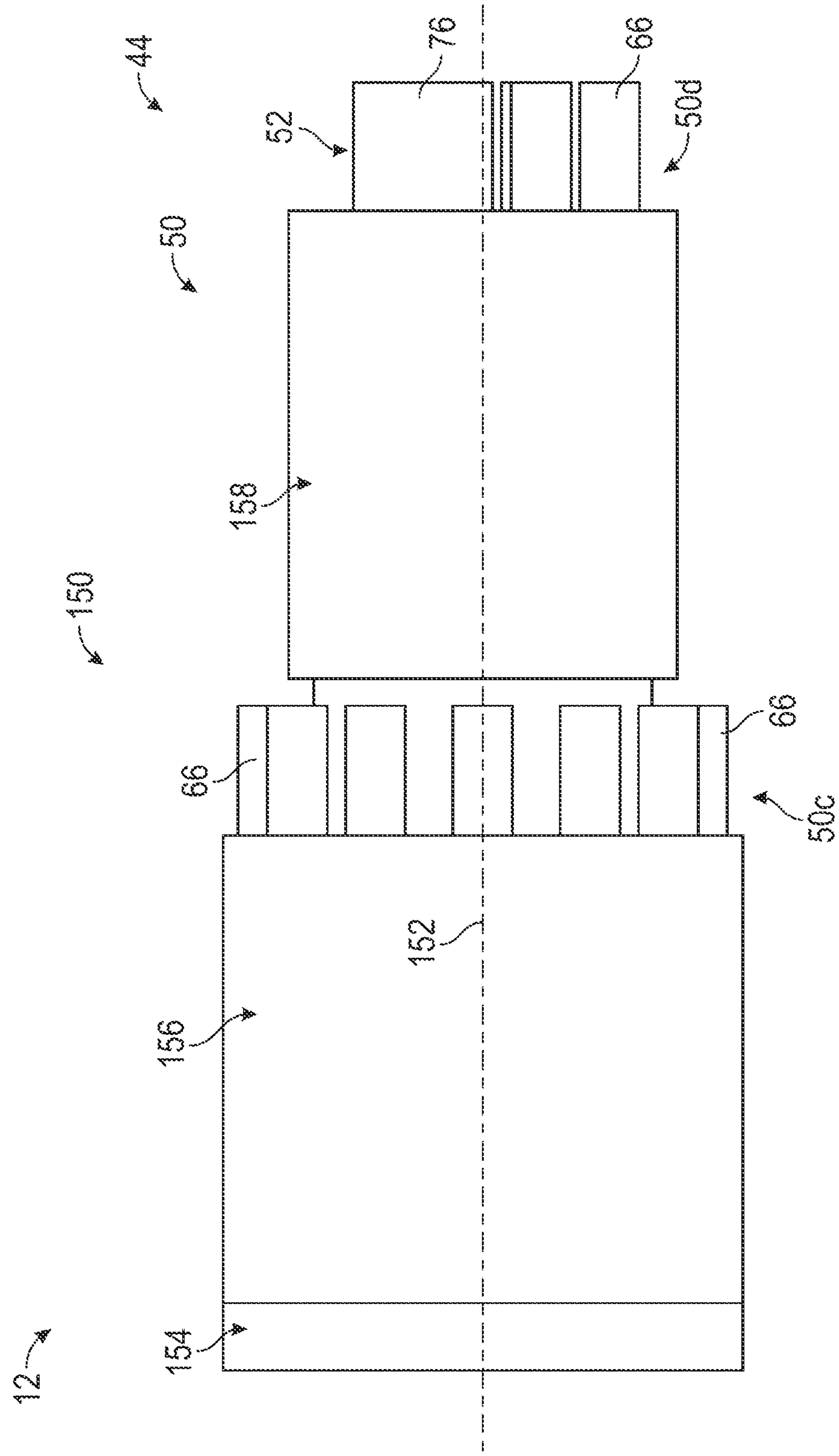

FIG. 9

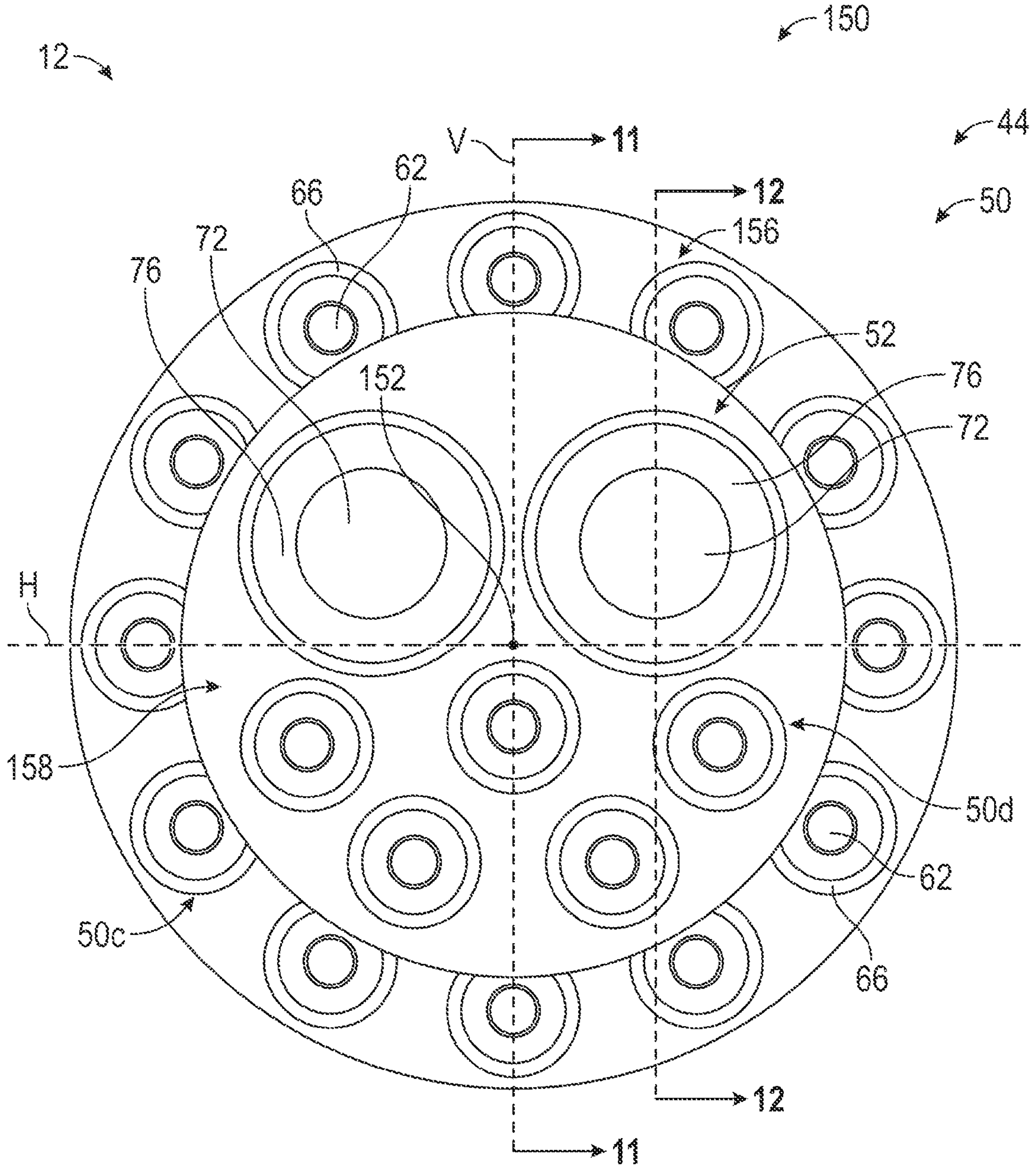
150
12
44
V
11
62
66
12
50
156
72
76
52
152
76
72
H
158
50d
62
50c
66
12
11

FIG. 10

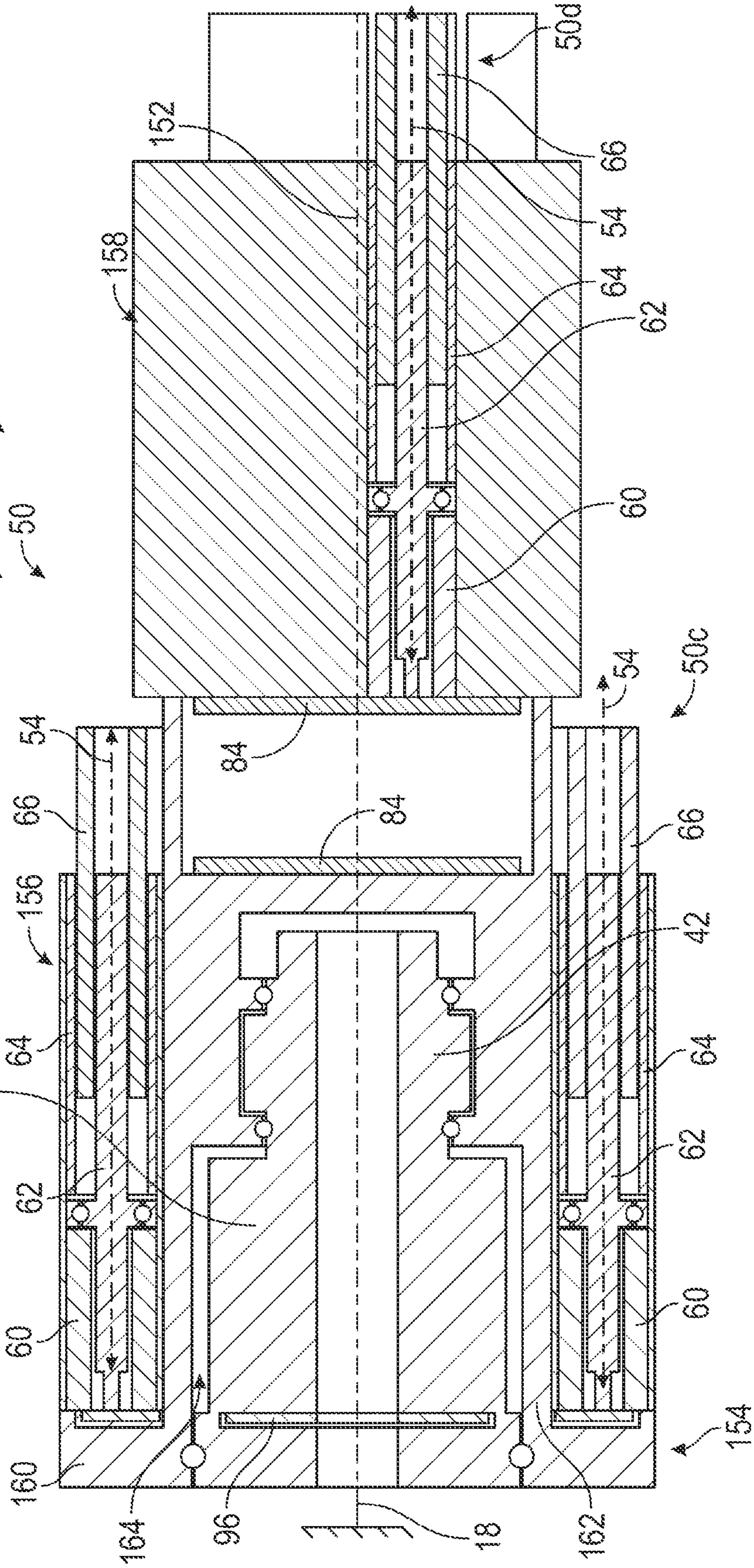
50d
66
54
152
158
64
62
12
44
150
50
60
80
54
50c
54
84
84
66
66
156
42
64
64
48
62
62
60
60
160
164
96
18
162
154

FIG. 11

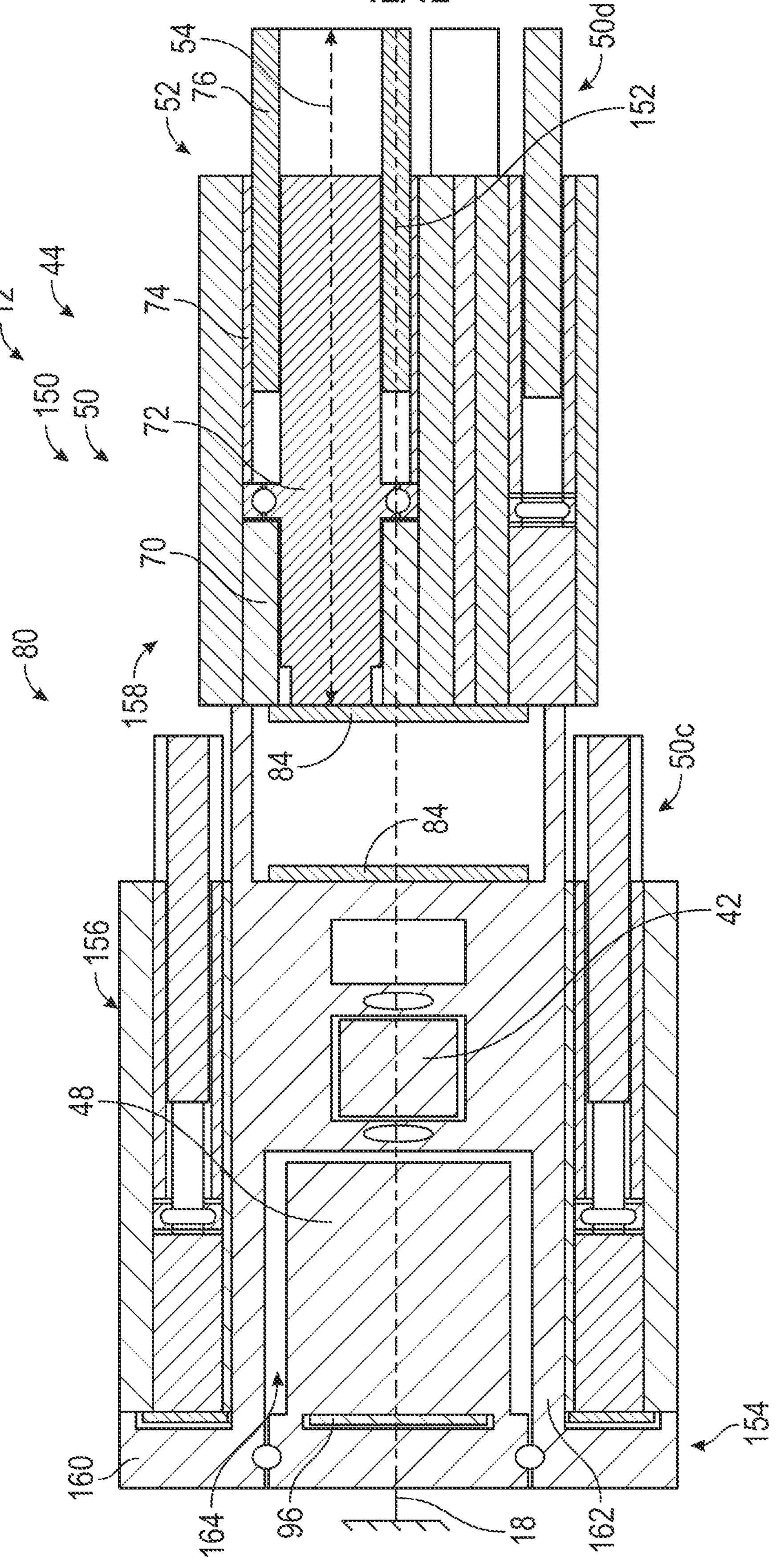
12
44
150
50
52
54
76
74
72
70
80
158
84
84
50d
152
50c
42
156
48
160
164
96
18
162
154

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2025/050215

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***B25J 15/12*** (2026.01); ***B25J 15/02*** (2026.01); ***B25J 17/02*** (2026.01); ***B25J 18/00*** (2026.01); ***B25J 15/00*** (2026.01); ***B25J 9/00*** (2026.01); *A61F 2/58* (2026.01)

CPC: ***B25J 15/12; B25J 15/024; B25J 17/02; B25J 18/00; B25J 15/0009; B25J 9/0009;*** *A61F 2002/543; A61F 2/586; A61F 2/585*

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)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	CN 106737789 A (Jiangsu Jingang Culture and Tech Group Co Ltd) 31 May 2017 (31.05.2017)	
X	fig. 1-5	1-2, 9-12
Y	entire document	14-15
A	fig. 1-3	3-8, 13
	US 2012/0194120 A1 (Reiland et al.) 02 August 2012 (02.08.2012)	
Y	para [0025], fig. 2-3	14-15
	"The Robonaut 2 Hand – Designed To Do Work With Tools" (Bridgewater) [online], 15 November 2013, [retrieved on 2025-12-15]. Retrieved from the internet: [URL: https://web.archive.org/web/20231115181232/https://ntrs.nasa.gov/api/citations/20110023122/downloads/20110023122.pdf]	
A	page 3, 5-6, 17, fig. 7, 15-16	3-8, 13

☑ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "D" document cited by the applicant in the international application
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 February 2026 (05.02.2026)	**12 February 2026 (12.02.2026)**

Name and mailing address of the ISA/US	Authorized officer
COMMISSIONER FOR PATENTS **MAIL STOP PCT, ATTN: ISA/US** **P.O. Box 1450** **Alexandria, VA 22313-1450** **UNITED STATES OF AMERICA**	**HARRY KIM**
Facsimile No. **571-273-8300**	Telephone No. **PCT Help Desk: 571-272-4300**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2025/050215

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	"Wrist and Forearm Rotation of the DLR Hand Arm System: Mechanical Design, Shape Analysis and Experimental Validation" (Friedl) [online], 02 December 2011, [retrieved on 2025-12-15]. Retrieved from the internet: [URL: https://elib.dlr.de/72934/1/06094616.pdf] entire document	1-15

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1.

Group I: Claims 1-15 directed to a wrist linear actuator.

Group II: Claim 16-19 directed to the first housing section extends axially from a first end to an interface between the first housing section and the second housing section.

Group III: Claims 20 directed to a rotary printed circuit board and a linear printed circuit board.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☑ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: **1-15**

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.