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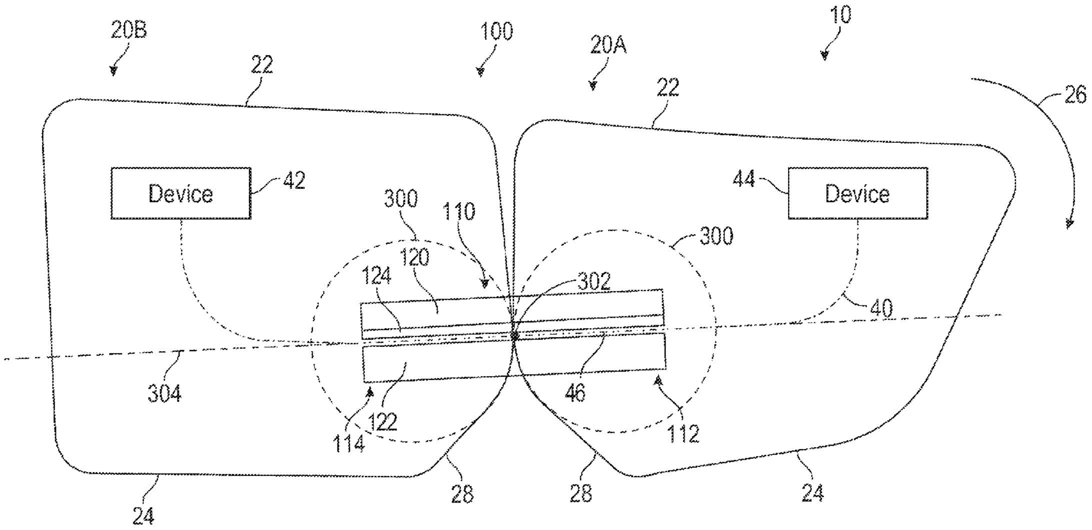

FIG. 4

(57) Abstract: A joint assembly for a robotic appendage includes: a first structure defining a first contact surface that is curved; a second structure defining a second contact surface that is curved and faces toward the first contact surface; and a composite flexible member having a first end portion fixedly coupled to the first structure and a second end portion fixedly coupled to the second structure. The composite flexible member movably couples the first structure to the second structure such that the second structure is pivotable relative to the first structure about a lateral axis that moves along the first contact surface and the second contact surface as the second structure pivots.

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JOINT ASSEMBLY FOR ROBOTIC APPENDAGE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/706,009 filed October 10, 2025, the entire contents of which are hereby incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure relates generally to robotics. More specifically, the present disclosure relates to a 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 a joint to movably connect two components while also permitting communication between those components.

SUMMARY

[0004] In at least one embodiment, a joint assembly for a robotic appendage includes: a first structure defining a first contact surface that is curved; a second structure defining a second contact surface that is curved and faces toward the first contact surface; and a composite flexible member having a first end portion fixedly coupled to the first structure and a second end portion fixedly coupled to the second structure. The composite flexible member movably couples the first structure to the second structure such that the second structure is pivotable relative to the first structure about a lateral axis that moves along the first contact surface and the second contact surface as the second structure pivots.

[0005] In some embodiments, the composite flexible member includes a first flexible layer, a second flexible layer, and an intermediate layer sandwiched between the first flexible layer and the second flexible layer. The intermediate layer is configured to inhibit stretching of the composite flexible member along a longitudinal axis of the joint assembly.

[0006] In some embodiments, the intermediate layer is configured to inhibit twisting of the composite flexible member along the longitudinal axis of the joint assembly.

[0007] In some embodiments, the first flexible layer is a first elastomeric layer, the second flexible layer is a second elastomeric layer, and the intermediate layer is at least one of a fabric layer or a metal layer.

[0008] In some embodiments, the intermediate layer extends along a longitudinal neutral axis of the composite flexible member,

[0009] In some embodiments, the intermediate layer is a first intermediate layer and the composite flexible member includes a third flexible layer and a second intermediate layer sandwiched between the second flexible layer and the third flexible layer. The intermediate layer is configured to inhibit translation of the composite flexible member along the longitudinal axis of the joint assembly.

[0010] In some embodiments, the first end portion of the composite flexible member defines one or more first apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; the first structure defines one or more second apertures; the second end portion of the composite flexible member defines one or more third apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; and the second structure defines one or more fourth apertures. The one or more second apertures are positioned to align with the one or more first apertures to receive one or more first fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the first structure. The one or more fourth apertures are positioned to align with the one or more second apertures to receive one or more second fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the second structure.

[0011] In some embodiments, the composite flexible member includes a harness permitting communication between a first device and a second device. The harness has a first portion coupled to the first structure, a second portion coupled to the second structure, and a flexible portion extending between the first structure and the second structure.

[0012] In some embodiments, the flexible portion of the harness is sandwiched between the first flexible layer and the second flexible layer.

[0013] In some embodiments, a hardness of the first flexible layer and the second flexible layer are between Shore 10A and Shore 80A.

[0014] In at least one embodiment, a joint assembly for a robotic appendage includes: a first body having a first exterior surface; a second body having a second exterior surface; and a composite flexible member coupled between the first body and the second body. The composite flexible member includes a first flexible layer, a second flexible layer, and an intermediate layer sandwiched between the first flexible layer and the second flexible layer, the intermediate layer configured to inhibit stretching of the composite flexible member along a longitudinal axis of the joint assembly. The composite flexible member permits the first body to pivot relative to the second body.

[0015] In some embodiments, the first flexible layer is a first elastomeric layer, the second flexible layer is a second elastomeric layer, and the intermediate layer is at least one of a fabric layer or a metal layer.

[0016] In some embodiments, the intermediate layer is a first intermediate layer and the composite flexible member includes a third flexible layer and a second intermediate layer sandwiched between the second flexible layer and the third flexible layer. The second intermediate layer is configured to inhibit stretching of the composite flexible member along the longitudinal axis of the joint assembly.

[0017] In some embodiments, the composite flexible member defines one or more first apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; the first body defines one or more second apertures; the composite flexible member defines one or more third apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; and the second body defines one or more fourth apertures. The one or more second apertures are positioned to align with the one or more first apertures to receive one or more first fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the first body. The one or more fourth apertures are positioned to align with the one or more second apertures to receive one or more second fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the second body.

[0018] In some embodiments, the composite flexible member comprises a harness permitting communication between a first device and a second device. The harness has a first portion coupled to the first body, a second portion coupled to the second body, and a flexible portion extending between the first body and the second body.

[0019] In at least one embodiment, a robotic appendage includes: a base body, a middle body, and a distal body; a first composite flexible member pivotably coupling the middle body to the base body; and a second composite flexible member pivotably coupling the distal body to the middle body. The first composite flexible member has a first thickness. The second composite flexible member has a second thickness. The second thickness is less than the first thickness.

[0020] In some embodiments, each of the first composite flexible member and the second composite flexible member includes: a first flexible layer; a second flexible layer; and an intermediate layer sandwiched between the first flexible layer and the second flexible layer. The intermediate layers are configured to inhibit stretching of the first composite flexible member and the second composite flexible member along a longitudinal axis of the robotic appendage.

[0021] In some embodiments, the robotic appendage also includes a harness extending from the base body, through the middle body, to the distal body and configured to transfer at least one of data or electrical energy between a first device and a second device. The harness extends between the first flexible layers and the second flexible layers of the first composite flexible member and the second composite flexible member.

[0022] In some embodiments, the first flexible layers are first elastomeric layers, the second flexible layers are second elastomeric layers, and the intermediate layers are at least one of fabric layers or metal layers.

[0023] In some embodiments, at least one of (i) the first flexible layer of the first composite flexible member is thicker than the first flexible layer of the second composite flexible member or (ii) the second flexible layer of the first composite flexible member is thicker than the second flexible layer of the second composite flexible member.

[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 perspective view of a portion of a finger, according to an embodiment.

[0026] FIG. 2 is a side view of the finger of FIG. 1.

[0027] FIG. 3 is a section view of the finger of FIG. 1.

[0028] FIG. 4 is a side view of the finger of FIG. 1 in an extended configuration.

[0029] FIG. 5 is a side view of the finger of FIG. 1 in a bent configuration.

[0030] FIG. 6 is a perspective view of a flexible member of the finger of FIG. 1, according to an embodiment.

[0031] FIG. 7 is a perspective view of a flexible member of the finger of FIG. 1, according to an alternate embodiment.

[0032] FIG. 8 is a second view of the flexible member of FIG. 7.

DETAILED DESCRIPTION

[0033] 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.

[0034] Referring generally to the figures, a humanoid appendage includes a pair of bodies that are movably coupled to one another through a joint assembly. The joint assembly includes a composite flexible ligament that connect the bodies to one another. The ligament include layers of different materials that soften impacts to the bodies of the joint assembly while limiting relative motion of the bodies to only rolling contact motion along a pair of curved contact surfaces. The ligaments further include a harness carrying electrical signals between the bodies. The layers of different materials in the ligaments in combination with the placement of the harness minimizes stresses on the harness and maximizes the lifespan of the joint assembly.

Overview

[0035] Referring to FIGS. 1–3, a humanoid appendage, robotic appendage, limb, jointed assembly, posable assembly, or digit, is shown as finger 10, according to an embodiment. The finger 10 may be a robotic appendage (e.g., a robotic finger, etc.) and/or may be a portion of a larger robotic appendage (e.g., a robotic hand, a robotic humanoid, etc.). The finger 10 may be utilized to press, grasp, grab, grapple, pull, push, twist, or otherwise interact with other objects. By way of example, a group of the fingers 10 may be used together to grab and lift an object, such as a tool, part, container, or other object. The finger 10 defines a longitudinal axis A_1 extending along a length of the finger 10. For example, the longitudinal axis A_1 may extend from a proximal end of the finger 10 to a distal end of the finger 10.

[0036] As shown in FIGS. 1–3, the finger 10 includes a series of jointed members, pivoting members, bodies, structures, elements, phalanxes, or phalanges, shown as finger members 20. The finger members 20 may form a structure of the finger 10. The finger members 20 include a distal body, distal structure, or finger member, shown as distal finger member 20A, a first intermediate or middle body, middle structure, or finger member, shown as middle finger member 20B, a second intermediate or middle body, middle structure, or finger member, shown as middle finger member 20C, and a proximal or base body, base structure, or finger member, shown as base finger member 20D.

[0037] As shown, the finger members 20 are generally arranged in line with one another, such that the finger members 20 are longitudinally offset from one another. The distal finger member 20A, the middle finger member 20B, the middle finger member 20C, and the base finger member 20D arranged in sequence along the longitudinal direction (e.g., along the longitudinal axis A_1, etc.). The base finger member 20D may include one or more mounting features (e.g., fasteners, bosses, etc.) that facilitate coupling the finger 10 to a larger structure (e.g., a wrist of a robotic hand, etc.).

[0038] Each of the finger members 20 includes a first surface, shown as top surface 22, and a second surface, bottom surface, engagement surface, or grasping surface, shown as bottom surface 24. As shown in FIG. 1, the top surface 22 faces upward, and the bottom surface 24 faces downward. Accordingly, the top surface 22 and the bottom surface 24 generally face in opposing directions.

[0039] Each adjacent pair of the finger members 20 are pivotably coupled to one another, such that the adjacent finger members 20 are pivotable about a lateral axis (e.g., an axis perpendicular to the plane of FIG. 3, an axis perpendicular to the longitudinal axis A_1, the lateral axis of rotation 302, etc.). By way of example, the distal finger member 20A may be pivotable relative to the middle finger member 20B about a lateral axis. The collective pivoting of each pair of finger members 20 may permit the finger 10 to bend in a pivoting direction, rotation direction, or bending direction, shown as grasping direction 26. The finger 10 may bend in the grasping direction 26 from a fully extended configuration (e.g., as shown in FIG. 1) to a bent configuration in which the finger 10 curves downward. Moving the finger 10 to the bent configuration may cause the bottom surfaces 24 to engage an object, permitting the finger 10 to grasp and manipulate the object.

[0040] Each of the finger members 20 includes at least one exterior surface, contact surface, rolling surface, or engagement surface, shown as contact surface 28. The contact surfaces 28 are curved and positioned to engage one another (e.g., arranged facing toward one another). As shown in FIG. 3, the distal finger member 20A includes a contact surface 28 positioned to engage a corresponding contact surface 28 of the middle finger member 20B. The middle finger member 20B includes a pair of contact surfaces 28 positioned to engage corresponding contact surfaces 28 of the distal finger member 20A and the middle finger member 20C, respectively. The middle finger member 20C includes a pair of contact surfaces 28 positioned to engage corresponding contact surfaces 28 of the middle finger member 20B and the base finger member 20D, respectively. The base finger member 20D includes a contact surface 28 positioned to engage a corresponding contact surface 28 of the middle finger member 20C.

[0041] As two finger members 20 pivot relative to one another, the contact surfaces 28 of those finger members 20 engage one another in rolling contact. The contact surfaces 28 may engage one another directly or indirectly through one or more intervening members. The lateral axis about which the finger members 20 pivot relative to one another may be positioned at the point of contact between the two contact surfaces 28. As the finger members 20 pivot, different portions of the contact surfaces 28 come into engagement with one another. Accordingly, the lateral axis may move along the contact surfaces 28 as the finger 10 moves through a range of motion between the fully extended configuration and the bent configuration. This relative motion of the finger members 20 may be referred to as rolling contact motion.

[0042] As shown in FIG. 2, the finger 10 includes a pair of cables or tensile members, shown as actuator cables 30. The actuator cables 30 extend throughout the finger 10 and are coupled to one or more of the finger members 20. When a tensile force is applied to the actuator cables 30, the actuator cables 30 may apply forces to one or more of the finger members 20, causing the finger members 20 to pivot and bend the finger 10 in the grasping direction 26. In some embodiments, the actuator cables 30 are coupled to an actuator (e.g., an electric motor, an electric linear actuator, etc.) that applies a tensile force to one or more of the actuator cables 30 to actuate the finger 10.

[0043] As shown in FIGS. 4 and 5, the finger 10 includes a cable, wire, fiber, optical fiber, conduit, or signal transfer member, shown as harness 40. The harness 40 extends through the finger members 20 along the length of the finger 10 from the base finger member 20D to the distal finger member 20A. The harness 40 may be coupled to each of the finger members 20 as the harness 40 passes through the finger members 20. By way of example, a first portion of the harness 40 may be coupled to the middle finger member 20B, and a second portion of the harness 40 may be coupled to the distal finger member 20A. The harness 40 may extend beyond the base finger member 20D and outside of the finger 10. In some embodiments, the harness 40 is flexible to permit elastic deformation (e.g., bending) of the harness 40 as the finger 10 moves (e.g., bends in the grasping direction 26). By way of example, at least the portions of the harness 40 that extend between the finger members 20 may be flexible portions that permit relative movement of the finger members 20.

[0044] The harness 40 may operatively couple (e.g., transfer signals between, permit communication between, etc.) a first device 42 and a second device 44. By way of example, the first device 42 may be coupled to one of the finger members 20 (e.g., the distal finger member 20A) and the second device 44 may be positioned offboard the finger 10. The first device 42 and the second device 44 may each be a sensor, an actuator, a controller (e.g., including a processor and a memory), an energy source (e.g., a battery, shore power, etc.), or another type of device. By way of example, the first device 42 may be a sensor coupled to a finger member 20, and the second device 44 may be a controller offboard the finger 10. In some embodiments, the finger 10 includes multiple first devices 42 (e.g., coupled to different finger members 20), and the harness 40 couples the first devices 42 to one or more second devices 44.

[0045] The harness 40 may permit any type of communication between the first device 42 and the second device 44. In some embodiments, the harness 40 permits the transfer of data between the first device 42 and the second device 44. By way of example, the harness 40 may include an optical fiber that transfers data as pulses of light, a set of wires that transfer data as electrical signals, or another type of data transfer medium. In some embodiments, the harness 40 permits the transfer of electrical energy between the first device 42 and the second device 44. By way of example, the harness 40 may include a set of wires that transfer electrical energy from the second device 44 to power the first device 42. In some embodiments, the harness 40 permits the transfer of fluid between the first device 42 and the second device 44. By way of example, the harness 40 may include a conduit (e.g., a hose, a pipe, etc.) that transfers a fluid (e.g., compressed air, hydraulic oil, water, etc.) between the first device 42 and the second device 44.

Joint Assemblies

[0046] Referring to FIGS. 1–3, the finger 10 includes a series of couplers, rolling joints, connections, or bending assemblies, shown as joint assemblies 100. FIGS. 1–3 show the joint assemblies 100 within the finger 10. Front and rear portions of each joint assembly 100 may be received within adjacent finger members 20, and a middle portion of each joint assembly 100 may be exposed between the adjacent finger members 20. Although the joint assemblies 100 are shown within a finger 10, the joint assembly 100 may be used to couple any two components (e.g., within a knee, an ankle, an elbow, a toe etc.).

[0047] Each joint assembly 100 is configured to pivotably couple an adjacent pair of the finger members 20. As shown in FIG. 3, a first joint assembly 100A couples the distal finger member 20A and the middle finger member 20B, a second joint assembly 100B couples the middle finger member 20B and the middle finger member 20C, and a third joint assembly 100C couples the middle finger member 20C and the base finger member 20D. The joint assemblies 100 may permit rolling contact between the finger members 20 (e.g., along the contact surfaces 28) while limiting movement other than rolling contact motion (e.g., vertical and lateral translation, rotation about the longitudinal axis A_1, stretching along the longitudinal axis A_1, etc.). The finger members 20 and the joint assembly 100 may be centered along the longitudinal axis A_1. In some embodiments, the finger members 20 and/or the joint assembly 100 are symmetrical about the longitudinal axis A_1.

[0048] As shown in FIGS. 1 and 3, each joint assembly 100 includes a composite flexible member, tensile member, layered member, or ligament, shown as flexible members 110. Each flexible member 110 is coupled (e.g., fixedly) between two of the finger members 20. As shown in FIGS. 1 and 3, a first flexible member 110A couples the couples the distal finger member 20A and the middle finger member 20B, a second flexible member 110B couples the middle finger member 20B and the middle finger member 20C, and a third flexible member 110C couples the middle finger member 20C and the base finger member 20D. The flexible members 110 couple the finger members to one another, limiting certain types of movement and permitting other types of movement. Specifically, the flexible members 110 may permit pivotal movement (e.g., rolling contact motion) of the finger members 20 relative to one another. The flexible members 110 may limit (e.g., prevent, inhibit) other types of movement, such as lateral translation, vertical translation, longitudinal translation (e.g., extension along a longitudinal axis, stretching of the finger 10 along the longitudinal axis A_1), rotation about a longitudinal axis (e.g., roll), and/or rotation about a vertical axis (e.g., yaw). In some embodiments, the flexible members 110 permit only rolling contact motion between the finger members 20. In some embodiments, the flexible members 110 may apply a biasing force onto the finger members 20. The biasing force of the flexible members 110 may oppose the tensile forces of the actuator cables 30, such that the biasing forces cause the finger 10 to bend opposite the grasping direction 26. When tension on the actuator cables 30 is released, the flexible members 110 may automatically return the finger 10 to the fully extended position.

[0049] As shown in FIGS. 3–6, the flexible members 110 have a thickness t. The thickness t of each of the flexible members 110 may vary based on which of the finger members 20 the flexible members 110 are coupled between. For example, as shown in FIG. 3, the first flexible member 110A may have a first thickness t_1, the second flexible member 110B may have a second thickness t_2, and the third flexible member 110C may have a third thickness t_3. The thickness t of each of the flexible members 110 may be sequentially greater (e.g., thicker, etc.) in a direction from a distal end of the finger 10 to a proximal end of the finger 10. For example, the second thickness t_2 of the second flexible member 110B may be greater than the first thickness t_1 of the first flexible member 110A and/or the third thickness t_3 of the third flexible member 110C may be greater than the second thickness t_2 of the second flexible member 110B. The thickness t of each of the flexible members 110 may increase sequentially in the direction from the distal end of the finger 10 to the proximal end of the finger 10 since the third flexible member 110C may experience greater forces than the first flexible member 110A (e.g., due to the third flexible member 110C being positioned further from the distal end of the finger 10 than the first flexible member 110A, etc.).

[0050] As shown in FIGS. 3–6, each of the flexible members 110 include a first end or distal end, shown as first end portion 112, coupled to one of the finger members 20 distal of the flexible members 110, and a second end or proximal end, shown as second end portion 114, coupled to another of the finger members 20 proximal of the flexible members 110. For example, as shown in FIG. 3, the first flexible member 110A includes a first end portion 112 coupled to the distal finger member 20A and a second end portion 114 coupled to the middle finger member 20B, the second flexible member 110B includes a first end portion 112 coupled to the middle finger member 20B and a second end portion 114 coupled to the middle finger member 20C, and the third flexible member 110C includes a first end portion first end portion 112 coupled to the middle finger member 20C and a second end portion 114 coupled to the base finger member 20D.

[0051] As shown in FIGS. 4–6, the flexible members 110 each include a first layer, inner layer, or first elastomeric layer, shown as first flexible layer 120, a second layer, outer layer, or second elastomeric layer, shown as second flexible layer 122, and a third layer, first fabric layer, or first metal layer, shown as first intermediate layer 124, sandwiched between the first flexible layer 120 and the second flexible layer 122. The second flexible layer 122 is positioned above the first flexible layer 120 within the finger 10, such that the second flexible layer 122 is closer to the top surface 22 and the first flexible layer 120 is closer to the bottom surface 24. The first intermediate layer 124 extends along a central longitudinal axis or longitudinal neutral axis of the flexible members 110, shown as longitudinal axis A_2. The first flexible layer 120 and the second flexible layer 122 may each be fixedly coupled to the first intermediate layer 124 to prevent the first flexible layer 120 and the second flexible layer 122 from separating from the first intermediate layer 124.

[0052] The first flexible layer 120 and the second flexible layer 122 may apply the biasing force onto the finger members 20. For example, during movement of the finger 10 in the grasping direction 26, the second flexible layer 122 may be extended, such that the second flexible layer 122 experiences tensile forces, and the first flexible layer 120 may be compressed, such that the first flexible layer 120 experiences compressive forces. The compressive forces experienced by the first flexible layer 120 may cause the first flexible layer 120 to generate a first biasing force that is applied onto the finger members 20 in the direction opposite the grasping direction 26 and the tensile forces experienced by the second flexible layer 122 may cause the second flexible layer 122 to generate a second biasing force that is applied onto the finger members 20 in the direction opposite the grasping direction 26.

[0053] The first intermediate layer 124 may limit the types of movement of the joint assembly 100 other than the pivotal movement of the finger members 20 relative to one another. For example, the first intermediate layer 124 may resist lateral translation of the finger members 20 relative to one another, vertical translation of the finger members 20 relative to each other, longitudinal translation of the finger members 20 relative to each other, rotation of the finger members 20 about the longitudinal axis A_1 of the finger 10, and/or rotation of the finger members 20 relative to each other about a vertical axis. The first intermediate layer 124 may limit the types of movement of the joint assembly 100 other than the pivotal movement of the finger members 20 relative to one another by having a first stiffness in rotational directions of the finger 10 (e.g., in the grasping direction 26, in a direction opposite the grasping direction 26, etc.) and second stiffness in other directions (e.g., lateral translation directions, vertical translation directions, longitudinal translation directions, rotational directions about the longitudinal axis A_1 of the finger 10, rotational directions about vertical axis, etc.) that are greater than the first stiffness.

[0054] In some embodiments, the first flexible layer 120 and the second flexible layer 122 are elastomeric layers (e.g., elastic members, etc.), such that the first flexible layer 120 and the second flexible layer 122 elastically deform under a load. For example, the first flexible layer 120 and the second flexible layer 122 may be formed from an elastic material such as a rubber and/or elastomer such as nitrile, silicone, or neoprene. In some embodiments, the first flexible layer 120 and the second flexible layer 122 have a hardness of less than or approximately equal to (e.g., within 95% to 105% of, etc.) Shore 60A. These hardness ranges were proven experimentally to maximize the number of bending cycles that the joint assembly 100 could complete before experiencing damage. In other embodiments, the first flexible layer 120 and the second flexible layer 122 have a hardness of greater than Shore 60A. In some embodiments, the first flexible layer 120 and the second flexible layer 122 have a tensile strength of greater than or approximately equal to 8.96 mega Pascals (MPa) (e.g., 1,300 pounds per square inch (psi), etc.). In other embodiments, the first flexible layer 120 and the second flexible layer 122 have a tensile strength of less than 8.96 MPa. In some embodiments, the first flexible layer 120 and the second flexible layer 122 are formed from the same material. In some embodiments, a first material of the first flexible layer 120 differs from a second material of the second flexible layer 122. By way of example, the first material and the second material may have different stiffnesses, hardnesses, or durometers.

[0055] In some embodiments, the first intermediate layer 124 is a fabric layer. For example, the first intermediate layer 124 may include natural and/or synthetic fibers extending from the first end portion 112 of the flexible members 110 to the second end portion 114 of the flexible members 110 to resist extension of the flexible members 110 along the longitudinal axis A_2 of the flexible members 110. The first intermediate layer 124 may be made from a liquid-crystal polymer fabric (e.g., Vectran). In other embodiments, the first intermediate layer 124 is a metal layer. For example, the first intermediate layer 124 may be formed from a metal alloy such as nitinol (e.g., nickel titanium, etc.). In some embodiments, the first intermediate layer 124 has a tensile strength greater than or approximately equal to 895 MPA (e.g., 130 ksi, etc.). These tensile ranges were proven experimentally to maximize the number of bending cycles that the joint assembly 100 could complete before experiencing damage. For example, these tensile ranges were proven experimentally to maximize the number of bending cycles that the joint assembly 100 could complete before the first intermediate layer 124 experienced plastic deformation.

[0056] In some embodiments, thicknesses of the first flexible layer 120 and/or the second flexible layer 122 vary based on which of the finger members 20 the flexible members 110 are coupled between. For example, the first flexible layer 120 of the first flexible member 110A may have a first thickness, the first flexible layer 120 of the second flexible member 110B may have a second thickness, and the first flexible layer 120 of the third flexible member 110C may have a third thickness. The thickness of the first flexible layer 120 of each of the flexible members 110 may be sequentially greater (e.g., thicker, etc.) in a direction from a distal end of the finger 10 to a proximal end of the finger 10 (e.g., the third thickness of the first flexible layer 120 of the third flexible member 110C is greater than the second thickness of the first flexible layer 120 of the second flexible member 110B, the second thickness of the first flexible layer 120 of the third flexible member 110C is greater than the first thickness of the first flexible layer 120 of the first flexible member 110A, etc.). As another example, the second flexible layer 122 of the first flexible member 110A may have a first thickness, the second flexible layer 122 of the second flexible member 110B may have a second thickness, and the second flexible layer 122 of the third flexible member 110C may have a third thickness. The thickness of the second flexible layer 122 of each of the flexible members 110 may be sequentially greater (e.g., thicker, etc.) in a direction from a distal end of the finger 10 to a proximal end of the finger 10 (e.g., the third thickness of the second flexible layer 122 of the third flexible member 110C is greater than the second thickness of the second flexible layer 122 of the second flexible member 110B, the second thickness of the second flexible layer 122 of the third flexible member 110C is greater than the first thickness of the second flexible layer 122 of the first flexible member 110A, etc.). The thickness of the first flexible layer 120 and/or the second flexible layer 122 each of the flexible members 110 may increase sequentially in the direction from the distal end of the finger 10 to the proximal end of the finger 10 since the third flexible member 110C may experience greater forces than the first flexible member 110A (e.g., due to the third flexible member 110C being positioned further from the distal end of the finger 10 than the first flexible member 110A, etc.).

[0057] In some embodiments, as shown in FIG. 6, the flexible members 110 includes a fourth layer or third elastomeric layer, shown as third flexible layer 126, sandwiched between the first intermediate layer 124 and the first flexible layer 120, a fifth layer, second fabric layer, or second metal layer, shown as second intermediate layer 128, sandwiched between the first flexible layer 120 and the third flexible layer 126, a sixth layer or fourth elastomeric layer, shown as fourth flexible layer 130, sandwiched between the first intermediate layer 124 and the second flexible layer 122, and a seventh layer third fabric layer, or third metal layer, shown as third intermediate layer 132, sandwiched between the second flexible layer 122 and the fourth flexible layer 130. Similar to the first flexible layer 120 and the second flexible layer 122, the third flexible layer 126 and the fourth flexible layer 130 may apply the biasing force onto the finger members 20. In some embodiments, the third flexible layer 126 and the fourth flexible layer 130 may be formed from a same material as the first flexible layer 120 and the second flexible layer 122. Similar to the first intermediate layer 124, the second intermediate layer 128 and the third intermediate layer 132 may limit the types of movement of the joint assembly 100 other than the pivotal movement of the finger members 20 relative to one another. In some embodiments, the second intermediate layer 128 and the third intermediate layer 132 may be formed from a same material as the first intermediate layer 124.

[0058] As shown in FIGS. 3, 6, and 7, the first end portion 112 of the flexible members 110 define one or more first end portion apertures, first holes, or first slots, shown as first apertures 140, extending through the first end portion 112 of the flexible members 110 and the finger members 20 coupled to the first end portion 112 of the flexible members 110 define one or more first finger member apertures, shown as second apertures 142, extending through the finger members 20. The first apertures 140 may extend through the first flexible layer 120, the second flexible layer 122, and the first intermediate layer 124. The first apertures 140 of the first end portion 112 of the flexible members 110 and the second apertures 142 of the finger members 20 align to selectively receive one or more first end fasteners, first pins, first shafts, first connectors, or first threaded couplers, shown as first fasteners 144, to couple the first end portion 112 of the flexible members 110 to the finger members 20. According to the exemplary embodiment shown in FIGS. 6 and 7, the first end portion 112 of the flexible members 110 defines a total of two of the first apertures 140 such that the first end portion 112 of the flexible member 110 is coupled to the finger members 20 using a total of two of the first fasteners 144. In other embodiments, the first end portion 112 of the flexible member 110 is coupled to the finger members 20 using a different number of the first fasteners 144 (e.g., one, three, four, etc.).

[0059] As shown in FIGS. 3, 6, and 7, the second end portion 114 of the flexible members 110 define one or more second end portion apertures, second holes, or second slots, shown as third apertures 146, extending through the second end portion 114 of the flexible members 110 and the finger members 20 coupled to the second end portion 114 of the flexible members 110 define one or more second finger member apertures, shown as fourth apertures 148, extending through the finger members 20. The third apertures 146 may extend through the first flexible layer 120, the second flexible layer 122, and the first intermediate layer 124. The third apertures 146 of the second end portion 114 of the flexible members 110 and the fourth apertures 148 of the finger members 20 align to selectively receive one or more second end fasteners, second pins, second shafts, second connectors, or second threaded couplers, shown as second fasteners 150, to couple the second end portion 114 of the flexible members 110 to the finger members 20. According to the exemplary embodiment shown in FIGS. 6 and 7, the second end portion 114 of the flexible members 110 defines a total of two of the third apertures 146 such that the second end portion 114 of the flexible member 110 is coupled to the finger members 20 using a total of two of the second fasteners 150. In other embodiments, the second end portion 114 of the flexible member 110 is coupled to the finger members 20 using a different number of the second fasteners 150 (e.g., one, three, four, etc.).

[0060] As shown in FIGS. 4, 5, and 8, the harness 40 includes a flexible portion, shown as flexible harness portion 46. The flexible harness portion 46 extends through the flexible member 110 and moves with the flexible member 110. For example, the flexible harness portion 46 may be formed from a flexible printed circuit (FPC) extending through the flexible member 110 such that the flexible harness portion 46 may move with the flexible member 110 In some embodiments, as shown in FIGS. 4, 5, and 6, the flexible harness portion 46 is sandwiched between the first intermediate layer 124 and the second flexible layer 122. The first intermediate layer 124 and the second flexible layer 122 may be coupled to the flexible harness portion 46 to prevent movement of the flexible harness portion 46 relative to the first intermediate layer 124 and the second flexible layer 122. In other embodiments, the flexible harness portion 46 is sandwiched between the first flexible layer 120 and the first flexible layer 120. In some embodiments, the flexible member 110 includes the flexible harness portion 46 of the harness 40.

[0061] In some embodiments, a first portion of the harness 40 on a first side of the flexible harness portion 46 is coupled to the finger member 20 coupled to the first end portion 112 of the flexible member 110, a second portion of the harness 40 on a second side of the flexible harness portion 46 is coupled to the finger member 20 coupled to the second end portion 114 of the flexible member 110, and the flexible harness portion 46 extends between the first portion of the harness 40 and the second portion of the harness 40 through the flexible members 110. For example, when the flexible harness portion 46 extends through the first flexible member 110A, a first portion of the harness 40 on a first side of the flexible harness portion 46 may be coupled to the distal finger member 20A and a second portion of the harness 40 on a second side of the flexible harness portion 46 may be coupled to the middle finger member 20B.

Joint Assembly Functionality

[0062] Referring to FIGS. 4 and 5, the function of the joint assembly 100 throughout the range of motion of a finger 10 is shown according to an embodiment. As the finger members 20 pivot relative to one another, the flexible member 110 controls the relative motion of the finger members 20 and the movement of the flexible harness portion 46. Accordingly, the joint assembly 100 ensures that rolling contact between the finger members 20 is maintained and that the harness 40 is guided safely.

[0063] The flexible member 110 limits the relative motion of the finger members 20 to rolling contact along the contact surfaces 28. The contact surfaces 28 each have a curved surface that extends along a circular path, shown as circle 300. The contact surfaces 28 contact one another directly. The finger members 20 pivot relative to one another about a lateral axis of rotation 302. This lateral axis of rotation 302 is located at the point where the circles 300 contact one another or are closest to contacting one another (e.g., where the contact surfaces 28 contact each other).

[0064] During rolling contact motion of the finger members 20, the position of the lateral axis of rotation 302 changes. As the finger members 20 rotate toward or away from one another, the point at which the circles 300 are closest to one another shifts along the contact surfaces 28. Accordingly, the position of the lateral axis of rotation 302 shifts along the contact surfaces 28. FIG. 4 illustrates the position of the lateral axis of rotation 302 when the finger 10 is extended, and FIG. 5 illustrates the position of the lateral axis of rotation 302 when the finger 10 is in a bent configuration. As shown, when the finger 10 bends along the grasping direction 26, the lateral axis of rotation 302 shifts downward along the contact surfaces 28.

[0065] In order to maintain the finger members 20 in rolling contact, the flexible member 110 applies tensile forces to limit (e.g., prevent) other types of motion. In the extended configuration of FIG. 4, the first intermediate layer 124 of the flexible member 110 limits (a) upward movement of the distal finger member 20A relative to the middle finger member 20B, (b) longitudinal movement of the distal finger member 20A away from the middle finger member 20B, and (c) lateral movement of the distal finger member 20A relative to the middle finger member 20B in either direction. In the extended configuration of FIG. 5, the first intermediate layer 124 of the flexible member 110 limits (a) downward movement of the distal finger member 20A relative to the middle finger member 20B, (b) longitudinal movement of the distal finger member 20A away from the middle finger member 20B, and (c) lateral movement of the distal finger member 20A relative to the middle finger member 20B in either direction.

[0066] As shown in FIGS. 4 and 5, the flexible member 110 may bend to facilitate rolling contact between the finger members 20. As the distal finger member 20A rotates in the grasping direction 26, the flexible member 110 bends along with the finger 10 in the grasping direction 26. As the flexible members 110 bends with the finger 10 in the grasping direction 26, the first flexible layer 120 experiences tensile forces and the second flexible layer 122 experiences compressive forces that apply biasing forces on the finger 10 to bias the finger 10 toward the extended configuration.

[0067] Referring to FIGS. 4 and 5, as the finger members 20 proceed with the rolling contact motion, the harness 40 bends from the configuration shown in FIG. 4 to the configuration shown in FIG. 5. In some embodiments, the flexible harness portion 46 of the harness 40 bends along a neutral bending plane 304 that is coplanar with the lateral axis of rotation 302, is coplanar with the longitudinal axis A_1 of the finger 10, and/or extends perpendicular to tangent with the circles 300. The neutral bending plane 304 may represent a plane above which the flexible member 110 is in tension and below which the flexible member 110 is in extension when the finger 10 is rotated in the grasping direction 26. A component positioned at the neutral bending plane 304 may experience neither tension nor compression.

[0068] As shown in FIGS. 4, 5, and 8, the flexible member 110 is positioned such that the neutral bending plane 304 extends through the flexible harness portion 46. Beneficially, this minimizes the stress on the harness 40, as the flexible harness portion 46 extends along the neutral bending plane 304. This positioning also ensures that the first flexible layer 120 is entirely or almost entirely in tension and the second flexible layer 122 is entirely or almost entirely in compression. The first flexible layer 120 and the second flexible layer 122 may be constructed differently to better accommodate the particular type of loading experienced and maximize bending life. By way of example, the second flexible layer 122 may be made stiffer than the first flexible layer 120 using a different hardness of elastomeric material.

[0069] As shown in FIGS. 4, 5, and 8, when the first intermediate layer 124 is positioned between the flexible harness portion 46 and the first flexible layer 120, the positioning of the flexible members 110 is such that the first intermediate layer 124 is entirely or almost entirely in tension. The first intermediate layer 124 may be constructed to better accommodate tension loading and maximize bending life. Additionally or alternatively, the first intermediate layer 124 may be constructed to apply a biasing force on the finger 10 when experiencing tensile loading to apply biasing forces on the finger 10 to bias the finger 10 toward the extended configuration.

[0070] 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.

[0071] 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).

[0072] 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.

[0073] 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.

[0074] 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.

[0075] 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.

[0076] 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.

[0077] It is important to note that the construction and arrangement of the finger 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. For example, the actuator cables 30 of the exemplary embodiment shown in at least FIG. 2 may be incorporated in the finger 10 of the exemplary embodiment shown in at least FIG. 1. Although only one example of an element from one embodiment that can be incorporated or utilized in another embodiment has been described above, it should be appreciated that other elements of the various embodiments may be incorporated or utilized with any of the other embodiments disclosed herein.

CLAIMS

What is claimed is:

1. A joint assembly for a robotic appendage, comprising:

a first structure defining a first contact surface that is curved;

a second structure defining a second contact surface that is curved and faces toward the first contact surface; and

a composite flexible member having a first end portion fixedly coupled to the first structure and a second end portion fixedly coupled to the second structure,

wherein the composite flexible member movably couples the first structure to the second structure such that the second structure is pivotable relative to the first structure about a lateral axis that moves along the first contact surface and the second contact surface as the second structure pivots.

2. The joint assembly of claim 1, wherein the composite flexible member comprises:

a first flexible layer;

a second flexible layer; and

an intermediate layer sandwiched between the first flexible layer and the second flexible layer, the intermediate layer configured to inhibit stretching of the composite flexible member along a longitudinal axis of the joint assembly.

3. The joint assembly of claim 2, wherein the intermediate layer is configured to inhibit twisting of the composite flexible member along the longitudinal axis of the joint assembly.

4. The joint assembly of claim 2, wherein:

the first flexible layer is a first elastomeric layer;

the second flexible layer is a second elastomeric layer; and

the intermediate layer is at least one of a fabric layer or a metal layer.

5. The joint assembly of claim 2, wherein the intermediate layer extends along a longitudinal neutral axis of the composite flexible member.

6. The joint assembly of claim 2, wherein:

the intermediate layer is a first intermediate layer; and

the composite flexible member comprises:

a third flexible layer; and

a second intermediate layer sandwiched between the second flexible layer and the third flexible layer, the intermediate layer configured to inhibit translation of the composite flexible member along the longitudinal axis of the joint assembly.

7. The joint assembly of claim 5, wherein:

the first end portion of the composite flexible member defines one or more first apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer;

the first structure defines one or more second apertures, the one or more second apertures positioned to align with the one or more first apertures to receive one or more first fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the first structure;

the second end portion of the composite flexible member defines one or more third apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; and

the second structure defines one or more fourth apertures, the one or more fourth apertures positioned to align with the one or more second apertures to receive one or more second fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the second structure.

8. The joint assembly of claim 2, wherein the composite flexible member comprises a harness permitting communication between a first device and a second device, wherein the harness has a first portion coupled to the first structure, a second portion coupled to the second structure, and a flexible portion extending between the first structure and the second structure.

9. The joint assembly of claim 8, wherein the flexible portion of the harness is sandwiched between the first flexible layer and the second flexible layer.

10. The joint assembly of claim 2, wherein a hardness of the first flexible layer and the second flexible layer are between Shore 10A and Shore 80A.

11. A joint assembly for a robotic appendage, comprising:

a first body having a first exterior surface;

a second body having a second exterior surface; and

a composite flexible member coupled between the first body and the second body, the composite flexible member comprising:

a first flexible layer;

a second flexible layer; and

an intermediate layer sandwiched between the first flexible layer and the second flexible layer, the intermediate layer configured to inhibit stretching of the composite flexible member along a longitudinal axis of the joint assembly;

wherein the composite flexible member permits the first body to pivot relative to the second body.

12. The joint assembly of claim 11, wherein:

the first flexible layer is a first elastomeric layer;

the second flexible layer is a second elastomeric layer; and

the intermediate layer is at least one of a fabric layer or a metal layer.

13. The joint assembly of claim 11, wherein:

the intermediate layer is a first intermediate layer; and

the composite flexible member comprises:

a third flexible layer; and

a second intermediate layer sandwiched between the second flexible layer and the third flexible layer, the second intermediate layer configured to inhibit stretching of the composite flexible member along the longitudinal axis of the joint assembly.

14. The joint assembly of claim 11, wherein:

the composite flexible member defines one or more first apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer;

the first body defines one or more second apertures, the one or more second apertures positioned to align with the one or more first apertures to receive one or more first fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the first body;

the composite flexible member defines one or more third apertures extending through the first flexible layer, the second flexible layer, and the intermediate layer; and the second body defines one or more fourth apertures, the one or more fourth apertures positioned to align with the one or more second apertures to receive one or more second fasteners to couple the first flexible layer, the second flexible layer, and the intermediate layer to the second body.

15. The joint assembly of claim 11, wherein the composite flexible member comprises a harness permitting communication between a first device and a second device, wherein the harness has a first portion coupled to the first body, a second portion coupled to the second body, and a flexible portion extending between the first body and the second body.

16. A robotic appendage comprising:

a base body, a middle body, and a distal body;

a first composite flexible member pivotably coupling the middle body to the base body, the first composite flexible member having a first thickness; and

a second composite flexible member pivotably coupling the distal body to the middle body, the second composite flexible member having a second thickness, the second thickness less than the first thickness.

17. The robotic appendage of claim 16, wherein each of the first composite flexible member and the second composite flexible member comprise:

a first flexible layer;

a second flexible layer; and

an intermediate layer sandwiched between the first flexible layer and the second flexible layer, the intermediate layers configured to inhibit stretching of the first composite flexible member and the second composite flexible member along a longitudinal axis of the robotic appendage.

18. The robotic appendage of claim 17, further comprising a harness extending from the base body, through the middle body, to the distal body and configured to transfer at least one of data or electrical energy between a first device and a second device, wherein the harness extends between the first flexible layers and the second flexible layers of the first composite flexible member and the second composite flexible member.

19. The robotic appendage of claim 17, wherein:

the first flexible layers are first elastomeric layers;

the second flexible layers are second elastomeric layers; and the intermediate layers are at least one of fabric layers or metal layers.

20. The robotic appendage of claim 17, wherein at least one of (i) the first flexible layer of the first composite flexible member is thicker than the first flexible layer of the second composite flexible member or (ii) the second flexible layer of the first composite flexible member is thicker than the second flexible layer of the second composite flexible member.

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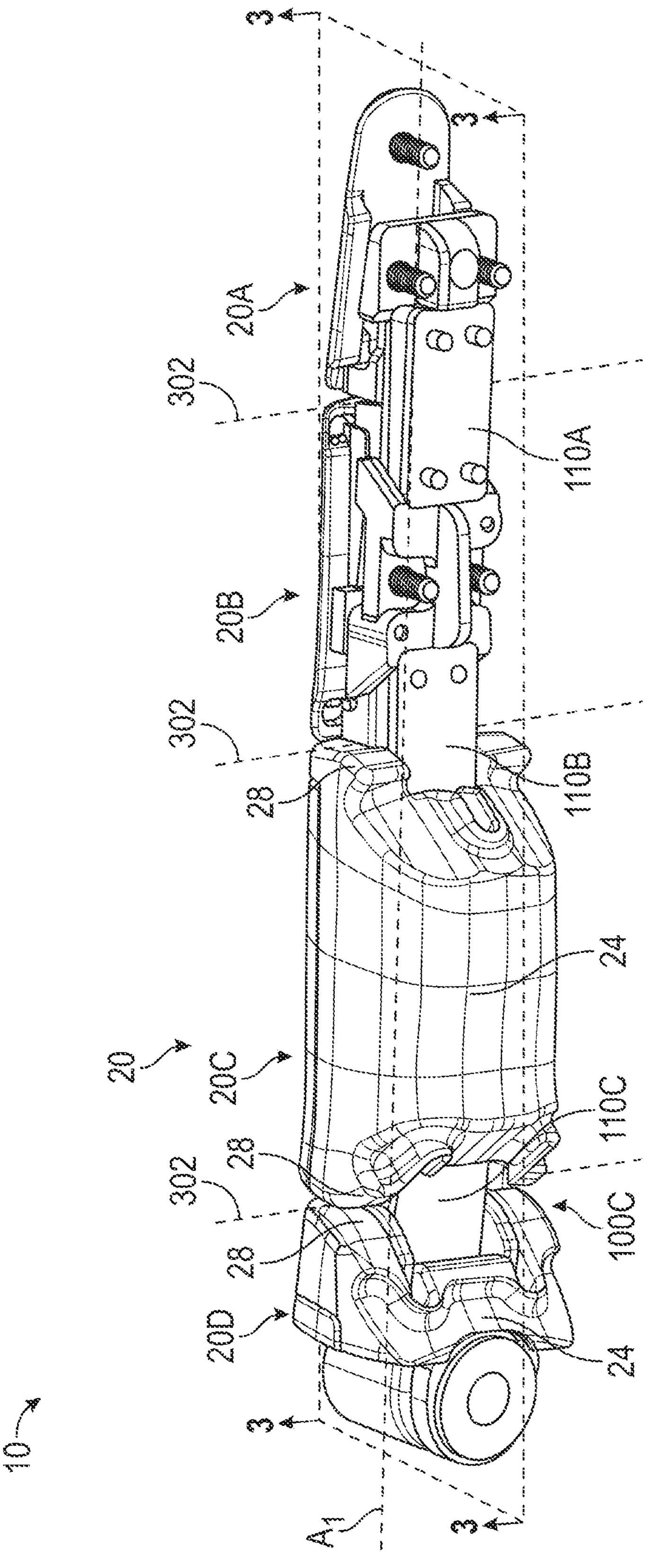
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FIG. 1

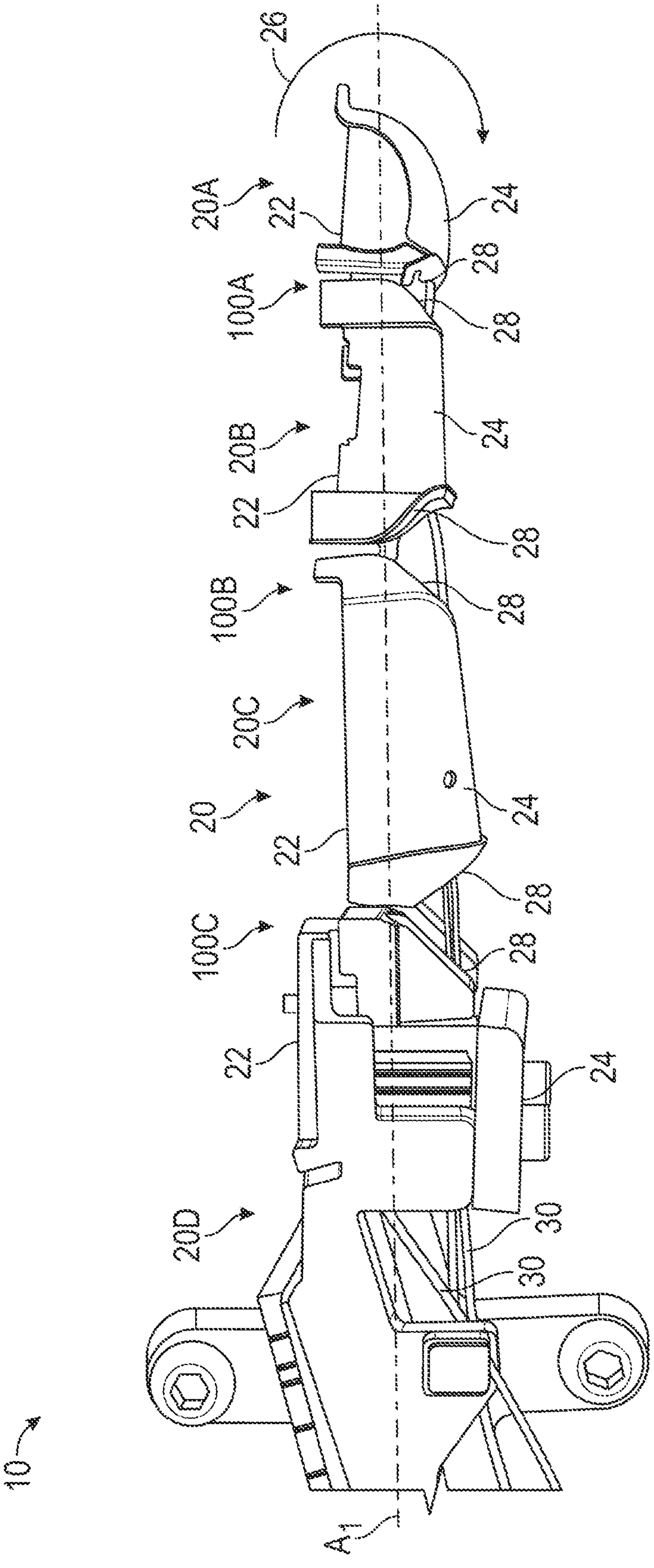
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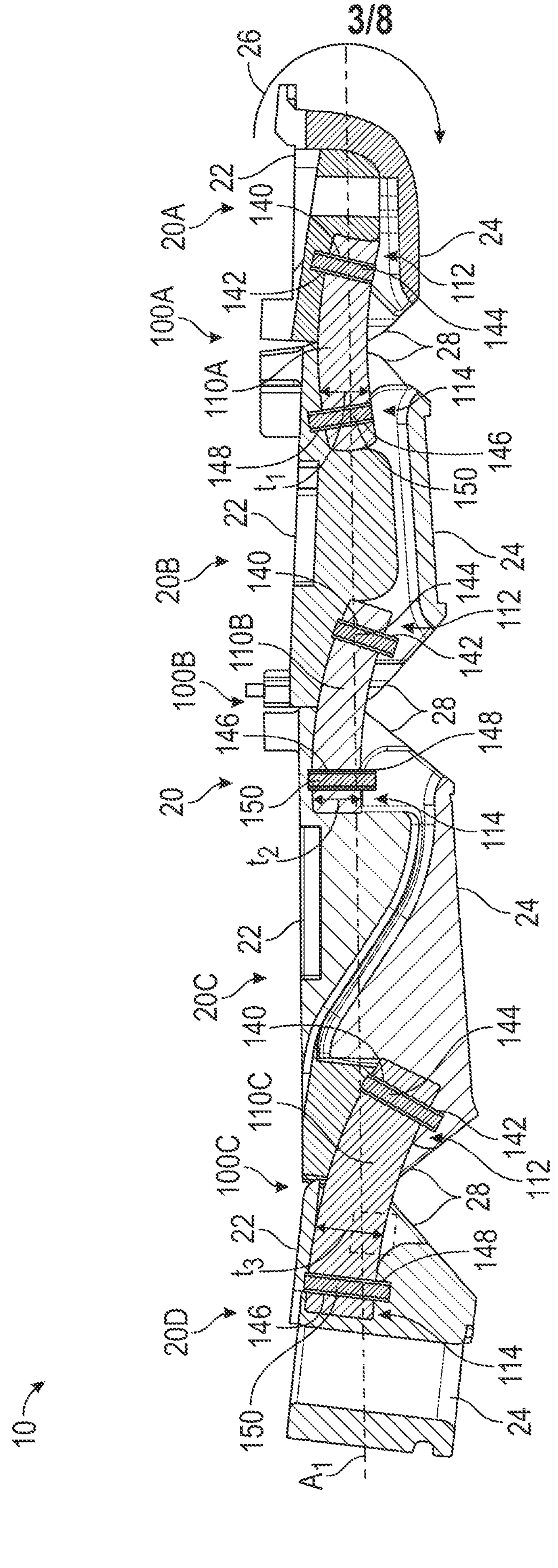
FIG. 2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100B
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20
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22
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FIG. 3

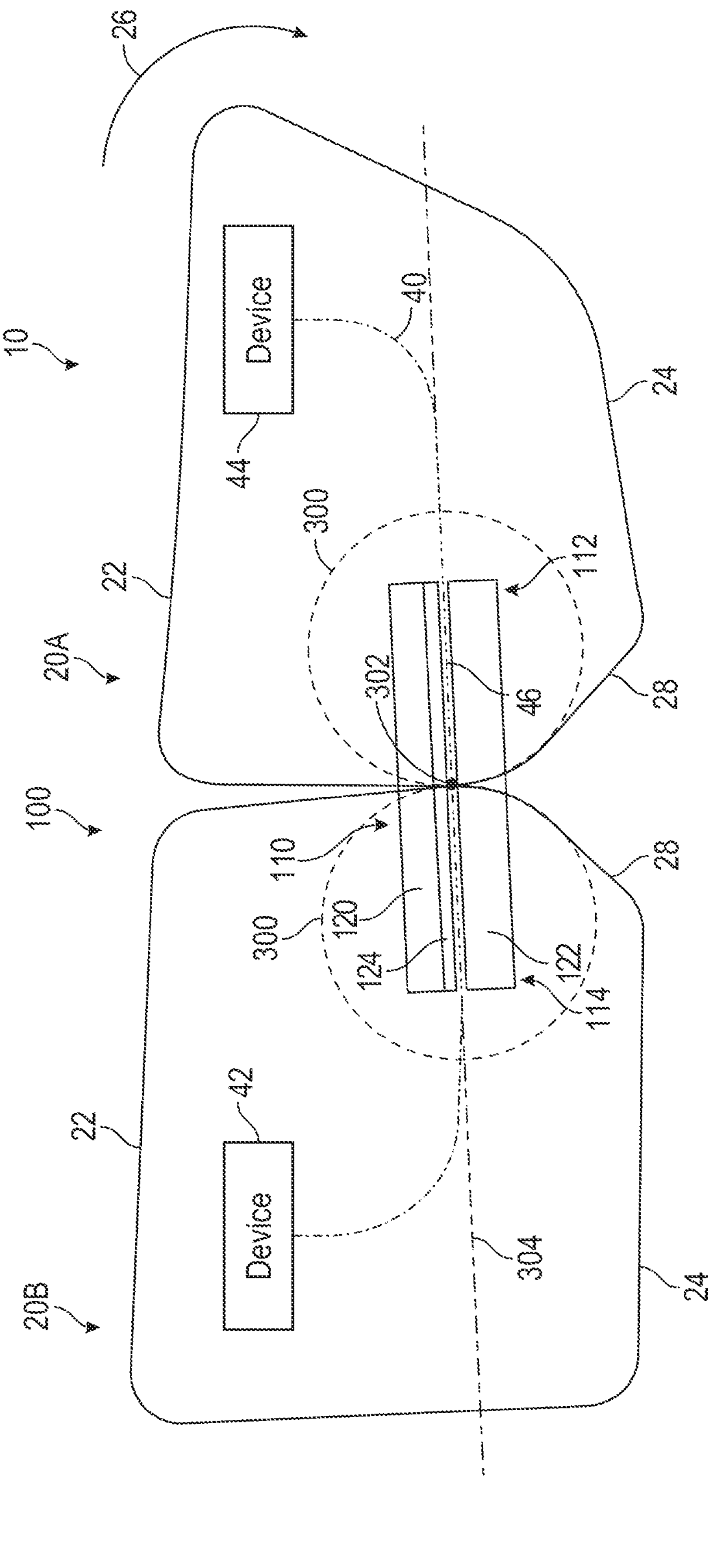
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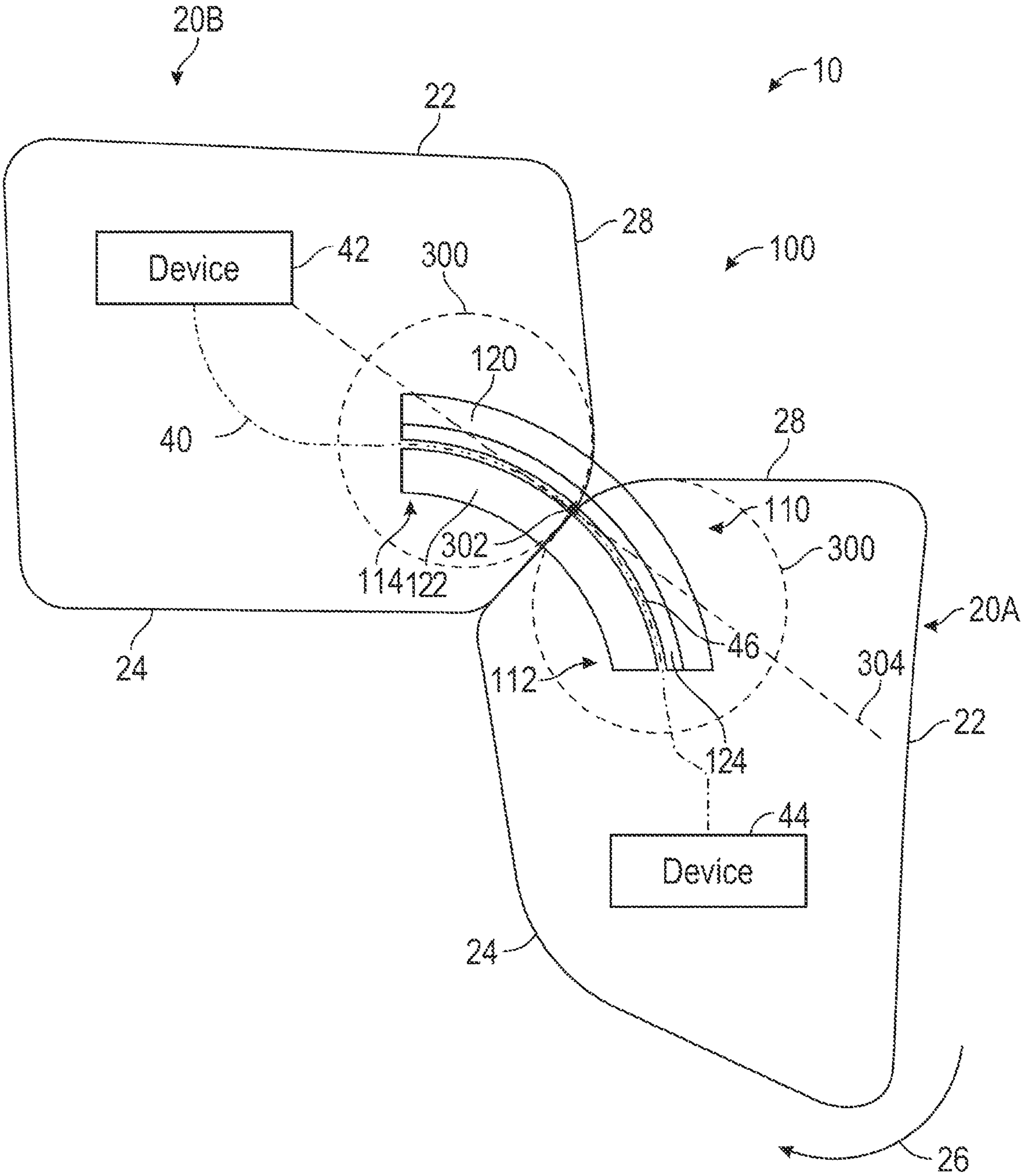
FIG. 4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Device
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FIG. 5

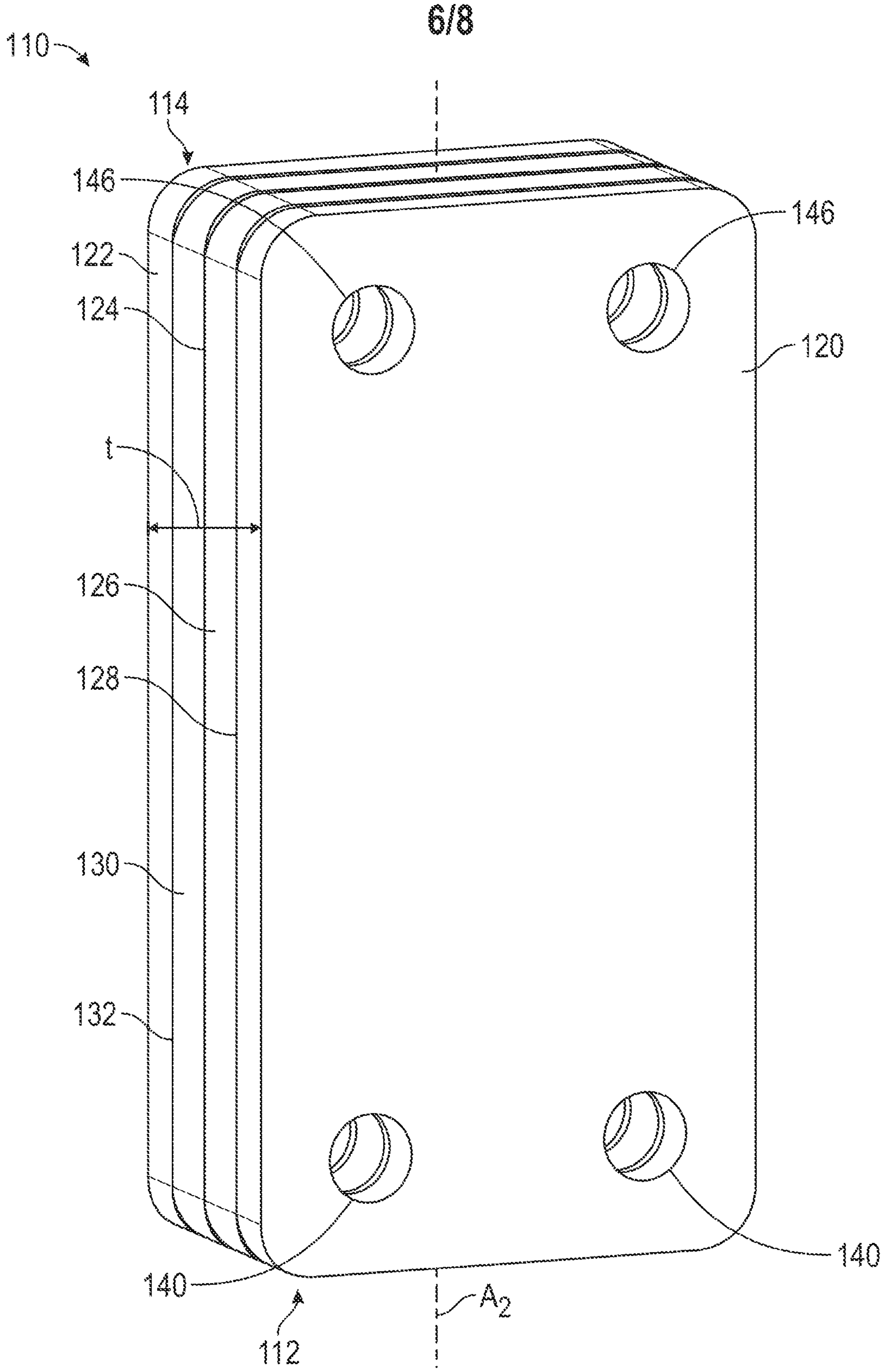

FIG. 6

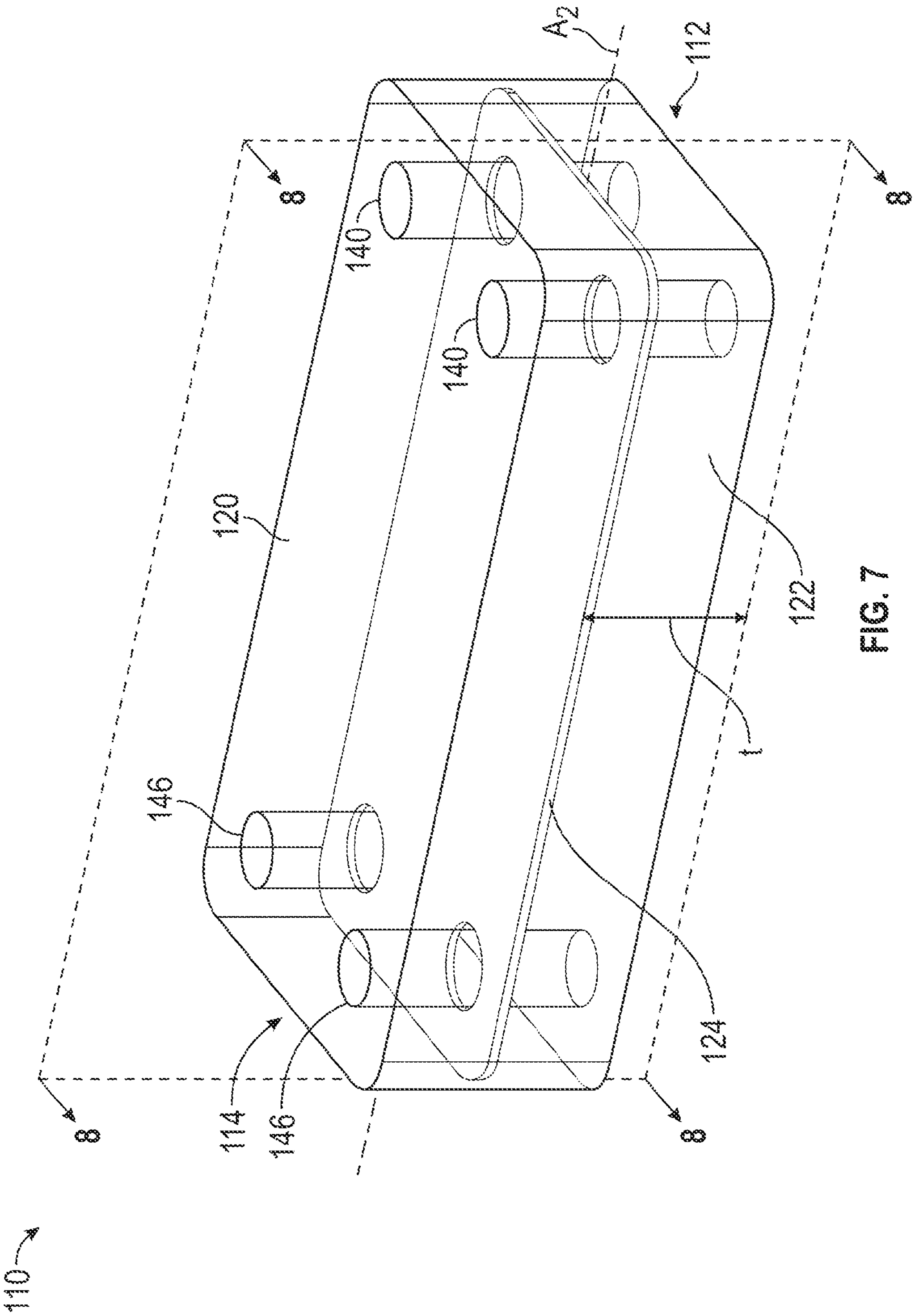

FIG. 7

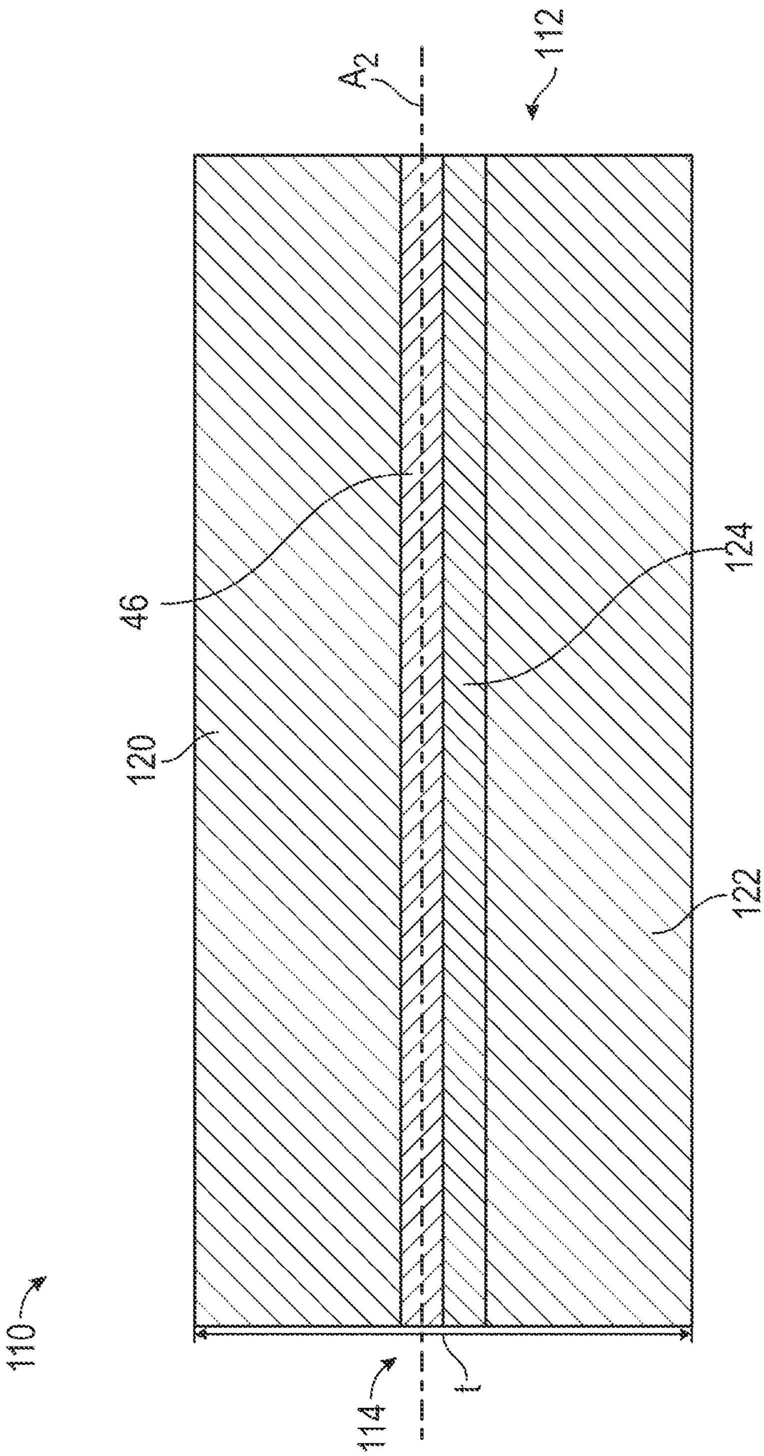

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2025/050217

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***B25J 15/12*** (2025.01); ***B25J 17/02*** (2025.01)

CPC: ***B25J 15/12; B25J 17/02***

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.
Y	US 4,558,911 A (RUOFF) 17 December 1985 (17.12.1985) entire document	1, 16
Y	US 2014/0366675 A1 (COMMISSARIAT À l'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES) 18 December 2014 (18.12.2014) entire document	1, 16
Y	US 2023/0102500 A1 (TATUM ROBOTICS LLC) 30 March 2023 (30.03.2023) entire document	16
A	US 2015/0289994 A1 (ENGEBERG et al.) 15 October 2015 (15.10.2015) entire document	1-20
A	US 10,456,929 B1 (SCHLUMBERGER TECHNOLOGY CORP) 29 October 2019 (29.10.2019) entire document	1-20
A	WO 2024/073138 A1 (TESLA INC.) 04 April 2024 (04.04.2024) entire document	1-20

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 December 2025 (15.12.2025)	**29 December 2025 (29.12.2025)**

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2025/050217

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2005/0218679 A1 (YOKOYAMA et al.) 06 October 2005 (06.10.2005) entire document	1-20