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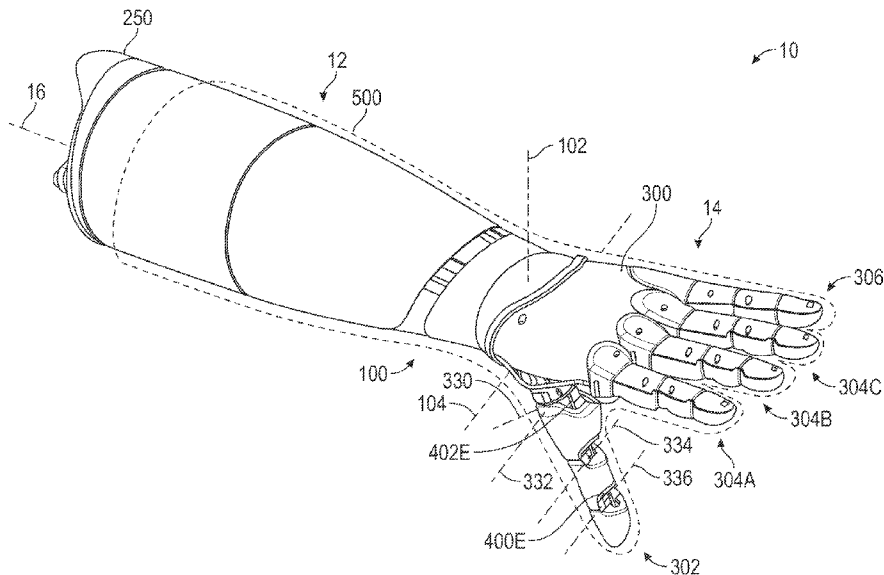
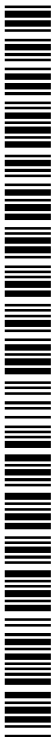


FIG. 8

(57) **Abstract:** A robotic appendage includes: a forearm body; a palm body movably coupled to the forearm body; a finger assembly coupled to the palm body, the finger assembly including a phalanx; a tensile member coupled to the phalanx and extending through the palm body; and an actuator coupled to the forearm body and the tensile member and configured to tension the tensile member to reposition the phalanx relative to the palm body.



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## **ROBOTIC APPENDAGE**

### **CROSS-REFERENCE TO RELATED PATENT APPLICATION**

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/706,010, 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 joint assemblies for movably connecting sections of robotic appendages.

### **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, a robotic appendage includes: a forearm body; a palm body movably coupled to the forearm body; a finger assembly coupled to the palm body, the finger assembly including a phalanx; a tensile member coupled to the phalanx and extending through the palm body; and an actuator coupled to the forearm body and the tensile member and configured to tension the tensile member to reposition the phalanx relative to the palm body.

[0005] In some embodiments, the phalanx is a first phalanx, the finger assembly further includes a second phalanx that couples the first phalanx to the palm body, and the tensile member extends through the second phalanx.

**[0006]** In some embodiments, the finger assembly further includes a third phalanx coupling the second phalanx to the palm body, and the actuator is configured to tension the tensile member to reposition the first phalanx and the second phalanx relative to the third phalanx and the palm body.

**[0007]** In some embodiments, the actuator is a first actuator, the finger assembly includes an opposition member coupling the second phalanx to the palm body, and the robotic appendage further includes a second actuator configured to reposition the opposition member relative to the palm body.

**[0008]** In some embodiments, the first actuator is configured to pivot the first phalanx relative to the second phalanx about a first axis, the second actuator is configured to pivot the opposition member relative to the palm body about a second axis, and the first axis is not parallel to the second axis.

**[0009]** In some embodiments, the finger assembly is a first finger assembly, the robotic appendage further includes a second finger assembly coupled to the palm body, the phalanx is pivotable relative to the palm body about an axis that extends through the palm body, and the actuator is configured to tension the tensile member to pivot the phalanx about the axis such that the phalanx moves toward or away from the second finger assembly.

**[0010]** In some embodiments, the actuator is a first actuator and the tensile member is a first tensile member, and the robotic appendage further includes: a second tensile member coupled to the phalanx and extending through the palm body; and a second actuator coupled to the forearm body and the second tensile member and configured to tension the second tensile member to pivot the phalanx about the axis.

**[0011]** In some embodiments, the axis extends between the first tensile member and the second tensile member, the first actuator is configured to tension the first tensile member to move the phalanx toward the second finger assembly, and the second actuator is configured to tension the second tensile member to move the phalanx away from the second finger assembly.

**[0012]** In some embodiments, the axis is a first axis, and the first actuator and the second actuator are configured to tension the first tensile member and the second tensile member

simultaneously to pivot the phalanx relative to the palm body about a second axis that extends substantially perpendicular to the first axis.

**[0013]** In some embodiments, the phalanx is a first phalanx, the first finger assembly further includes a second phalanx coupled to the first phalanx, and the robotic appendage further includes: a third tensile member coupled to the phalanx and extending through the first phalanx and the palm body; and a third actuator coupled to the forearm body and the third tensile member and configured to tension the third tensile member to pivot the second phalanx relative to the first phalanx.

**[0014]** In some embodiments, the actuator is a finger actuator, and the robotic appendage further includes a wrist actuator coupled to the forearm body and configured to pivot the palm body relative to the forearm body.

**[0015]** In some embodiments, the wrist actuator is a first wrist actuator configured to pivot the palm body relative to the forearm body about a first axis, further including a second wrist actuator coupled to the forearm body and configured to pivot the palm body relative to the forearm body about a second axis substantially perpendicular to the first axis.

**[0016]** In some embodiments, the robotic appendage further includes a rigid link coupling the palm body to the wrist actuator.

**[0017]** In some embodiments, the actuator is a finger actuator, and the robotic appendage further includes: an arm base pivotably coupled to the forearm body such that the forearm body extends between the arm base and the palm body; and a forearm actuator coupled to the forearm body and configured to pivot the forearm body relative to the arm base.

**[0018]** In some embodiments, the phalanx is a first phalanx, the finger assembly further includes a second phalanx and a third phalanx coupling the first phalanx to the palm body, and the robotic appendage further includes: a first sensor coupled to the first phalanx; a second sensor coupled to the second phalanx; a third sensor coupled to the third phalanx; and a fourth sensor coupled to the palm body.

[0019] In some embodiments, the first sensor includes at least one of a resistive tactile sensor or a capacitive tactile sensor.

[0020] In some embodiments, the robotic appendage further includes a glove at least partially containing the finger assembly, the palm body, and the forearm body.

[0021] In some embodiments, the actuator is an electric linear actuator.

[0022] In at least one embodiment, a robotic appendage includes: a palm body; a first finger assembly coupled to the palm body; a second finger assembly coupled to the palm body; a plurality of tensile members coupled to the first finger assembly and extending through the palm body; and a plurality of electric actuators each coupled to one of plurality of the tensile members, the plurality of electric actuators including: a first electric actuator configured to cause flexion of the first finger assembly toward the palm body; a second electric actuator configured to cause abduction of the first finger assembly away from the second finger assembly; and a third electric actuator configured to cause adduction of the first finger assembly toward the second finger assembly.

[0023] In at least one embodiment, a robotic appendage includes: a forearm body; a palm body pivotably coupled to the forearm body; an opposition body pivotably coupled to the palm body; a first finger assembly including: a first phalanx pivotably coupled to the opposition body; a second phalanx pivotably coupled to the first phalanx; and a third phalanx pivotably coupled to the second phalanx; a second finger assembly coupled to the palm body; a plurality of tensile members extending through the palm body to the forearm body, the plurality of tensile members including: a first tensile member coupled to the opposition body; a second tensile member and a third tensile member coupled to the first phalanx; and a fourth tensile member coupled to the third phalanx; a first actuator configured to tension the first tensile member to pivot the opposition body relative to the palm body about an opposition axis; a second actuator configured to tension the second tensile member to pivot the first phalanx relative to the palm body about a splaying axis in a first direction, the splaying axis extending through the palm body; a third actuator configured to tension the third tensile member to pivot the first phalanx relative to the palm body about the splaying axis in a second direction; and a fourth actuator configured to tension the fourth tensile member to pivot the second phalanx

relative to the first phalanx about a flexing axis. The flexing axis is not parallel to the opposition axis.

### **BRIEF DESCRIPTION OF THE FIGURES**

[0024] FIG. 1 is a side view of a robotic arm assembly including a wrist assembly, according to an embodiment.

[0025] FIG. 2 is a top view of the robotic arm assembly of FIG. 1.

[0026] FIG. 3 is a perspective view of the wrist assembly of the robotic arm assembly of FIG. 1 in a first position about a pivot axis.

[0027] FIG. 4 is a perspective view of the wrist assembly of FIG. 1 in a second position about the pivot axis.

[0028] FIG. 5 is a perspective view of the wrist assembly of FIG. 1 in a first position about a yaw axis.

[0029] FIG. 6 is a perspective view of the wrist assembly of FIG. 1 in a second position about the yaw axis.

[0030] FIG. 7 is side view of a bearing of the wrist assembly of FIG. 1.

[0031] FIG. 8 is a perspective view of the robotic arm assembly of FIG. 1 including a hand, according to an embodiment.

[0032] FIG. 9 is a bottom view of the robotic arm assembly of FIG. 1.

[0033] FIG. 10 is a bottom perspective view of the hand of FIG. 8.

[0034] FIG. 11 is a bottom perspective view of the hand of FIG. 8.

[0035] FIG. 12 is a schematic view of the hand of FIG. 8.

[0036] FIG. 13 is a side view of a joint of the hand of FIG. 8, according to an embodiment.

[0037] FIG. 14 is a schematic view of the hand of FIG. 8.

[0038] FIG. 15 is a block diagram of a control system for the robotic arm assembly of FIG. 1, according to an embodiment.

### **DETAILED DESCRIPTION**

[0039] 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.

[0040] Referring generally to the figures, a robotic appendage for a robot includes a first member (e.g., a forearm) and a second member (e.g., a hand). The second member is coupled with the first member through a linkage (e.g., a wrist assembly). The linkage allows rotation of the second member relative to the first member about a yaw axis and a pitch axis. The second member can be driven to rotate about the yaw axis or the pitch axis by a pair of actuators. The linkage includes a universal joint (e.g., a central universal joint) that defines the yaw axis. In particular, the universal joint is rotatably coupled with a bracket of the first member about the yaw axis such that the universal joint can be rotated in a first or second direction (e.g., clockwise or counter-clockwise, radial and ulnar deviation, etc.) relative to the first member. The linkage also includes a structure that is pivotably coupled with the universal joint about the pitch axis. The pitch axis is perpendicular to the yaw axis. The pitch axis is disposed forwards of the first axis positioned more proximate the structure than the yaw axis.

[0041] The linkage also includes a pair of links. The pair of links are each coupled, at a first end, with an end of a corresponding one of the linear actuators. The pair of links are each coupled, at a second end, with a corresponding one of a pair of coupling universal joints. The pair of links are constrained at their first ends to move in a linear direction without lateral movement. The second ends of the pair of links are pivotably coupled to the coupling universal joints and can rotate relative to the coupling universal joints about first axes of the coupling universal joints. The coupling universal joints can also define second axes that are parallel with the pitch axis. The linkage can include a track extending centrally through the bracket and can include sliders that are slidably coupled with the track on opposite sides of the track.

The first ends of the links are coupled with the sliders on opposite sides of the track to constrain the first ends of the links and ends of the actuators to linear motion (e.g., translation) along the track. The universal joint can be coupled with the bracket through a bearing in a cantilevered arrangement such that a space is provided beneath the universal joint for control cables (e.g., tendons). The actuators can be operated to rotate the second member about the yaw axis or the pitch axis relative to the first member. For example, if the actuators are both extended or retracted at a same speed or rate, the second member can be rotated relative to the first member about the pitch axis. Likewise, if the actuators are extended or retracted at a different speed or rate, the second member can be rotated relative to the first member about the yaw axis.

**[0042]** The hand includes a palm body coupled to a series of finger assemblies. Each of the finger assemblies include a series of phalanges that are pivotably coupled to one another. Tensile members (e.g., tendons) are fixedly coupled to the phalanges and extend through the fingers and the palm body to linear actuators housed within the forearm. By activating the linear actuators, the tensile members can be tensioned to move the fingers in desired directions. The tensile members may control flexion, abduction, and adduction of the fingers. Beneficially, this arrangement facilitates engaging a variety of different objects with complex shapes. In total, the robotic appendage may provide twenty-five degrees of freedom (e.g., one at an elbow, two at the wrist, and twenty-two at the fingers).

### **Wrist Assembly**

**[0043]** 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 forearm 12 (e.g., a first member, a forearm member, an upper member, a forearm body, etc.) and a hand 14 (e.g., a second member, a hand member, a hand assembly, a lower member, an articulatable member, etc.). The hand 14 is coupled with the forearm 12 via a joint assembly 100 (e.g., a linkage, a wrist assembly, a joint, etc.). The joint assembly 100 allows rotation of the hand 14 relative to the forearm 12 about a first axis, shown as yaw axis 102, and about a second axis, shown as pitch axis 104.

**[0044]** The joint assembly 100 includes a bracket 112 (e.g., a fixed member, a forearm frame, etc.), a hand structure 120 (e.g., a structure, a hand frame member, a hand frame, a palm

member, a palm body, etc.), and a universal joint 118. The bracket 112 is contained within or forms a part of the forearm 12. In some embodiments, the bracket 112 is fixed to (e.g., anchored to) the forearm 12. In some embodiments the bracket 112 is fixed to a forearm frame member 110. The hand structure 120 (e.g., a frame, a palm member, a hand frame, a hand member, etc.) is similarly disposed within the hand 14. The hand structure 120 can be fixed to the hand 14, and the hand structure 120 may be contained within or form part of the hand 14.

**[0045]** The universal joint 118 rotatably couples with both the bracket 112 and the hand structure 120. In particular, the universal joint 118 pivotably couples with the bracket 112 about the yaw axis 102 and pivotably couples with the hand structure 120 about the pitch axis 104. The universal joint 118 can define both the yaw axis 102 and the pitch axis 104. The yaw axis 102 and the pitch axis 104 are perpendicular to each other and are defined by corresponding portions of the universal joint 118. The universal joint 118 can be rotatably coupled to the bracket 112 about the yaw axis 102 and the hand structure 120 about the pitch axis 104 via bearings (e.g., ball bearings, roller bearings, etc.). In particular, the universal joint 118 can be coupled to an end of the bracket 112. The joint assembly 100 facilitates radial and ulnar deviation of the hand 14 about the yaw axis 102, and flexion and extension of the hand 14 about the pitch axis 104. The bracket 112 includes an upper member 113a and a lower member 113b that are offset from each other to define a space. The universal joint 118 is positioned between the upper member 113a and the lower member 113b. As shown in FIG. 2, the pitch axis 104 is offset a distance 136 from the yaw axis 102 along the centerline 16 or in a direction parallel with the centerline 16 (e.g., a longitudinal direction). The centerline 16 may represent a central longitudinal axis of the forearm 12, such that the forearm 12 is centered about the centerline 16.

**[0046]** The joint assembly 100 also includes a plurality of wrist actuators 116 including a first wrist actuator 116a and a second wrist actuator 116b, and a plurality of rigid members or rigid links, shown as links 114, including a first link 114a (e.g., a connecting member, a bar, a rod, etc.) and a second link 114b (e.g., a connecting member, a bar, a rod, etc.). The links 114 may be rigid, such that the links 114 maintain their shape under both compressive and tensile loadings. The first wrist actuator 116a and the second wrist actuator 116b can be linear actuators that extend and retract. In some embodiments, the wrist actuators 116 are electric

linear actuators (e.g., electric motors that provide rotational mechanical energy that is converted to linear motion (e.g., through a lead screw or ball screw)). The first wrist actuator 116a and the second wrist actuator 116b are coupled to the forearm frame member 110. In particular, the first wrist actuator 116a and the second wrist actuator 116b are constrained such that the first wrist actuator 116a and the second wrist actuator 116b do not pivot or move laterally while extending and retracting. In this way, the first wrist actuator 116a and the second wrist actuator 116b are configured to only provide linear motion without themselves rotating or otherwise moving. The first wrist actuator 116a and the second wrist actuator 116b are disposed on opposite sides of the bracket 112. In particular, the first wrist actuator 116a and the second wrist actuator 116b can be offset from the yaw axis 102 such that a moment arm is defined and the first wrist actuator 116a and the second wrist actuator 116b can provide torque in either direction to drive rotation of the universal joint 118 about the yaw axis 102 (e.g., to independently control a position of the hand 14 relative to the forearm 12. As shown in FIG. 2, the first link 114a and the second link 114b are disposed on opposite sides of a centerline 16 of the forearm 12. The first wrist actuator 116a is configured to exert a first force on a first side 140 of the hand structure 120 via the first link 114a, and the second wrist actuator 116b is configured to exert a second force on a second side 142 of the hand structure 120 via the second link 114b.

**[0047]** As shown in FIGS. 1–6, the joint assembly 100 also includes a pair of links, shown as first link 114a and second link 114b. The first link 114a is coupled at its proximate end 126 (e.g., a first end) with an end of the first wrist actuator 116a and is coupled at its distal end 128 (e.g., a second end) with the hand structure 120. Likewise, the second link 114b is coupled at its proximate end 126 (e.g., a first end) with an end of the second wrist actuator 116b and is coupled at its distal end 128 (e.g., a second end) with the hand structure 120. The first link 114a and the second link 114b are disposed on opposite sides of the centerline 16 of the forearm 12. The distal ends 128 of the links 114 can be provided as yoked ends, clevises, U-shape protrusions, etc.

**[0048]** As shown in FIG. 2, the first link 114a and the second link 114b each have a curved shape or angled shape. In particular, the first link 114a and the second link 114b each have a first portion that is angled outwards from their proximate ends 126 relative to the centerline 16,

and a second portion that is angled inwards towards the distal ends 128 relative to the centerline 16. For example, as shown in FIG. 2, the first link 114a and the second link 114b protrude outwards from the wrist actuators 116 and then protrude inwards to opposite sides of the hand structure 120. The angled shapes of the first link 114a and the second link 114b facilitate improved rotational range of the universal joint 118 about the yaw axis 102 and the pitch axis 104 by providing additional space or clearance between the bracket 112 and the links 114.

**[0049]** As shown in FIGS. 1–6, the links 114 are coupled with the hand structure 120 via secondary universal joints, shown as coupling universal joints 122. In some embodiments, the universal joint 118 is a central universal joint. The coupling universal joints 122 are disposed on opposite sides of the hand structure 120 such that the links 114 are configured to exert a torque to rotate the hand structure 120 and the universal joint 118 about the yaw axis 102 in either direction. The coupling universal joints 122 pivotably couple with the distal ends 128 of the links 114 on opposite sides (e.g., fore and aft sides or left and right sides) of the hand structure 120 about first axes 106, shown as first axis 106a and first axis 106b. The first axes 106 are generally perpendicular to the pitch axis 104. The first axes 106, as viewed from the side of the robotic arm assembly 10, are angularly offset relative to the yaw axis 102. In particular, the first axes 106 are non-parallel with the yaw axis 102. For example, as shown in FIG. 1, the yaw axis 102 is perpendicular to both the pitch axis 104 and the centerline 16 and extends in a vertical or upwards direction. However, as shown in FIG. 1, the first axes 106 are angled such that, when the hand 14 is in the neutral position as shown in FIG. 1, the first axes 106 extend upwards and also forwards towards the hand 14. As shown in FIG. 2, the first axes 106 extend inwards towards the centerline 16. In this way, the first axes 106 are angled both towards the hand 14 and also inwards towards the centerline 16. The coupling universal joints 122 can include bores or openings that define the first axes 106 and are aligned with corresponding openings of the distal ends 128. In some embodiments, pins or cylindrical members are received within the openings of the distal ends 128 (e.g., formed in opposing portions of the yoked ends) and the bore of the coupling universal joints 122 that define the first axes 106.

**[0050]** In certain embodiments, the orientation and offset of the yaw axis 102, pitch axis 104, and first axes 106 of the coupling universal joints 122 are selected to enable independent and

simultaneous control of both yaw and pitch rotation of the hand 14 relative to the forearm 12 using only two wrist actuators 116. Specifically, the first axes 106 of the coupling universal joints 122 are radially offset from and non-parallel to the yaw axis 102, while the second axes 108 of the coupling universal joints 122 are substantially parallel to the pitch axis 104 of the central universal joint. This geometric relationship allows differential actuation between the first and second wrist actuators 116 to effect rotation about the yaw axis 102, while uniform actuation of the first and second wrist actuators 116 effects rotation about the pitch axis 104. As a result, the wrist assembly (i.e., the joint assembly 100) achieves full two-degree-of-freedom control without requiring separate dedicated actuators for each axis, reducing part count, mechanical complexity, and weight while maintaining precise and responsive motion in both yaw and pitch directions.

**[0051]** The coupling universal joints 122 also define second axes 108, shown as second axis 108a and second axis 108b. The second axes 108 are parallel with the pitch axis 104. The second axes 108 are positioned above (e.g., higher than, offset in a direction parallel with the yaw axis 102) the pitch axis 104. The second axes 108 are co-axial with each other. The coupling universal joints 122 are pivotably coupled with the hand structure 120 about the second axes 108. The coupling universal joints 122 facilitate coupling the first link 114a and the second link 114b with the hand structure 120 such that the first link 114a and the second link 114b can move the universal joint 118 and the hand structure 120 to rotate about the yaw axis 102 and the pitch axis 104. The coupling universal joints 122 can be coupled with the first side 140 and the second side 142 of the hand structure 120 similarly to the coupling between the distal ends 128 of the links 114 and the coupling universal joints at the first axes 106.

**[0052]** As shown in FIGS. 1 and 3-6, the joint assembly 100 includes a track 132 (e.g., an elongated member, etc.). The track 132 is disposed between the upper member 113a and the lower member 113b of the bracket 112. The wrist actuators 116 can also be positioned between the upper member 113a and the lower member 113b and are configured to extend and retract in directions parallel with the centerline 16. The track 132 likewise extends in a direction parallel with the centerline 16 (e.g., lengthwise). The track 132 is configured to receive a pair of track members 134 (e.g., sliders, slidable members, etc.) that slidably couple with the track 132. Ends of the wrist actuators 116 are coupled with the track members 134. The proximate

ends 126 of the links 114 are also coupled with the corresponding track members 134. In particular, the proximate end 126 of the first link 114a is coupled with a first of the track members 134 (e.g., a first slider) on a first side of the track 132, and the proximate end 126 of the second link 114b is coupled with a second of the track members 134 (e.g., a second slider) on a second side of the track 132.

**[0053]** The track members 134 constrain movement of ends of the wrist actuators 116 and proximate ends 126 of the links 114 to linear motion along the track 132. The wrist actuators 116 are configured to extend or retract to drive motion of the respective track members 134 along the track 132. The links 114 are coupled to the track members 134 at their proximate ends 126 in order to constrain motion of the proximate ends 126 of the links 114 to linear motion along the track 132.

**[0054]** As shown in FIGS. 3 and 4, the wrist actuators 116 are operable to drive rotation of the hand structure 120 about the pitch axis 104. The wrist actuators 116 may both extend at a same rate or a same amount of displacement in a same direction in order to rotate the hand structure 120 and the hand 14 in a first direction about the pitch axis 104 (e.g., in a flexion direction). The wrist actuators 116 can both retract at a same rate or a same amount of displacement in order to rotate the hand structure 120 and the hand 14 in a second direction about the pitch axis 104 (e.g., in an extension direction). In this way, the wrist actuators 116 can be operated to cause the hand structure 120 and the hand 14 to undergo extension or flexion relative to the forearm 12, the forearm frame member 110, the bracket 112, and the universal joint 118. For example, both the first wrist actuator 116a and the second wrist actuator 116b can be operable to extend or retract in unison in order to rotate the hand structure 120 about the pitch axis 104 in either the flexion or the extension direction. The flexion direction of rotation about the pitch axis 104 is the direction of rotation that the hand structure 120 undergoes when moving from the position shown in FIG. 3 to the position shown in FIG. 4. On the contrary, the hand structure 120 undergoes extension direction of rotation about the pitch axis 104 from the position shown in FIG. 4 to the position shown in FIG. 3.

**[0055]** Referring to FIGS. 2, 3, and 4, the hand structure 120 includes a notch 124 (e.g., a space, an area, a void, a recess, etc.) that faces the universal joint 118. The hand structure 120 can generally have a U-shape that defines the notch 124. The notch 124 can have a width

corresponding to or greater than an outer diameter of the bracket 112 at the yaw axis 102. In this way, the upper member 113a of the bracket 112 at the yaw axis 102 can be received within the notch 124 when the hand structure 120 is rotated in the extension direction to an extension bounds (e.g., an outer limit of rotation in the extension direction), as shown in FIG. 3. The notch 124 can enable further movement or increased range of the hand structure 120 about the pitch axis 104 in the extension direction.

**[0056]** As shown in FIGS. 5 and 6, the wrist actuators 116 are operable to drive rotation of the hand structure 120 and the universal joint 118 about the yaw axis 102. The wrist actuators 116 can extend at different rates or different amounts of displacement in a same or different directions in order to rotate the hand structure 120, the hand 14, and the universal joint 118 about the yaw axis 102. The wrist actuators 116 can be operated to rotate the hand structure 120, the hand 14, and the universal joint 118 in a first direction about the yaw axis 102 (e.g., a radial deviation direction) or in a second direction about the yaw axis 102 (e.g., an ulnar deviation direction). For example, the first wrist actuator 116a and the second wrist actuator 116b can extend or retract at different rates in order to rotate the hand structure 120, the hand 14, and the universal joint 118 in the ulnar or radial direction about the yaw axis 102.

**[0057]** Referring to FIG. 7, the universal joint 118 can be coupled with the bracket 112 via a cantilevered bearing arrangement. The cantilevered bearing arrangement includes a bearing assembly 200 having a bearing 202 disposed within and extending between openings in the upper member 113a and the lower member 113b. In some embodiments, a portion of the universal joint 118 is positioned between the upper member 113a and the lower member 113b. The universal joint 118 can be supported from and hang from the upper member 113a and the lower member 113b of the bracket 112. The universal joint 118 is rotatably coupled with the bracket 112 via the bearing 202. In some embodiments, the universal joint 118 is coupled to an outer race of the bearing 202. For example, the universal joint 118 can include a bore at the first portion within which the bearing 202 is positioned. In some embodiments, the universal joint 118 is coupled to an outer race of the bearing 202 via an inner surface of the bore. The upper member 113a and the lower member 113b can be coupled with an inner race of the bearing 202 via a first fastener 204 and a second fastener 206, respectively.

**[0058]** In some embodiments, the cantilevered arrangement is provided such that a volume 130 (e.g., a space, an area, a void, etc.) is formed beneath the bearing 202. The volume 130 provides clearance for control cables 208 (e.g., hand tendons, hand control lines, etc.) such that the control cables 208 do not interfere with each other or with movement of the hand 14. In some embodiments, the volume 130 provides space so that hand control cables and finger control cables have sufficient clearance.

**[0059]** In some embodiments, the spatial arrangement of the universal joint 118, wrist actuators 116, links 114, and associated track 132 within the forearm 12 (e.g., the forearm member) is specifically configured to optimize available interior volume of the forearm 12. This arrangement, including the cantilevered mounting of the universal joint 118 to create cable clearance beneath the joint and the positioning of the wrist actuators 116 along opposite sides of a central track, enables the forearm 12 to accommodate a greater number of finger actuators than would otherwise be possible in conventional wrist joint configurations. By reducing interference between wrist actuation components and finger tendon routing, the design allows for an increased actuator capacity within the forearm 12, thereby providing enhanced dexterity, strength, and range of motion in the robotic hand without increasing the overall size of the forearm assembly.

**[0060]** 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.

## Overview of Robotic Arm Assembly

**[0061]** Referring to FIGS. 8–10, the robotic arm assembly 10 is shown according to an embodiment. The robotic arm assembly 10 includes the forearm 12, the hand 14, and an elbow portion, base portion, fixed portion, or proximal section, shown as arm base 250. The arm base 250 is pivotably coupled to a proximal end portion of the forearm 12 (e.g., the forearm frame member 110). The hand 14 is pivotably coupled to a distal end portion of the forearm 12. Accordingly, the forearm 12 extends longitudinally along the centerline 16 between the arm base 250 and the hand 14.

**[0062]** The arm base 250 may support the other components of the robotic arm assembly 10. In some embodiments, the arm base 250 is a part of a larger robotic assembly. By way of example, the arm base 250 may be an elbow of a larger humanoid robot (e.g., a humanoid robot including multiple robotic arm assemblies 10 coupled to a torso). In such an embodiment, the arm base 250 may be coupled to an upper arm of the humanoid robot. The arm base 250 may be repositioned to control the position and/or the orientation of the robotic arm assembly 10 relative to the other components of the humanoid robot.

**[0063]** The forearm 12 is pivotably coupled to the arm base 250, such that the forearm 12 is pivotable relative to the arm base 250. Specifically, the forearm 12 may be pivotable relative to the arm base 250 about the centerline 16. In other embodiments, the forearm 12 may be pivotable about a different longitudinal axis. Accordingly, the forearm 12 may pivot relative to the arm base 250 to facilitate roll adjustment of the forearm 12 and the hand 14.

**[0064]** As shown in FIG. 9, the robotic arm assembly 10 includes an actuator or motor, shown as forearm actuator 252. The forearm actuator 252 is coupled to the arm base 250 and to the forearm 12 (e.g., the forearm frame member 110). The forearm actuator 252 may drive rotation of the forearm 12 relative to the arm base 250 to adjust the roll position of the robotic arm assembly 10. By way of example, the forearm actuator 252 may be directly coupled to the arm base 250 and the hand 14. As shown, the forearm actuator 252 is positioned within the forearm 12 (e.g., at least partially contained within the forearm 12). In some embodiments, the forearm actuator 252 is an electric motor.

**[0065]** Referring to FIGS. 10 and 11, the hand 14 is shown according to an embodiment. The hand 14 includes a series of bodies, members, sections, structures, or hand portions that are movably coupled to one another to form the hand 14. The structures include a palm body 300 and a series of phalanges coupled to the palm body 300. The phalanges form a series of appendages or finger assemblies, shown as thumb 302, central fingers 304, and pinky 306. The central fingers 304 include an index finger 304A, a middle finger 304B, and a ring finger 304C. The palm body 300 acts as a central portion of the hand 14, and the thumb 302, the central fingers 304, and the pinky 306 are each directly coupled to and extend away from the palm body 300. The thumb 302, the central fingers 304, and/or the pinky 306 may each be actuated to control movement of the hand 14.

**[0066]** The thumb 302, the central fingers 304, and the pinky 306 are positioned at different lateral locations along a perimeter of the palm body 300. The central fingers 304 are positioned between the thumb 302 and the pinky 306. The middle finger 304B is positioned between the index finger 304A and the ring finger 304C. Accordingly, the middle finger 304B is the most central of the fingers.

**[0067]** Referring still to FIGS. 10 and 11, the structure of the index finger 304A is shown according to an embodiment. Each of the central fingers 304 may have a similar structure, such that the structure of the index finger 304A may be substantially similar to the middle finger 304B and the ring finger 304C. Accordingly, any description of the index finger 304A may apply to the middle finger 304B and the ring finger 304C, except as otherwise specified herein. The middle finger 304B is longer than the index finger 304A and the ring finger 304C, such that the middle finger 304B extends furthest out from the palm body 300.

**[0068]** The index finger 304A includes a series of bodies, members, sections, structures, finger portions, or phalanges, shown as proximal phalanx 310, middle phalanx 312, and distal phalanx 314. A proximal end portion of the proximal phalanx 310 is coupled to the palm body 300 by a first joint, coupler, connection, pivot, or metacarpophalangeal (MCP) joint, shown as MCP joint 320. A proximal end portion of the middle phalanx 312 is coupled to a distal end portion of the proximal phalanx 310 by a second joint, coupler, connection, pivot, or proximal interphalangeal (PIP) joint, shown as PIP joint 322. A proximal end portion of the distal phalanx 314 is coupled to a distal end portion of the middle phalanx 312 by a third joint,

coupler, connection, pivot, or distal interphalangeal (DIP) joint, shown as DIP joint 324. The MCP joint 320, the PIP joint 322, and the DIP joint 324 each pivotably couple the phalanges to one another to permit articulation of the hand 14. The proximal phalanx 310 is coupled to a forward side of the palm body 300 such that the index finger 304A extends longitudinally forward from the opposition member 340 (e.g., opposite the direction of the forearm 12).

**[0069]** The MCP joint 320 permits pivoting of the proximal phalanx 310 relative to the palm body 300 about two different axes, such that the MCP joint 320 provides two degrees of freedom to the hand 14. Specifically, the MCP joint 320 permits pivoting (e.g., rotation) of the proximal phalanx 310 relative to the palm body 300 about a vertical axis, splaying axis, adduction axis, or abduction axis, shown as splaying axis 330. The splaying axis 330 passes through (e.g., intersects) the palm body 300, and the splaying axis 330 extends substantially perpendicular to a plane that contains the palm body 300 and the central fingers 304. Rotation about the splaying axis 330 facilitates moving the central fingers 304 toward and away from one another. By way of example, rotation of the proximal phalanx 310 of the index finger 304A in a first direction about the splaying axis 330 (e.g., clockwise) may move the index finger 304A toward the middle finger 304B (e.g., adduction of the index finger 304A). By way of another example, rotation of the proximal phalanx 310 of the middle finger 304B in a second direction about the splaying axis 330 opposite the first direction (e.g., counter-clockwise) may move the index finger 304A away from the middle finger 304B (e.g., abduction of the index finger 304A).

**[0070]** The MCP joint 320 further permits pivoting (e.g., rotation) of the proximal phalanx 310 relative to the palm body 300 about a lateral axis, flexion axis, or extension axis, shown as flexing axis 332. The flexing axis 332 may extend substantially perpendicular to the splaying axis 330. The flexing axis 332 passes laterally between the proximal phalanx 310 and the palm body 300. Rotation about the flexing axis 332 permits bending the central fingers 304 (e.g., to permit grasping or releasing an object). By way of example, rotation of the proximal phalanx 310 of the index finger 304A in a first direction about the flexing axis 332 may move the index finger 304A toward the palm body 300 (e.g., flexion of the index finger 304A to close the hand 14 and grasp an object). By way of another example, rotation of the proximal phalanx 310 of the index finger 304A in a second direction about the flexing axis 332 opposite the first

direction may move the index finger 304A away from the palm body 300 (e.g., extension of the index finger 304A to open the hand 14 and release an object).

**[0071]** The PIP joint 322 permits pivoting (e.g., rotation) of the middle phalanx 312 relative to the proximal phalanx 310 about a lateral axis, flexion axis, or extension axis, shown as flexing axis 334, such that the PIP joint 322 provides one degree of freedom to the hand 14. The flexing axis 334 may extend substantially perpendicular to the splaying axis 330 and substantially parallel to the flexing axis 332. The flexing axis 334 passes laterally between the middle phalanx 312 and the proximal phalanx 310. Rotation about the flexing axis 334 permits bending the central fingers 304 (e.g., to permit grasping or releasing an object). By way of example, rotation of the middle phalanx 312 of the index finger 304A in a first direction about the flexing axis 334 may move the index finger 304A toward the palm body 300 (e.g., flexion of the index finger 304A to close the hand 14 and grasp an object). By way of another example, rotation of the middle phalanx 312 of the index finger 304A in a second direction about the flexing axis 334 opposite the first direction may move the index finger 304A away from the palm body 300 (e.g., extension of the index finger 304A to open the hand 14 and release an object).

**[0072]** The DIP joint 324 permits pivoting (e.g., rotation) of the distal phalanx 314 relative to the middle phalanx 312 about a lateral axis, flexion axis, or extension axis, shown as flexing axis 336, such that the DIP joint 324 provides one degree of freedom to the hand 14. The flexing axis 336 may extend substantially perpendicular to the splaying axis 330 and substantially parallel to the flexing axis 332 and the flexing axis 334. The flexing axis 336 passes laterally between the distal phalanx 314 and the middle phalanx 312. Rotation about the flexing axis 336 permits bending the central fingers 304 (e.g., to permit grasping or releasing an object). By way of example, rotation of the distal phalanx 314 of the index finger 304A in a first direction about the flexing axis 336 may move the index finger 304A toward the palm body 300 (e.g., flexion of the index finger 304A to close the hand 14 and grasp an object). By way of another example, rotation of the distal phalanx 314 of the index finger 304A in a second direction about the flexing axis 336 opposite the first direction may move the index finger 304A away from the palm body 300 (e.g., extension of the index finger 304A to open the hand 14 and release an object).

**[0073]** Due to the pivoting of the central fingers 304 about the respective splaying axes 330, the orientations of the central fingers 304 may vary throughout operation of the robotic arm assembly 10. In some embodiments, in at least one configuration of the robotic arm assembly 10, the flexing axes 332, the flexing axes 334, and the flexing axes 336 of the central fingers 304 extend substantially parallel to one another. The flexing axes 332, the flexing axes 334, and the flexing axes 336 of the central fingers 304 may be longitudinally offset from one another due to the differing lengths of the central fingers 304.

**[0074]** Referring still to FIGS. 10 and 11, the pinky 306 includes a proximal phalanx 310, a middle phalanx 312, and a distal phalanx 314 similar to the index finger 304A. The pinky 306 further includes an opposable body, member, section, structure, finger portion, or phalanx, shown as opposition member 340. The opposition member 340 is positioned between the proximal phalanx 310 and the palm body 300, such that the opposition member 340 couples the proximal phalanx 310 to the palm body 300.

**[0075]** Within the pinky 306, the proximal phalanx 310 is coupled to the middle phalanx 312 by a PIP joint 322, and the distal phalanx 314 is coupled to the middle phalanx 312 by a DIP joint 324. The pinky 306 further includes a MCP joint 320. However, instead of coupling the proximal phalanx 310 to the palm body 300 directly, the MCP joint 320 couples the proximal phalanx 310 to the opposition member 340. The proximal phalanx 310 is coupled to a forward side of the opposition member 340 such that the pinky 306 extends longitudinally forward from the opposition member 340. The pivotable relationship between the proximal phalanx 310 and the opposition member 340 may be substantially similar to the pivotable connection that the MCP joint 320 provides between the proximal phalanx 310 and the palm body 300 for the central fingers 304.

**[0076]** The opposition member 340 is pivotably coupled to the palm body 300 by a palmar pinky opposition joint, shown as opposition joint 342, such that the opposition member 340 is pivotable (e.g., rotatable) relative to the palm body 300 about an axis of rotation, shown as opposition axis 344. The opposition axis 344 extends generally within the plane of the palm body 300, however the opposition axis 344 is oriented at an angle (e.g., skewed) relative to the flexing axis 332 (e.g., the opposition axis 344 extends longitudinally and laterally). Accordingly, the opposition axis 344 permits movement of the pinky 306 in a different

direction than the MCP joint 320, the PIP joint 322, and the DIP joint 324. The opposition joint 342 provides an additional degree of freedom to the pinky 306 beyond the four total degrees of freedom provided by each of the central fingers 304.

**[0077]** Rotation of the pinky 306 about the opposition axis 344 permits bending the pinky 306 (e.g., to permit grasping or releasing an object). The opposition axis 342 accordingly permits inward lateral motion of the pinky 306 (e.g., adduction). By way of example, rotation of the opposition member 340 of the pinky 306 in a first direction about the opposition axis 344 may move the pinky 306 laterally inward and toward the palm body 300 (e.g., flexion of the pinky 306 to close the hand 14 and grasp an object). By way of another example, rotation of the opposition member 340 of the pinky 306 in a second direction about the opposition axis 344 opposite the first direction may move the pinky 306 away from the palm body 300 (e.g., extension of the pinky 306 to open the hand 14 and release an object).

**[0078]** Referring to FIGS. 8–11, the thumb 302 has a similar structure to the pinky 306. The thumb 302 includes a proximal phalanx 310, a middle phalanx 312, and a distal phalanx 314 similar to the pinky 306. The thumb 302 further includes an opposable body, member, section, structure, finger portion, or phalanx, shown as opposition member 350. The opposition member 350 is positioned between the proximal phalanx 310 and the palm body 300, such that the opposition member 350 couples the proximal phalanx 310 to the palm body 300. The opposition member 340 and the opposition member 350 are positioned on opposite sides of the palm body 300, such that the palm body 300 extends laterally between the opposition member 340 and the opposition member 350.

**[0079]** Within the thumb 302, the proximal phalanx 310 is coupled to the middle phalanx 312 by a PIP joint 322, and the distal phalanx 314 is coupled to the middle phalanx 312 by a DIP joint 324. The pinky 306 further includes a MCP joint 320. However, instead of coupling the proximal phalanx 310 to the palm body 300 directly, the MCP joint 320 couples the proximal phalanx 310 to the opposition member 350. The proximal phalanx 310 is coupled to a laterally-facing or vertically-facing side of the opposition member 340 such that the pinky 306 extends substantially perpendicular to the longitudinal direction (e.g., laterally and/or vertically). The pivotable relationship between the proximal phalanx 310 and the opposition

member 350 may be substantially similar to the pivotable connection that the MCP joint 320 provides between the proximal phalanx 310 and the palm body 300 for the central fingers 304.

**[0080]** The opposition member 350 is pivotably coupled to the palm body 300 by a palmar thumb opposition joint, shown as opposition joint 352, such that the opposition member 350 is pivotable (e.g., rotatable) relative to the palm body 300 about an axis of rotation, shown as opposition axis 354. The opposition axis 354 extends generally within the plane of the palm body 300, however the opposition axis 354 is oriented at an angle (e.g., skewed) relative to the flexing axis 332 (e.g., the opposition axis 354 extends longitudinally and laterally). Accordingly, the opposition axis 354 permits movement of the thumb 302 in a different direction than the MCP joint 320, the PIP joint 322, and the DIP joint 324. The opposition joint 352 provides an additional degree of freedom to the thumb 302 beyond the four total degrees of freedom provided by each of the central fingers 304.

**[0081]** The thumb 302 is oriented differently than the central fingers 304 and the pinky 306. As shown in FIG. 10, the thumb 302 extends substantially perpendicular to the plane of the palm body 300, the central fingers 304, and the pinky 306. The thumb 302 is oriented such that the splaying axis 330 extends longitudinally (e.g., substantially perpendicular to the splaying axes 330 of the central fingers 304). Additionally, the thumb 302 is oriented such that flexion of the thumb 302 bends the thumb 302 toward the central fingers 304. Such an opposing arrangement may facilitate grasping an object between (a) one or more of the central fingers 304 and the pinky 306 and (b) the thumb 302.

**[0082]** Rotation of the thumb 302 about the opposition axis 354 permits adjusting an orientation of the thumb 302 (e.g., to permit grasping an object from different directions). The opposition axis 354 permits lateral motion of the thumb 302. By way of example, rotating the thumb 302 about the opposition axis 354 may permit lateral movement between a first end position (e.g., the position shown in FIG. 10) and a second end position (e.g., a position in which the thumb 302 and the central fingers 304 extend within a common plane or within parallel planes).

**[0083]** Referring to FIGS. 10–12, the robotic arm assembly 10 includes a series of tensile members (e.g., cables, ropes, lines, strings, sheets, tendons, etc.) that facilitate actuation of the

hand 14. Each of the tensile members has a first end portion that is fixedly coupled to a portion of the hand 14 (e.g., one of the phalanges) and a second end portion that is coupled to a linear actuator, shown as finger actuator 410. The finger actuators 410 may apply a tensile force (e.g., pull) onto the tensile members to cause a desired motion of the corresponding component of the hand 14. Each of the tensile members may be coupled to a separate one of the finger actuators 410, such that each tensile member may be individually controlled.

**[0084]** The tensile members include a set of flexion members 400, each fixedly coupled to one of the distal phalanges 314. As shown, the set of flexion members 400 each pass from the corresponding distal phalanx 314, through the corresponding middle phalanx 312 and the corresponding proximal phalanx 310, through the palm body 300, through the joint assembly 100, and couple to a corresponding finger actuator 410 within the forearm 12. The flexion members 400 are visible through (e.g., exposed by) the PIP joint 322 and the DIP joint 324 of the corresponding finger. When tensioned, the set of flexion members 400 cause flexion of the middle phalanx 312 and the distal phalanx 314 of the corresponding finger (e.g., movement of the corresponding finger toward the palm body 300, gripping of the corresponding finger, etc.).

**[0085]** The set of flexion members 400 include a flexion member 400A fixedly coupled to the distal phalanx 314 of the index finger 304A, a flexion member 400B fixedly coupled to the distal phalanx 314 of the middle finger 304B, a flexion member 400C fixedly coupled to the distal phalanx 314 of the ring finger 304C, a flexion member 400D fixedly coupled to the distal phalanx 314 of the pinky 306, and a flexion member 400E fixedly coupled to the distal phalanx 314 of the thumb 302.

**[0086]** The tensile members further include a set of splaying members 402 and a set of splaying members 404, each fixedly coupled to one of the proximal phalanges 310. As shown, the splaying members 402 and the splaying members 404 each pass from the corresponding proximal phalanx 310, through the palm body 300, through the joint assembly 100 and couple to a corresponding finger actuator 410 within the forearm 12. As shown, the splaying members 402 and the splaying members 404 are visible through (e.g., exposed by) the MCP joint 320 of the corresponding finger.

**[0087]** For each finger, the splaying member 402 and the splaying member 404 pass on opposite sides of the corresponding splaying axis 330, such that the splaying axis 330 extends between the splaying member 402 and the splaying member 404. Accordingly, when tensioned, the splaying member 402 and the splaying member 404 apply opposing moment loadings on the proximal phalanx 310. When the splaying member 402 is tensioned with a lesser tension (e.g., a small tension, no additional tension, etc.) on the splaying member 404, the moment effect of the splaying member 402 causes the proximal phalanx 310 to pivot about the splaying axis 330 in a first direction. When the splaying member 404 is tensioned with a lesser tension (e.g., a small tension, no additional tension, etc.) on the splaying member 402, the moment effect of the splaying member 404 causes the proximal phalanx 310 to pivot about the splaying axis 330 in a second direction opposite the first direction. When both the splaying member 402 and the splaying member 404 are tensioned, the moment effects of the splaying member 402 and the splaying member 404 may cancel one another out, such that the splaying member 402 and the splaying member 404 cause flexion of the proximal phalanx 310 (e.g., movement of the finger actuators 410 toward the palm body 300, gripping motion, etc.).

**[0088]** The tensile members include a set of opposition members 406, each fixedly coupled to either the opposition member 340 or the opposition member 350. As shown, the opposition members 406 each pass from either the opposition member 340 or the opposition member 350, through the palm body 300, through the joint assembly 100, and couple to a corresponding finger actuator 410 within the forearm 12. When tensioned, the opposition members 406 cause flexion of the corresponding one of the opposition member 340 or the opposition member 350 (e.g., movement of the corresponding finger toward the palm body 300, gripping of the corresponding finger, etc.). The set of opposition members 406 includes an opposition member 406D fixedly coupled to the opposition member 340 of the pinky 306 and an opposition member 406E fixedly coupled to the opposition member 350 of the thumb 302.

**[0089]** Referring to FIG. 9, the finger actuators 410 are shown within the forearm 12. The finger actuators 410 may be completely contained within the forearm 12, such that the finger actuators 410 are not visible from the exterior of the robotic arm assembly 10. As shown, the finger actuators 410 extend longitudinally, such that the finger actuators 410 each exert a longitudinal tensile force on the corresponding tensile member. In some embodiments, the

finger actuators 410 are electric linear actuators. By way of example, the finger actuators 410 may each include an electric motor that is coupled to a screw, such as a ball screw or lead screw, which converts rotational mechanical energy into linear motion. In some embodiments, the robotic arm assembly 10 includes one finger actuator 410 for each of the tensile members. Accordingly, in one embodiment, the robotic arm assembly 10 includes seventeen finger actuators 410. Together, the finger actuators 410 may control twenty-two degrees of freedom of the robotic arm assembly 10 (e.g., four degrees of freedom for each central fingers 304, five degrees of freedom for the thumb 302, and five degrees of freedom for the pinky 306).

**[0090]** Referring to FIG. 13, the DIP joint 324 between the middle phalanx 312 and the distal phalanx 314 of the index finger 304A is shown. It should be understood that each of the MCP joints 320, the PIP joints 322, and the DIP joints 324 may have similar structures to permit rotation about lateral axes (e.g., the flexing axes 332, the flexing axes 334, and the flexing axes 336). As shown, the 324 forms a rolling contact joint between the middle phalanx 312 and the distal phalanx 314. The rolling contact joint may form a point of contact between the middle phalanx 312 and the distal phalanx 314, through which the flexing axis 336 passes. As the middle phalanx 312 and the distal phalanx 314 rotate (e.g., roll) relative to one another, the position of the point of contact and the flexing axis 336 moves along the surfaces of the middle phalanx 312 and the distal phalanx 314, changing the position of the flexing axis 336. Each of the MCP joints 320, the PIP joints 322, and the DIP joints 324 may form a similar point of contact through which the flexing axis 332, the flexing axis 334, or the flexing axis 336 extends.

**[0091]** As shown, the flexion member 400A extends beneath the flexing axis 336. Accordingly, when the flexion member 400A is tensioned, the tensile force on the flexion member 400A causes a moment loading of the distal phalanx 314 about the flexing axis 336. This moment loading drives the distal phalanx 314 to rotate clockwise about the flexing axis 336 relative to the middle phalanx 312.

**[0092]** The DIP joint 324 further includes a biasing member, shown as spring 420. The spring 420 is coupled to the middle phalanx 312 and the distal phalanx 314 and configured to apply a tensile biasing force that pulls the distal phalanx 314 toward the middle phalanx 312. The spring 420 is offset above the flexing axis 336, such that the biasing force of the spring 420 causes a moment loading of the distal phalanx 314 about the flexing axis 336. This moment

loading opposes the moment loading of the flexion member 400A, driving the distal phalanx 314 to rotate counter-clockwise about the flexing axis 336 relative to the middle phalanx 312.

**[0093]** If the moment effect of the flexion member 400A is larger than the moment effect of the spring 420 (e.g., due to activation of the finger actuator 410), the distal phalanx 314 experiences flexion. If the moment effect of the flexion member 400A is smaller than the moment effect of the spring 420 (e.g., the finger actuators 410 releases tension on the flexion member 400A), the distal phalanx 314 is extended by the spring 420. Accordingly, the spring 420 permits the distal phalanx 314 to extend simply by releasing the finger actuators 410. Such an arrangement may be advantageous, as the positive force from the finger actuators 410 may be desirable when grasping an object, whereas the passive force from the spring 420 may be sufficient when releasing an object.

**[0094]** Each of the joints of the fingers (e.g., the MCP joint 320, the PIP joint 322, the DIP joint 324, the opposition joint 342, and the opposition joint 352) may include a spring 420 that opposes the tension of the corresponding tensile member or tensile members. Accordingly, the active forces from the finger actuators 410 may be used for flexion, adduction, and abduction of the fingers, whereas extension of the fingers may be managed by passive biasing forces of the springs. Accordingly, each finger may include at least one spring 420 (e.g., one spanning all of the joints, one at each joint, etc.).

**[0095]** The middle phalanx 312 and the distal phalanx 314 may engage one another to limit a range of motion of the DIP joint 324. Specifically, to limit extension of the DIP joint 324, the middle phalanx 312 may engage the distal phalanx 314 above the flexing axis 336, forming a hyperextension hard stop. The middle phalanx 312 and the distal phalanx 314 may be shaped such that further extension beyond this position is prevented. To limit flexion of the DIP joint 324, the middle phalanx 312 may engage the distal phalanx 314 below the flexing axis 336, forming a flexion hard stop. The middle phalanx 312 and the distal phalanx 314 may be shaped such that further flexion beyond this position is prevented. Each of the joints of the hand 14 may include similar flexion hard stops and hyperextension hard stops.

**[0096]** Referring to FIG 14, the hand 14 is shown to include a series of input devices, shown as sensors 430. Each of the sensors 430 may provide sensor data indicating a status or

measurement of the robotic arm assembly 10 or the surrounding environment. By way of example, the sensors 430 may indicate a position of a portion of the hand 14, whether a portion of the hand 14 is contacting another object, a force with which a portion of the hand 14 is contacting another object, or other information.

**[0097]** In some embodiments, the sensors 430 include tactile sensors (e.g., resistive tactile sensors, capacitive tactile sensors, etc.). Such a tactile sensor may be positioned along a portion of the hand 14 (e.g., along an exterior surface of a phalanx). The tactile sensor may provide sensor data indicating whether the corresponding portion of the hand 14 is contacting another object, a force with which that portion of the hand 14 is being contacted, a temperature at that portion of the hand 14, or other information. By way of example, a tactile sensor may be utilized to determine how hard the hand 14 is grasping an object.

**[0098]** In some embodiments, the sensors 430 include position sensors (e.g., proprioceptive sensors) that provide sensor data indicating a position and/or an orientation of a portion of the hand 14. By way of example, the sensors 430 may include encoders that measure relative movement (e.g., rotation) of two components of the hand 14. By way of another example, the sensors 430 may include inertial measurement units (IMUs) that utilize measured accelerations to determine a position and/or orientation of a portion of the hand 14 in space. By way of another example, the sensors 430 may include a camera that, in combination with one or more visual markers coupled to the hand 14, visually determines a position and/or orientation of a portion of the hand 14 relative to the camera.

**[0099]** As shown in FIG. 14, the sensors 430 are positioned throughout the hand 14. One or more sensors 430 may be coupled to each section of the hand 14. By spacing the sensors 430 in this way, sensor data about each section of the hand 14 may be collected. As shown, the sensors 430 include a proximal sensor 430A coupled to each of the proximal phalanges 310. The sensors 430 include a middle sensor 430B coupled to each of the middle phalanges 312. The sensors 430 include a distal sensor 430C coupled to each of the distal phalanges 314. The sensors 430 include an opposition sensor 430D coupled to each of the opposition member 340 and the opposition member 350. The sensors 430 include a palm sensor 430E coupled to the palm body 300.

**[0100]** As shown in FIG. 13, the sensors 430 are coupled to one or more wires, conduits, or transfer devices, shown as cables 432. The cables 432 are configured to transfer signals (e.g., electrical energy, sensor data, etc.) to and from the sensors 430. As shown, the cables 432 pass through the joints to couple to the sensors 430. In some embodiments, the cables 432 pass near the flexing axis 336 to minimize strain on the flexing axis 332 as the hand 14 flexes. By way of example, the cables 432 may be positioned between the tensile members and the springs 420. The cables 432 may follow a similar path to the flexion members 400 to reach the forearm 12.

**[0101]** Referring to FIG. 15, a control system 450 for the robotic arm assembly 10 is shown according to an embodiment. The control system 450 may facilitate control over the robotic arm assembly 10 (e.g., autonomously, in response to an input from a user, etc.). The control system 450 includes a processing circuit, shown as controller 452. The controller 452 includes a processor 454 and a memory device, shown as memory 456. The memory 456 may store instructions thereon that, when executed by the processor 454, cause the controller 452 to perform the various processes described herein.

**[0102]** The controller 452 is in communication with (e.g., operatively coupled to) the wrist actuators 116, the forearm actuator 252, the finger actuators 410, and the sensors 430. The controller 452 may receive sensor data from the sensors 430. The controller 452 may control operation of the wrist actuators 116, the forearm actuator 252, and/or the finger actuators 410. In some embodiments, the controller 452 utilizes the sensor data from the sensors 430 to provide closed-loop control over the position of the robotic arm assembly 10.

**[0103]** Overall, the robotic arm assembly 10 may achieve twenty-five total degrees of freedom under control of the controller 452. This includes (a) one degree of freedom controlled by the forearm actuator 252, (b) two degrees of freedom controlled by the wrist actuators 116, (c) five degrees of freedom for the thumb 302, (d) four degrees of freedom for each of the three central fingers 304, and (e) five degrees of freedom for the pinky 306. Each of these degrees of freedom may be independently controlled by the controller 452 to permit performing complex movements of the robotic arm assembly 10 to facilitate grasping or otherwise interacting with other objects.

**[0104]** Referring to FIG. 8, the robotic arm assembly 10 includes a cover, coating, sleeve, or glove, shown as glove 500. As shown, the glove 500 extends around (e.g., receives, covers, at least partially contains, etc.) the forearm 12, the joint assembly 100, and the links 114. The glove 500 may be made from a flexible material (e.g., rubber, fabric, etc.) to permit motion of the robotic arm assembly 10. The glove 500 may be textured to facilitate the hand 14 gripping objects. Beneficially, the glove 500 may protect the components of the robotic arm assembly 10 from contact with outside debris.

**[0105]** 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).

**[0106]** 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.

**[0107]** 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.

**[0108]** 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.

**[0109]** 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.

**[0110]** 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.

**[0111]** It is important to note that the construction and arrangement of the robotic arm assembly 10 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 appendage comprising:  
a forearm body;  
a palm body movably coupled to the forearm body;  
a finger assembly coupled to the palm body, the finger assembly including a phalanx;  
a tensile member coupled to the phalanx and extending through the palm body; and  
an actuator coupled to the forearm body and the tensile member and configured to tension the tensile member to reposition the phalanx relative to the palm body.
2. The robotic appendage of claim 1, wherein the phalanx is a first phalanx, wherein the finger assembly further includes a second phalanx that couples the first phalanx to the palm body, and wherein the tensile member extends through the second phalanx.
3. The robotic appendage of claim 2, wherein the finger assembly further includes a third phalanx coupling the second phalanx to the palm body, wherein the actuator is configured to tension the tensile member to reposition the first phalanx and the second phalanx relative to the third phalanx and the palm body.
4. The robotic appendage of claim 2, wherein the actuator is a first actuator, wherein the finger assembly includes an opposition member coupling the second phalanx to the palm body, further comprising a second actuator configured to reposition the opposition member relative to the palm body.
5. The robotic appendage of claim 4, wherein the first actuator is configured to pivot the first phalanx relative to the second phalanx about a first axis, wherein the second actuator is configured to pivot the opposition member relative to the palm body about a second axis, and wherein the first axis is not parallel to the second axis.

6. The robotic appendage of claim 1, wherein the finger assembly is a first finger assembly, further comprising a second finger assembly coupled to the palm body, wherein the phalanx is pivotable relative to the palm body about an axis that extends through the palm body, and wherein the actuator is configured to tension the tensile member to pivot the phalanx about the axis such that the phalanx moves toward or away from the second finger assembly.

7. The robotic appendage of claim 6, wherein the actuator is a first actuator and the tensile member is a first tensile member, further comprising:

a second tensile member coupled to the phalanx and extending through the palm body; and

a second actuator coupled to the forearm body and the second tensile member and configured to tension the second tensile member to pivot the phalanx about the axis.

8. The robotic appendage of claim 7, wherein the axis extends between the first tensile member and the second tensile member, wherein the first actuator is configured to tension the first tensile member to move the phalanx toward the second finger assembly, and wherein the second actuator is configured to tension the second tensile member to move the phalanx away from the second finger assembly.

9. The robotic appendage of claim 8, wherein the axis is a first axis, wherein the first actuator and the second actuator are configured to tension the first tensile member and the second tensile member simultaneously to pivot the phalanx relative to the palm body about a second axis that extends substantially perpendicular to the first axis.

10. The robotic appendage of claim 9, wherein the phalanx is a first phalanx, wherein the first finger assembly further includes a second phalanx coupled to the first phalanx, further comprising:

a third tensile member coupled to the phalanx and extending through the first phalanx and the palm body; and

a third actuator coupled to the forearm body and the third tensile member and configured to tension the third tensile member to pivot the second phalanx relative to the first phalanx.

11. The robotic appendage of claim 1, wherein the actuator is a finger actuator, further comprising a wrist actuator coupled to the forearm body and configured to pivot the palm body relative to the forearm body.

12. The robotic appendage of claim 11, wherein the wrist actuator is a first wrist actuator configured to pivot the palm body relative to the forearm body about a first axis, further comprising a second wrist actuator coupled to the forearm body and configured to pivot the palm body relative to the forearm body about a second axis substantially perpendicular to the first axis.

13. The robotic appendage of claim 11, further comprising a rigid link coupling the palm body to the wrist actuator.

14. The robotic appendage of claim 1, wherein the actuator is a finger actuator, further comprising:

an arm base pivotably coupled to the forearm body such that the forearm body extends between the arm base and the palm body; and

a forearm actuator coupled to the forearm body and configured to pivot the forearm body relative to the arm base.

15. The robotic appendage of claim 1, wherein the phalanx is a first phalanx, wherein the finger assembly further includes a second phalanx and a third phalanx coupling the first phalanx to the palm body, further comprising:
- a first sensor coupled to the first phalanx;
  - a second sensor coupled to the second phalanx;
  - a third sensor coupled to the third phalanx; and
  - a fourth sensor coupled to the palm body.
16. The robotic appendage of claim 15, wherein the first sensor includes at least one of a resistive tactile sensor or a capacitive tactile sensor.
17. The robotic appendage of claim 1, further comprising a glove at least partially containing the finger assembly, the palm body, and the forearm body.
18. The robotic appendage of claim 1, wherein the actuator is an electric linear actuator.
19. A robotic appendage comprising:
- a palm body;
  - a first finger assembly coupled to the palm body;
  - a second finger assembly coupled to the palm body;
  - a plurality of tensile members coupled to the first finger assembly and extending through the palm body; and
  - a plurality of electric actuators each coupled to one of plurality of the tensile members, the plurality of electric actuators including:
    - a first electric actuator configured to cause flexion of the first finger assembly toward the palm body;
    - a second electric actuator configured to cause abduction of the first finger assembly away from the second finger assembly; and
    - a third electric actuator configured to cause adduction of the first finger assembly toward the second finger assembly.
20. A robotic appendage comprising:
- a forearm body;

a palm body pivotably coupled to the forearm body;  
an opposition body pivotably coupled to the palm body;  
a first finger assembly including:  
    a first phalanx pivotably coupled to the opposition body;  
    a second phalanx pivotably coupled to the first phalanx; and  
    a third phalanx pivotably coupled to the second phalanx;  
a second finger assembly coupled to the palm body;  
a plurality of tensile members extending through the palm body to the forearm body, the plurality of tensile members including:  
    a first tensile member coupled to the opposition body;  
    a second tensile member and a third tensile member coupled to the first phalanx; and  
    a fourth tensile member coupled to the third phalanx;  
a first actuator configured to tension the first tensile member to pivot the opposition body relative to the palm body about an opposition axis;  
a second actuator configured to tension the second tensile member to pivot the first phalanx relative to the palm body about a splaying axis in a first direction, the splaying axis extending through the palm body;  
a third actuator configured to tension the third tensile member to pivot the first phalanx relative to the palm body about the splaying axis in a second direction; and  
a fourth actuator configured to tension the fourth tensile member to pivot the second phalanx relative to the first phalanx about a flexing axis, wherein the flexing axis is not parallel to the opposition axis.

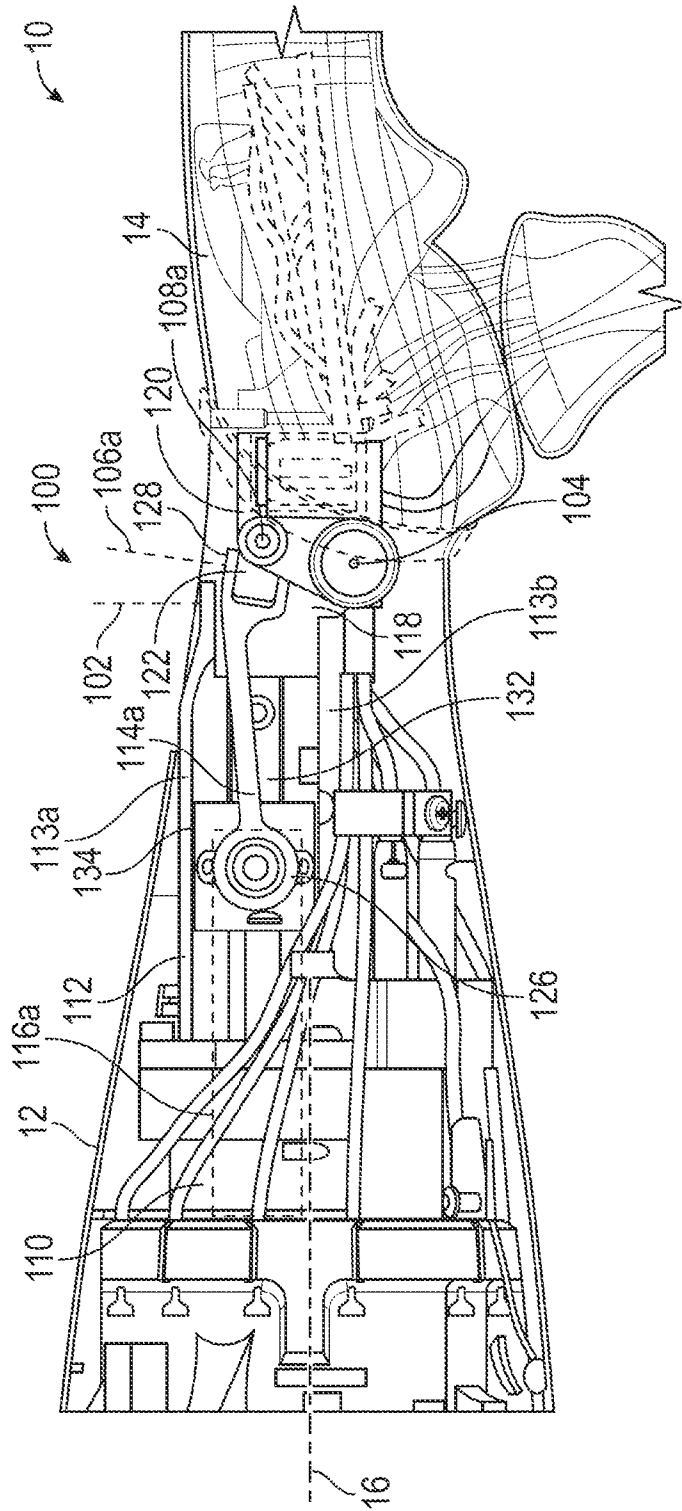


FIG. 1

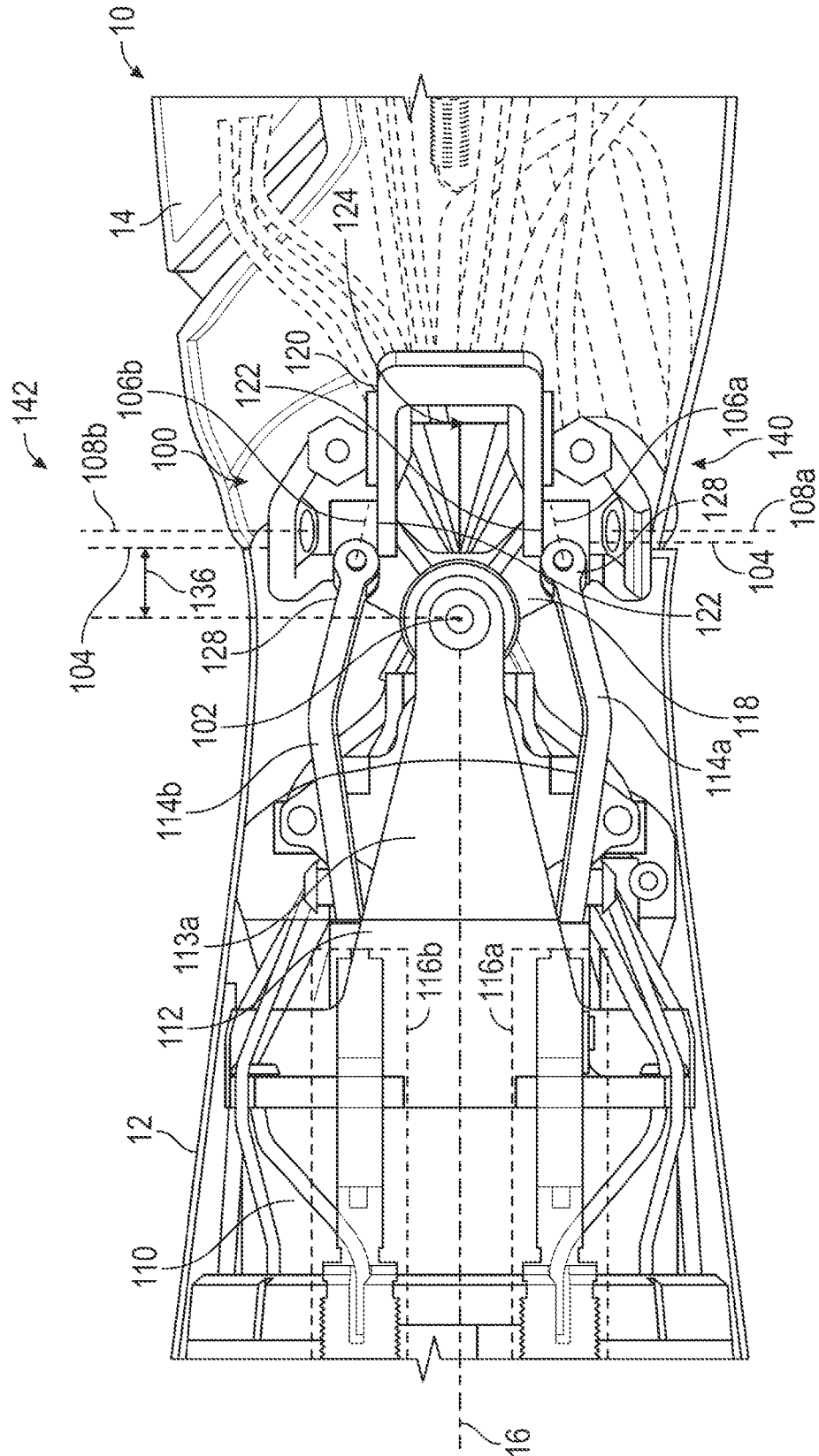


FIG. 2

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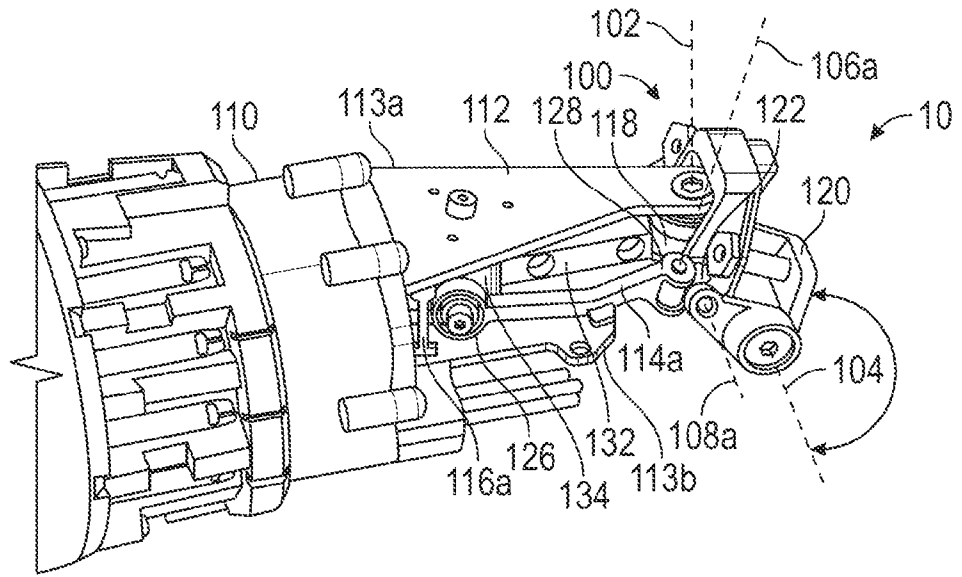


FIG. 3

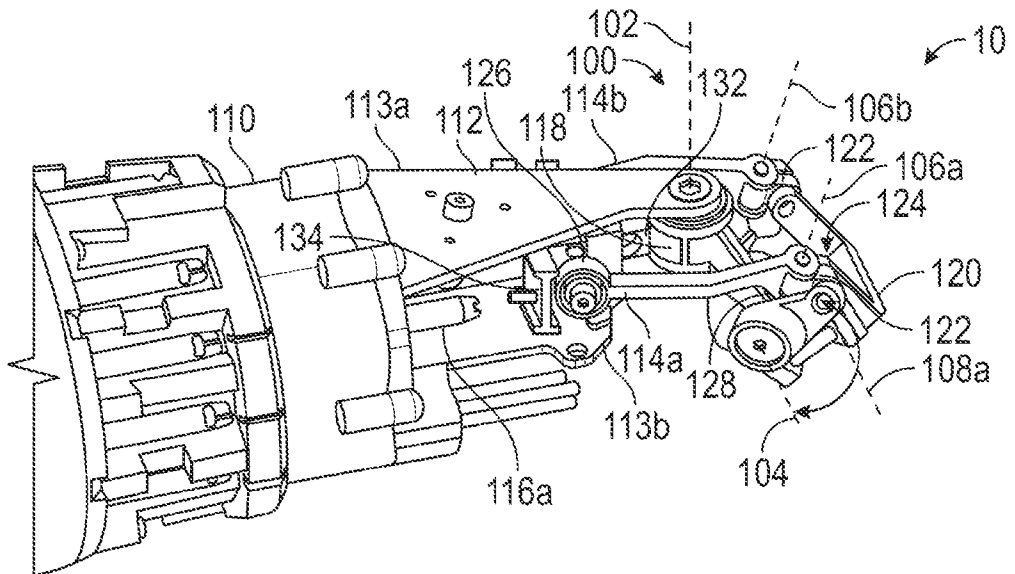


FIG. 4

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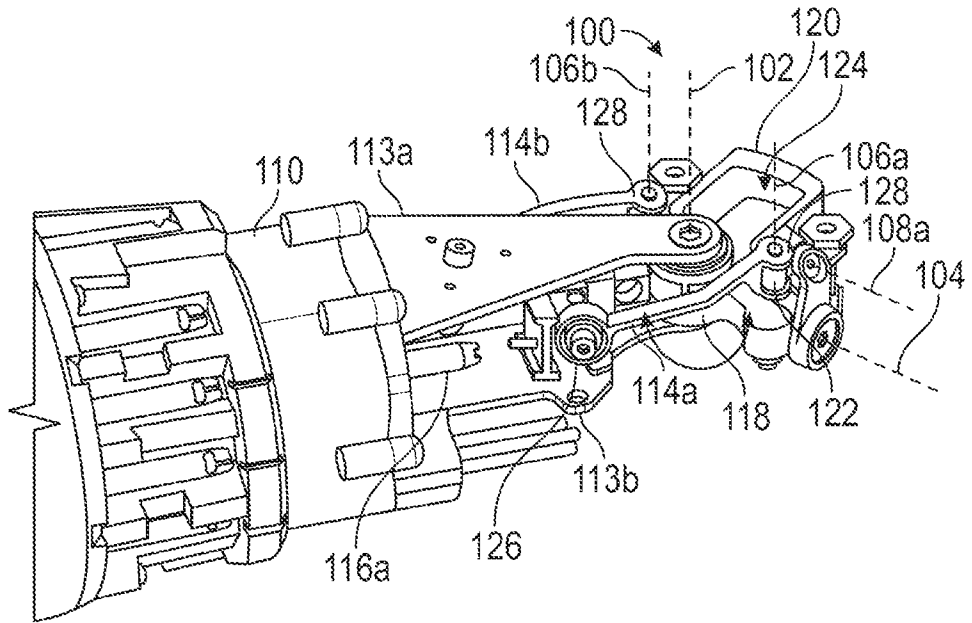


FIG. 5

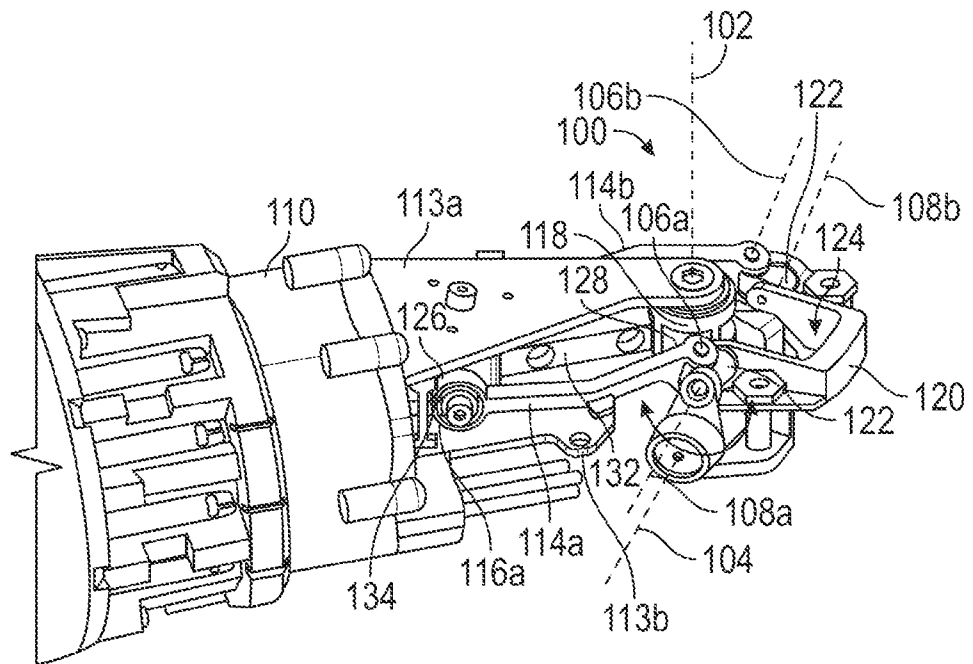


FIG. 6

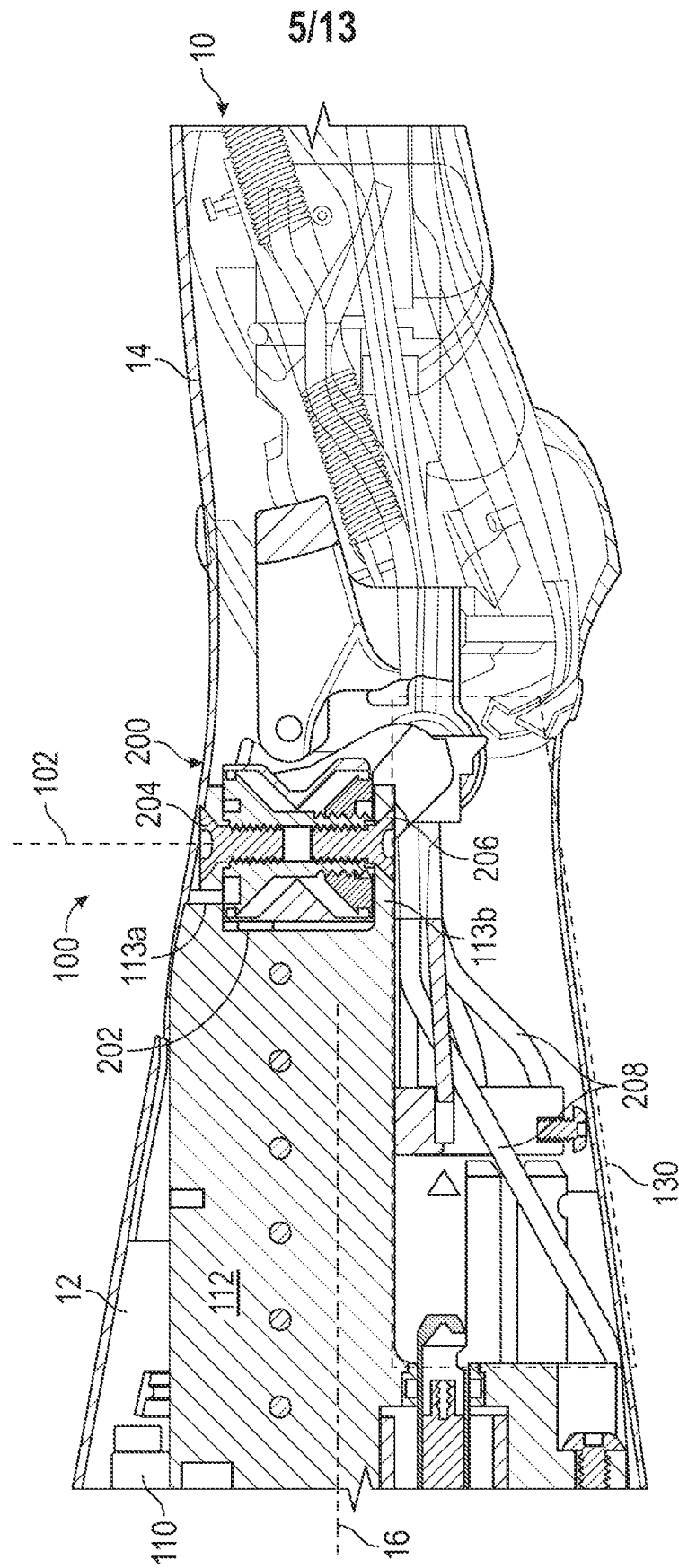


FIG. 7

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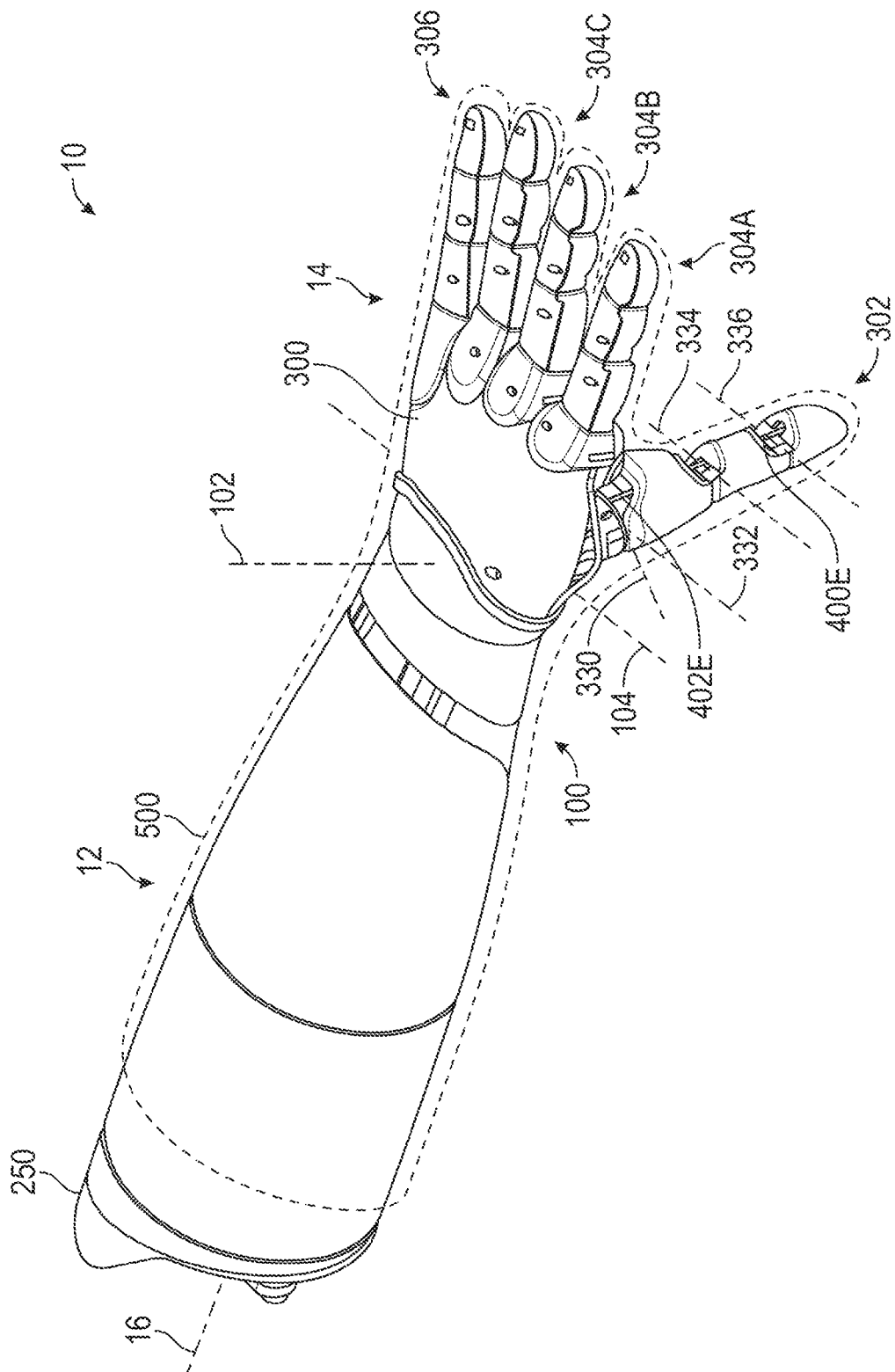


FIG. 8

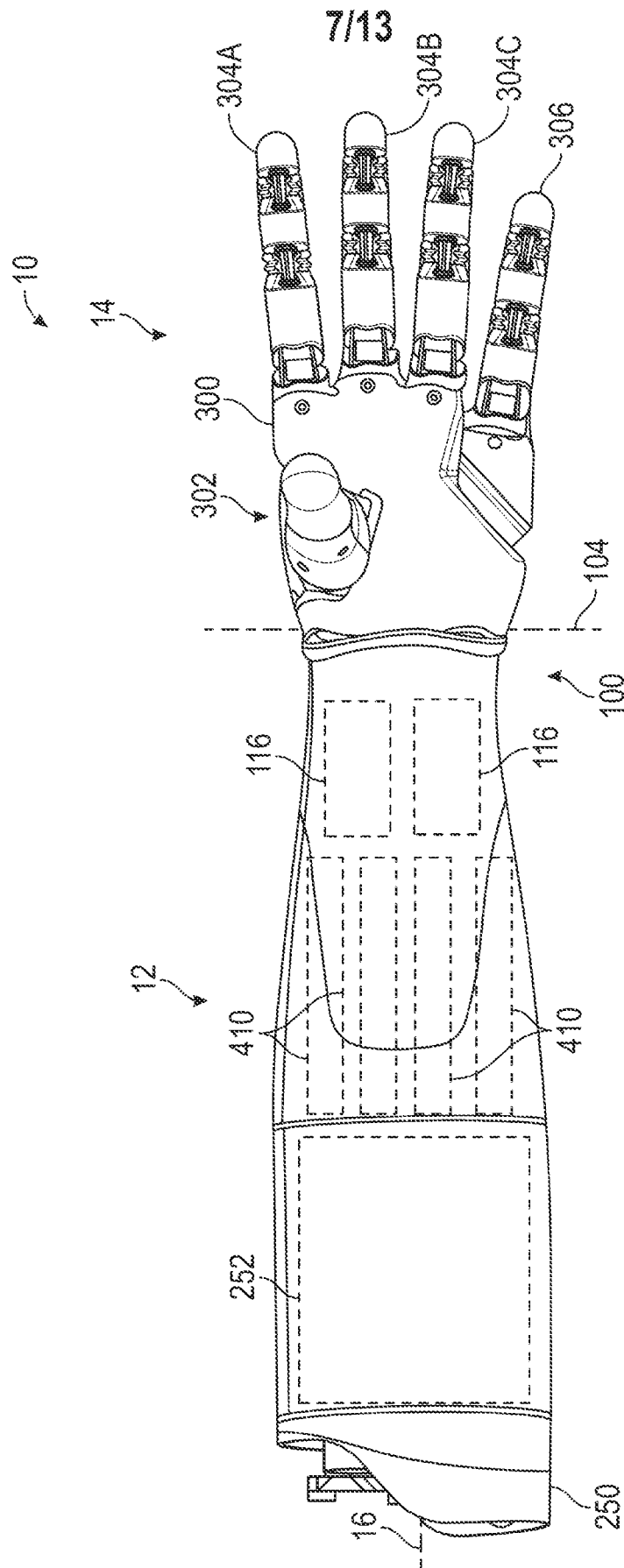


FIG. 9

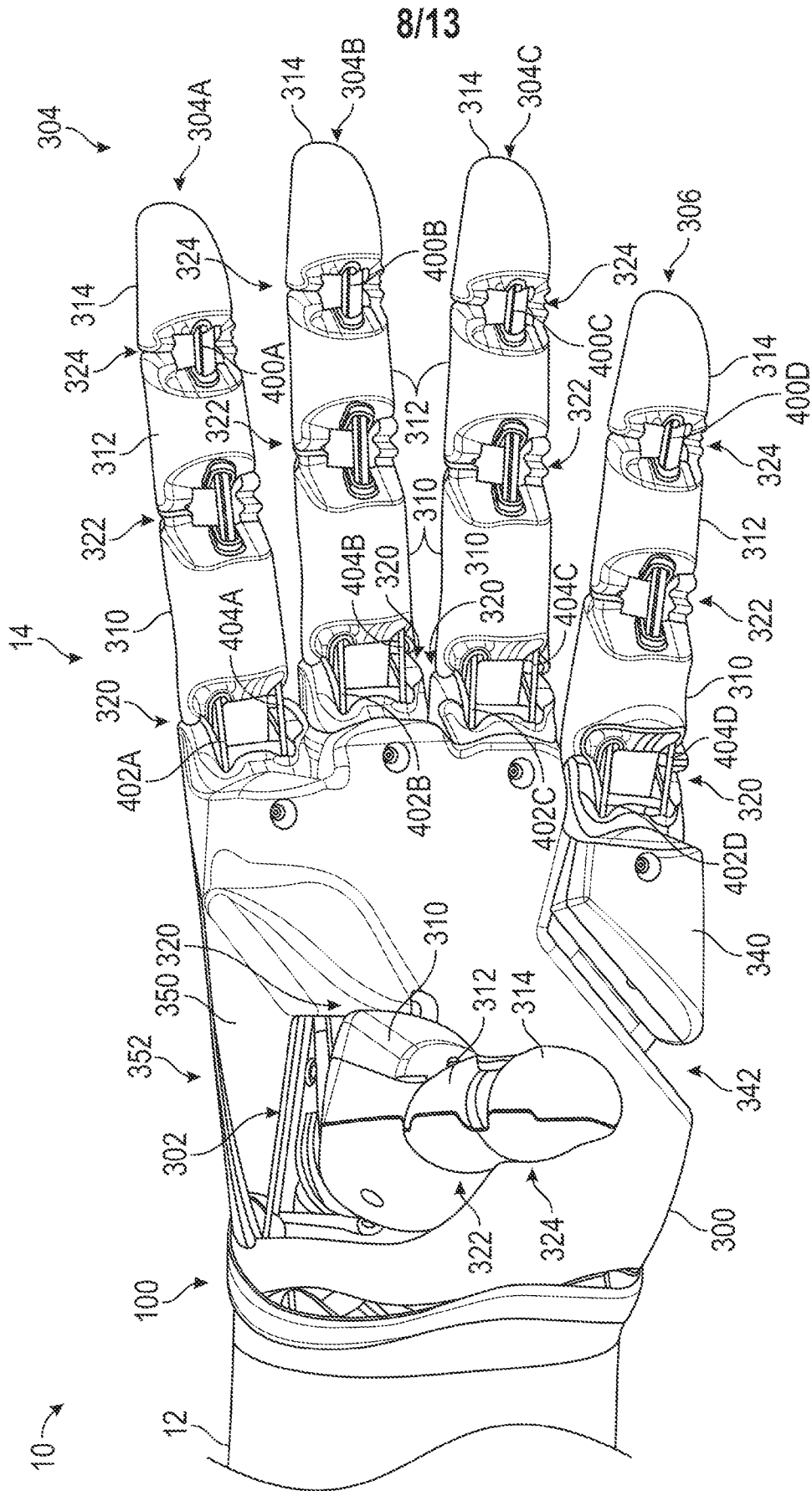


FIG. 10

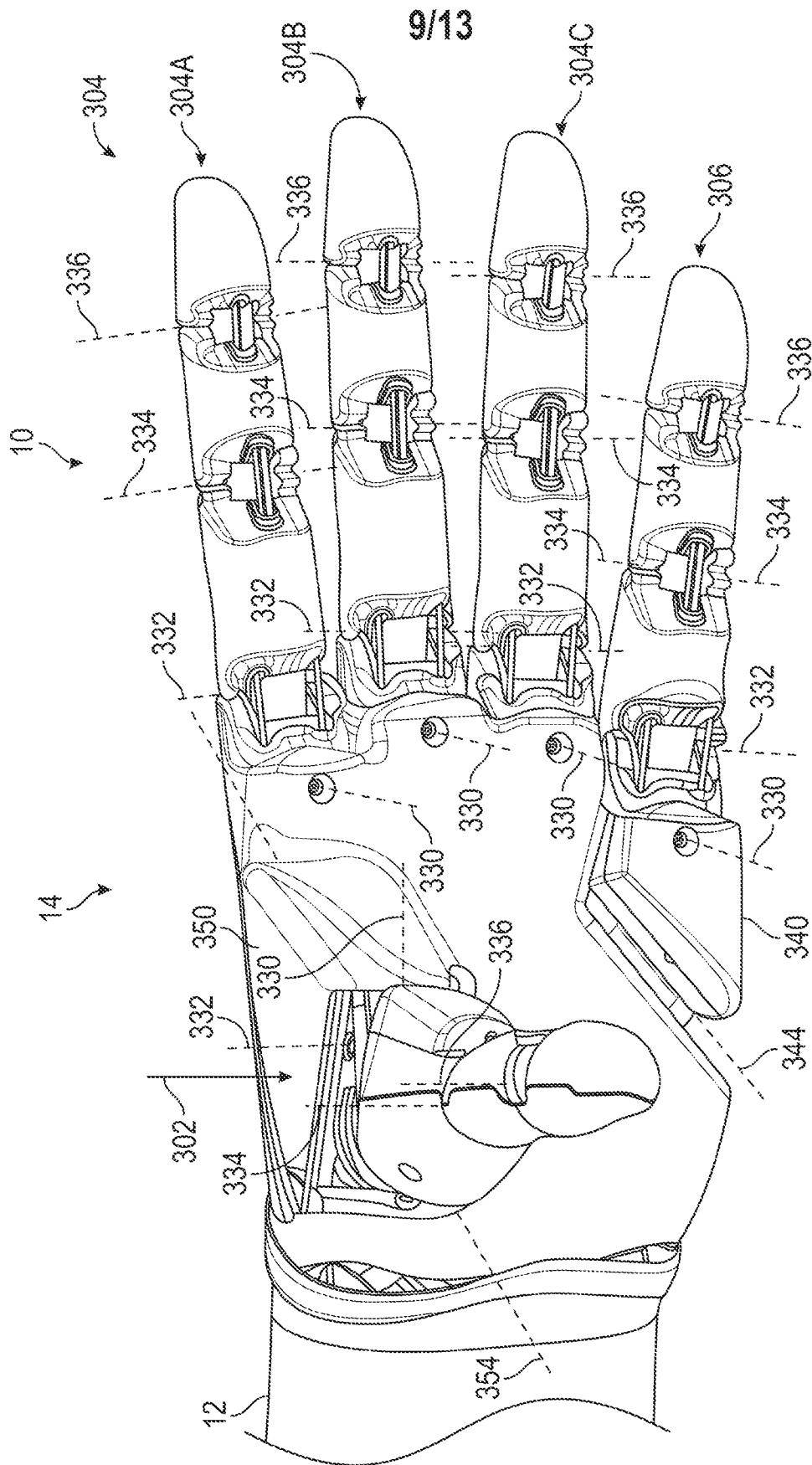


FIG. 11



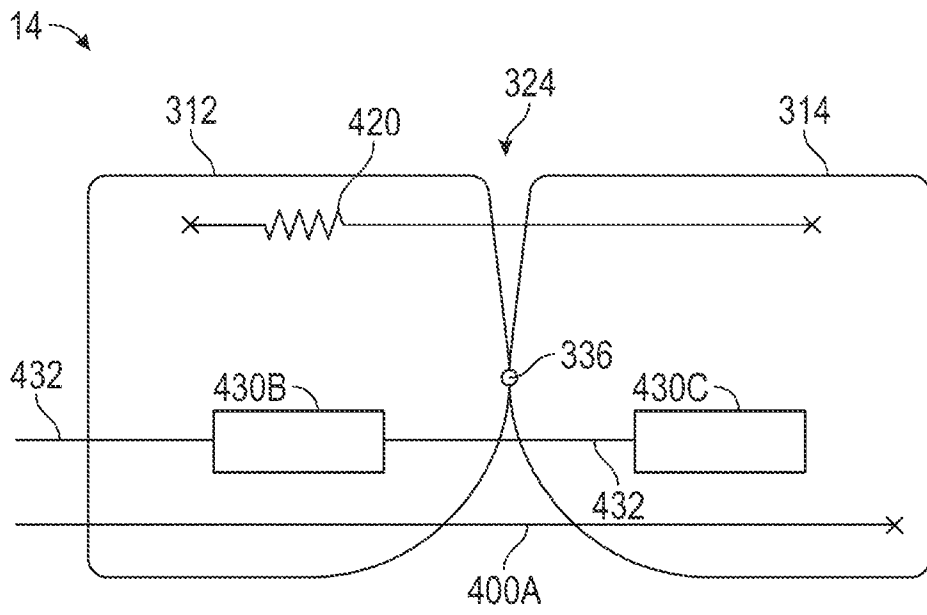


FIG. 13



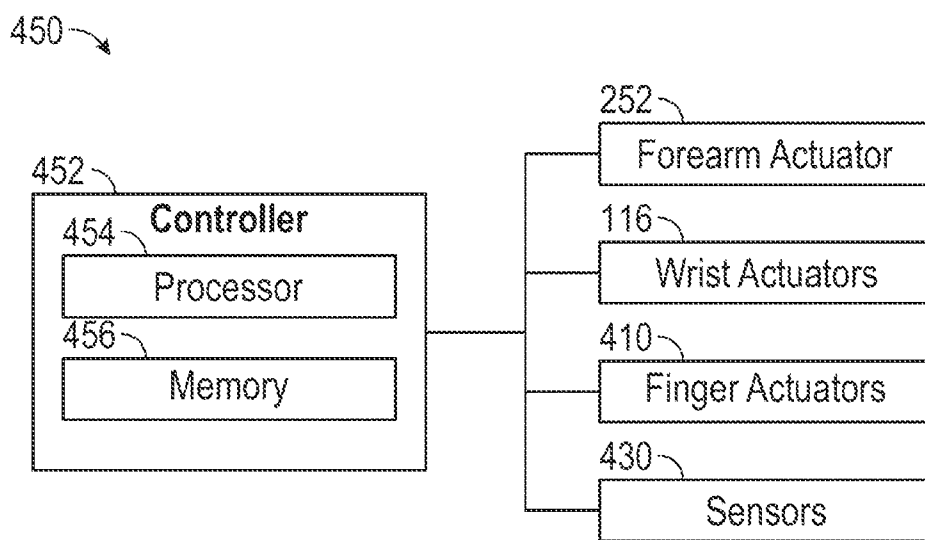


FIG. 15

## INTERNATIONAL SEARCH REPORT

International application No.

**PCT/US2025/050227**

<b>A. CLASSIFICATION OF SUBJECT MATTER</b>		
IPC: <b>B25J 15/10</b> (2025.01); <b>B25J 9/10</b> (2025.01); <i>B25J 15/12</i> (2025.01)		
CPC: <b>B25J 15/10; B25J 15/0009; B25J 15/0233; B25J 9/104; B25J 15/12</b>		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
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		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/0298319 A1 (GM GLOBAL TECHNOLOGY OPERATIONS LLC et al.) 22 October 2015 (22.10.2015) entire document	1-7, 11, 13, 18
Y	entire document	17
X	US 2022/0288792 A1 (CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE et al.) 15 September 2022 (15.09.2022) entire document	19
Y	US 2023/0234242 A1 (SANCTUARY COGNITIVE SYSTEMS CORPORATION) 27 July 2023 (27.07.2023) entire document	17
A	US 2022/0305669 A1 (HONDA MOTOR CO. LTD.) 29 September 2022 (29.09.2022) entire document	1-20
A	US 2013/0285404 A1 (LIN et al.) 31 October 2013 (31.10.2013) entire document	1-20
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
* Special categories of cited documents: "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 <b>02 December 2025 (02.12.2025)</b>		Date of mailing of the international search report <b>11 December 2025 (11.12.2025)</b>
Name and mailing address of the ISA/US <b>COMMISSIONER FOR PATENTS MAIL STOP PCT, ATTN: ISA/US P.O. Box 1450 Alexandria, VA 22313-1450 UNITED STATES OF AMERICA</b>		Authorized officer  <b>TAINA MATOS</b>
Facsimile No. <b>571-273-8300</b>		Telephone No. <b>571-272-4300</b>

**INTERNATIONAL SEARCH REPORT**

International application No.  
**PCT/US2025/050227**

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,921,293 A (RUOFF et al.) 01 May 1990 (01.05.1990) entire document	1-20