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SYSTEMS, DEVICES, AND METHODS FOR ROBOTIC END EFFECTORS

Abstract

A robotic end effector or end-of-arm tool may take the form of a mechanical digit (e.g., mechanical finger), or employ one or more mechanical digits (e.g., mechanical fingers), controllable in multiple degrees of freedom, e.g., pitch, yaw, curl. The mechanical digit(s) advantageously comprise a skeleton and three (3) piston/cylinders combinations, one controlling curl, and the other two controlling pitch and/or yaw. Mechanical digits may comprise a number of rolling contact joints. A flexible printed circuit board (PCB) carrying a variety of sensors covers the skeleton and runs inside the rolling contact joints to provide a zero length change path. Knuckle imitators may cause a membrane cast or sheath joint to resemble human knuckles.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 17/491,586, filed Oct. 1, 2021, which claims the benefit of U.S. Provisional Application No. 63/086,258, filed Oct. 1, 2020, the disclosures of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present systems, devices, and methods are generally related to robotics and more particularly to robot end effectors or end-of-arm tools and/or actuators, for example mechanical hands or mechanical hands with mechanical digits having multiple degrees of freedom.

BACKGROUND

[0003] Robots or robotic appendages typically employ an end-of-arm tool or end effector to interact with objects in an environment in which the robot operates. Some end-of-arm tools or end effectors are relatively simple articles, without moving elements (e.g., push bar, hook, suction cup) allowing simple interactions or engagement (e.g., push, pull, lift) with objects in the environment. Other end-of-arm tools or end effectors are relatively complex machines, with moving elements (e.g., grippers, digits) allowing complex interactions or engagement (e.g., grasping) with objects in the environment.

[0004] As the field of robots develops, more sophisticated and/or robust end-of-arm tools or end effectors are desirable.

SUMMARY

[0005] Described and illustrated herein are robot end effectors, end-of-arm tools and/or actuators that take the form of a mechanical digit (e.g., mechanical finger), or employ one or more mechanical digits (e.g., mechanical fingers), that can be controlled in three (3) degrees of freedom (pitch and yaw of a first (1.sup.st) joint, and combined curl of a second (2.sup.nd) joint and a third (3.sup.rd) joint). The mechanical digit(s) advantageously comprise a skeleton and three (3) pistons and associated cylinders, one controlling the curl, and the other two controlling the pitch and/or yaw. One or more valves fluidly couple one or more sources of pressurized fluid (e.g., liquid for instance hydraulic fluid; gas for instance air) to the cylinders and are operable to control a pressure on one or both sides of the piston in the respective cylinder to cause the piston to translate with respect to the respective cylinder to set the position of the pistons to obtain a desired or directed amount of rotation about a curl axis, rotation about a pitch axis and/or rotation about a yaw axis. The pistons and cylinders may take the form of hydraulic piston and cylinder combinations, or alternatively take the form of pneumatic piston and cylinder combinations.

[0006] Each joint of the mechanical digit may advantageously be comprised or take the form of a rolling contact joint. There may also be a single sheet of flexible printed circuit board (PCB) carrying a variety of sensors that covers an outer surface of the skeleton, the flexible PCB advantageously running inside of the rolling contact joint (which provides a zero length change path for the flexible PCB through a full range of motion).

[0007] All three pistons and cylinders may be located in a base of the mechanical digit, or alternatively in a palm to which the mechanical digit is coupled. The curl degree of freedom may be transmitted through a set of gears and linkages. The skeleton may also include two knuckle

imitators, each located at a respective one of the curl joints, and which extend past the curl joints to provide a shape similar to a human finger knuckle when a flexible, resilient skin (e.g., silicone membrane) is cast around the skeleton or when a silicone skin glove or sheath is placed around the skeleton.

[0008] A mechanical digit may be summarized as including: a fluid manifold; a first phalanx; a first cylinder at least partially contained within the fluid manifold; a first piston slidably received by the first cylinder for translation along a first translation axis extending outside of the fluid manifold; a first linkage that mechanically couples the first piston with the first phalanx; and a first valve positioned at a perimeter of the fluid manifold and operable to selectively open and close a first fluidly communicative path between a portion of an interior of the first cylinder and a first source of a first pressurized fluid outside of the fluid manifold.

[0009] The mechanical digit may further include: a second phalanx; a second cylinder at least partially contained within the fluid manifold; a second piston slidably received by the second cylinder for translation along a second translation axis extending outside of the fluid manifold; a second linkage that mechanically couples the second piston with the second phalanx; and a second valve positioned at the perimeter of the fluid manifold and operable to selectively open and close a second fluidly communicative path between a portion of an interior of the second cylinder and a second source of a second pressurized fluid outside of the fluid manifold. Rotation about a first curl axis may be actuated by movement of the second piston along the second translation axis. The mechanical digit may further include: a third phalanx; and a third linkage that mechanically couples the second piston with the third phalanx, wherein rotation about the first curl axis and rotation about a second curl axis are both actuated by movement of the second piston along the second translation axis. The first source of the first pressurized fluid and the second source of the second pressurized fluid may be a same source of a same pressurized fluid.

[0010] The first linkage may mechanically couple the first piston with the first phalanx at a position laterally spaced on a first side of a centerline of the first phalanx. The mechanical digit may further include: a second cylinder at least partially contained within the fluid manifold; a second piston slidably received by the second cylinder for translation along a second translation axis extending outside of the fluid manifold; a second linkage that mechanically couples the second piston with the first phalanx at a position laterally spaced on a second side of the centerline of the first phalanx; and a second valve positioned at a perimeter of the fluid manifold and operable to selectively open and close a third fluidly communicative path between a portion of an interior of the second cylinder and a second source of a second pressurized fluid outside of the fluid manifold. Rotation about a pitch axis may be actuated by movement of both the first piston along the first translation axis and the second piston along the second translation axis. Rotation about the pitch axis without rotation about a yaw axis may be actuated by concurrent movements of the first piston along the first translation axis and the second piston along the second translation axis that are equal in speed, magnitude and direction with respect to one another along the respective first and second translation axes. Rotation about a yaw axis may be actuated by movement of one or both of the first piston along the first translation axis and the second piston along the second translation axis. Rotation about the yaw axis without rotation about a pitch axis may be actuated by concurrent movements of the first piston along the first translation axis and the second piston along the second translation axis that are equal in speed and magnitude but opposite in direction with respect to one another along the respective first and second translation axes. Rotation about a pitch axis may be actuated by movement of both the first piston along the first translation axis and the second piston along the second translation axis. Rotation about the yaw axis with rotation about the pitch axis may be actuated by movements of the first piston along the first translation axis and the second piston along the second translation axis that are at least one of: not concurrent, not matched in speed, or not matched in magnitude, along the respective first and second translation axes. The second translation axis may be parallel to the first translation axis, and a yaw axis may be

perpendicular to a plane in which the first and the second translation axes lie.

[0011] The first linkage may include a first piston rod having a first end and a second end, the first end of the first piston rod coupled to the first piston to rotate about two axes that are orthogonal to the first translation axis. The first end of the first piston rod may include a first ball joint that is directly coupled to the first piston to rotate about the two axes that are orthogonal to the first translation axis. The second end of the first piston rod may be coupled to the first phalanx to rotate about two axes that are orthogonal to the first phalanx.

[0012] The mechanical digit may further include a first spring positioned to bias the first piston toward a first piston position in the first cylinder.

[0013] The mechanical digit may further include a bleed valve positioned at the perimeter of the fluid manifold and operable to selectively open and close a second fluidly communicative path between the portion of the interior of the first cylinder and a volume outside of the fluid manifold.

[0014] The mechanical digit may further include a volume of the first pressurized fluid contained in the portion of the interior of the first cylinder. The first pressurized fluid may be a hydraulic fluid.

[0015] The fluid manifold may include at least one fixture to mechanically connect the fluid manifold to a palm of a robotic hand.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative states of elements in the drawings are not necessarily drawn to scale. For example, the positions of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

[0017] FIG. 1 is a front, top, left side isometric view of a robotic mechanical digit in a straight or neutral pose and without a membrane or artificial skin, according to the present systems, devices, and methods.

[0018] FIG. 2 is a rear, bottom, right side isometric view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, according to the present systems, devices, and methods.

[0019] FIG. 3 is a top, rear, left side isometric view of a robotic mechanical digit of FIG. 1 in a full curl and pitch down pose, according to the present systems, devices, and methods.

[0020] FIG. 4A is a top plan view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, according to the present systems, devices, and methods.

[0021] FIG. 4B is a left side elevational view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, according to the present systems, devices, and methods.

[0022] FIG. 5A is a cross-sectional view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose taken along a first plane 402 (FIG. 4A), according to the present systems, devices, and methods.

[0023] FIG. 5B is a cross-sectional view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, the section taken along a second plane 404 (FIG. 4A), according to the present systems, devices, and methods.

[0024] FIG. 5C is a cross-sectional view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, the section along a third plane 406 (FIG. 4A), according to the present systems, devices, and methods.

[0025] FIG. 5D is a cross-sectional view of the robotic mechanical digit of FIG. 1 in the straight or neutral pose, the section along a fourth plane 408 (FIG. 4A), according to the present systems,

devices, and methods.

[0026] FIG. 6 is a cross-sectional view of the robotic mechanical digit of FIG. 1 in the fully curled, pitch-down pose, the section along the fourth plane 408 (FIG. 4A), according to the present systems, devices, and methods.

[0027] FIG. 7 is a cross-sectional view of a portion of the robotic mechanical digit of FIG. 1 in the straight or neutral pose taken along a sixth plane 412 (FIG. 4B), according to the present systems, devices, and methods.

[0028] FIG. 8 is a cross-sectional view of a portion of the robotic mechanical digit of FIG. 1 in a pose with a rotation counterclockwise about a yaw axis, the section taken along a sixth plane 412 (FIG. 4B), according to the present systems, devices, and methods.

[0029] FIG. 9A is a cross-sectional view of a portion of the robotic mechanical digit of FIG. 1 in a straight or neutral pose, the section taken along a fifth plane, according to the present systems, devices, and methods.

[0030] FIG. 9B is a cross-sectional view of a portion of the robotic mechanical digit of FIG. 1 in a pitched-up pose rotated counterclockwise about a pitch axis, the section taken along the fifth plane, according to the present systems, devices, and methods.

[0031] FIG. 9C is a cross-sectional view of a portion of the robotic mechanical digit of FIG. 1 in a pitched-down pose rotated clockwise about the pitch axis, the section taken along the fifth plane, according to the present systems, devices, and methods.

[0032] FIG. 10A is a front, top, right side isometric view of the robotic mechanical digit of FIG. 1 with a flexible printed circuit board (PCB) omitted to better illustrate various joints, according to the present systems, devices, and methods.

[0033] FIG. 10B is a plan view of a first side of a flexible printed circuit board (PCB) of the robotic mechanical digit of FIG. 1, the flexible PCB illustrated in a flattened configuration, according to the present systems, devices, and methods.

[0034] FIG. 10C is a plan view of a second side of a flexible printed circuit board (PCB) of the robotic mechanical digit of FIG. 1, the second side opposite the first side across a thickness of the flexible PCB, the flexible PCB illustrated in a flattened configuration, according to the present systems, devices, and methods.

[0035] FIG. 11A is a top, left side, rear isometric view of the robotic mechanical digit of FIG. 1 in a pitched-down pose rotated counterclockwise about a pitch axis and actuated by an outward extension of both a right piston and a left piston, according to the present systems, devices, and methods.

[0036] FIG. 11B is a top, left side, rear isometric view of the robotic mechanical digit of FIG. 1 in a pitched-up pose rotated clockwise about the pitch axis and actuated by an inward retraction of both the right piston and the left piston, according to the present systems, devices, and methods.

[0037] FIG. 12A is a top, left side, rear isometric view of the robotic mechanical digit of FIG. 1 in a yaw-right pose rotated clockwise about a yaw axis and actuated by an outward extension of the left piston and an inward retraction of the right piston, according to the present systems, devices, and methods.

[0038] FIG. 12B is a top, left side, rear isometric view of the robotic mechanical digit of FIG. 1 in a yaw-left pose rotated counterclockwise about the yaw axis and actuated by an outward extension of the right piston and an inward retraction of the left piston, according to the present systems, devices, and methods.

[0039] FIG. 12C is a top, left side, rear isometric view of the robotic mechanical digit of FIG. 1 in a curled pose rotated counterclockwise about one or more curl axes and actuated by an outward extension of a third piston, according to the present systems, devices, and methods.

[0040] FIG. 13A is a front, bottom, left side isometric view of a portion of the robotic mechanical digit of FIG. 1, according to the present systems, devices, and methods.

[0041] FIG. 13B is a front, top, left side isometric view of the portion of a robotic mechanical digit

of FIG. 1, according to the present systems, devices, and methods.

[0042] FIG. 14 is a top plan view of a robotic end effector comprising a hand with a palm and a plurality of mechanical digits that include four mechanical fingers and a mechanical thumb, according to the present systems, devices, and methods.

DETAILED DESCRIPTION

[0043] In the following description, certain specific details are set forth in order to provide a thorough understanding of various disclosed implementations and embodiments. However, one skilled in the relevant art will recognize that implementations and embodiments may be practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, certain structures associated with robots, robotic appendages, linkages, valves, cables or actuators, reservoirs of pressurized fluid (e.g., liquid, gas), and/or compressors, have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the implementations or embodiments.

[0044] Unless the context requires otherwise, throughout the specification and claims which follow, the word “comprise” and variations thereof, such as, “comprises” and “comprising” are to be construed in an open, inclusive sense, that is, as “including, but not limited to.”

[0045] Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0046] As used in this specification and the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the content clearly dictates otherwise. It should also be noted that the term “or” is generally employed in its sense including “and/or” unless the content clearly dictates otherwise.

[0047] The headings and Abstract of the Disclosure provided herein are for convenience only and do not interpret the scope or meaning of the embodiments.

[0048] FIGS. 1, 2 and 3 show an example of a robotic mechanical digit **100**, according to the present systems, devices, and methods. In particular, FIG. 1 shows a front, top, left side isometric view of robotic mechanical digit **100** in a straight or neutral pose and without any membrane or artificial skin, which may be included in some implementations; FIG. 2 shows a rear, bottom, right side isometric view of robotic mechanical digit **100** in the straight or neutral pose and without any membrane or artificial skin; and FIG. 3 shows a top, rear, left side isometric view of robotic mechanical digit **100** in a full curl and pitch down pose, according to the present systems, devices, and methods.

[0049] Robotic mechanical digit **100** comprises skeleton that includes a base **102**. The base **102** may have one or more mechanical coupling or attachment points or features that allow attachment to a palm or similar robotic structure, which may or may not be analogous to a human hand. The base **102** includes a right cylinder **104a** and a left cylinder **104b**, where “right” and “left” respectively correspond to first and second lateral sides of a centerline that passes longitudinally through mechanical digit (i.e., through base **102**, first phalanx **112**, second phalanx **114**, and third phalanx **114**) along the y-axis of FIG. 1. A right piston rod **106a** and a left piston rod **106b** are partially within, and extend outwardly from, the left and right cylinders **104a** and **104b** respectively. Coupled to a second end of the right piston rod **106a** is a right pitch-yaw linkage **108a**, and coupled to a second end of the left piston **106b** is a left pitch-yaw linkage **108b**. Additional details of the inside of the left and right cylinders and their couplings are visible in FIGS. 6, 7, and 9. The right and left pitch-yaw linkages **108a**, **108b** are rotatably coupled to opposite sides of a yaw carriage **110** which is rotatably coupled around a z-axis to a bottom plate **111** which is fixed to the base **102**. Also rotatably coupled to the right and left pitch-yaw linkages

108a, **108b** is the first phalanx **112** at a first end of the first phalanx **112**. Also rotatably coupled near the first end of the first phalanx **112** is the yaw carriage **110** by a first rolling surface joint **113**. Additional details of the pitch-yaw linkages **108a**, **108b** and yaw carriage couplings and their locations are visible in FIGS. **3** and **9**. The first phalanx **112** is coupled at a second end to a first end of a second phalanx **114** by a second rolling surface joint **115** as illustrated in FIGS. **5A-5D**. Similarly, the second phalanx **114** is coupled at a second end thereof to a first end of a third phalanx **116** by a third rolling surface joint **117**. The first, second, and third phalanges **112**, **114**, **116**, and their rolling surface joints **113**, **115**, and **117** (respectively), are illustrated in FIGS. **5A-5D** and **6**. Woven into the rolling surface joints and coupled to the phalanges is a first flexible printed circuit board (flexPCB) **118** which, in this implementation, is electrically and mechanically coupled to the yaw carriage **110** (as visible in FIG. **13A** and **13B**) and then woven through the rolling surface joints **113**, **115**, and **117** of the phalanges **112**, **114**, and **116**, and fixed to the third phalanx **116** (as visible in FIGS. **5A-5D**). The first flexPCB **118** also comprises a set of folding faces that cover the sides of the phalanges **112**, **114**, and **116**. More details of the first flexPCB **118**, the path of the first flexPCB **118**, and the mechanical and electrical couplings of the first flexPCB **118** are visible in FIGS. **5A**, **9A**, **9B**, **9C**, **10B**, and **10C**. The first flexPCB **118** may also include or electrically couple to a set of tactile sensors, which are not illustrated in FIGS. **1**, **2** and **3** but are illustrated in FIGS. **10B** and **10C**. Finally, a bottom cylinder **120** sits within the base (more detail visible in FIG. **6**).

[0050] As illustrated in FIG. **2**, an electrical connector port **202** may be provided that electrically connects to flexPCB **118** and allows flexPCB **118** to be electrically coupled to a palm or similar robotic structure. The electrical connector port **202** is held in place by a retaining piece **204** fixed to the bottom plate **111** to which the yaw carriage **110** is rotatably coupled at pin joint **206**.

Furthermore, in the illustrated implementation base **102** comprises a fluid manifold (e.g., a hydraulic manifold) including a volume that contains at least respective portions of the right cylinder **104a**, the left cylinder **104b**, and the bottom cylinder **120** and fluid ports and/or valves for the three cylinders: a bottom cylinder fluid port **208** that provides a fluidly communicative path from a source of pressurized fluid (e.g., hydraulic or pneumatic fluid) to bottom cylinder **120** (FIG. **6**), a right cylinder fluid port **210a** that provides a fluidly communicative path from a source of pressurized fluid (which may be the same source of pressurized fluid that is fluidly communicatively coupled to bottom cylinder **120** by port **208**, or which may be a separate source of pressurized fluid) to right cylinder **104a** (FIG. **7**), and a left cylinder fluid port **210b** that provides a fluidly communicative path from a source (again, a same source or a different source) of pressurized fluid to left cylinder **104b** (FIG. **7**). One or more hydraulic or pneumatic fluid conduit(s) may be coupled to the fluid ports **208**, **210a**, **210b** in order to supply varying pressures of a hydraulic or pneumatic fluid to control a position of pistons within the respective cylinders **120**, **104a**, **104b**.

[0051] As noted above, FIG. **3** shows the robotic mechanical digit **100** in a full curl and pitch down pose **300**. FIG. **3** also clearly shows a right spherical or ball joint **304a** coupling the right piston rod **106a** to the right pitch-yaw linkage **108a** and a left spherical or ball joint **304b** coupling the left piston rod **106b** to the left pitch-yaw linkage **108b**. Right spherical or ball joint **304a** is directly attached to right piston rod **106a** and left spherical or ball joint **304b** is directly attached to left piston rod **106b**. Also visible due to the curled pose are a first knuckle **306a** and a second knuckle **306b**, both of which protrude in order to, when covered by a stretchable artificial skin layer, simulate the external shape of a human knuckle bone. More details of the mechanics of the first and second knuckles **306a**, **306b** are illustrated in FIG. **5C**, FIG. **5D**, and FIG. **6**.

[0052] In FIG. **3**, robotic mechanical digit **100** is in a fully pitched down pose, meaning that the first phalanx **112** has pitched forward (e.g., counterclockwise around a “pitch axis” or x-axis in the view of FIG. **3**) such that its longitudinal axis points in a direction of a z-axis. This is caused by a simultaneous actuation of a right and left piston **106a**, **106b** sitting within the right and left

cylinders **104a**, **104b**. This action is further illustrated in FIGS. **9A**, **9B**, and **9C**. Similarly, the curling of the second and third phalanges **114**, **116** in this pose is due to the actuation of a bottom piston **604** within the bottom cylinder **120** as illustrated in FIG. **6**.

[0053] FIG. **4A** shows robotic mechanical digit **100** in the straight or neutral pose. Shown by broken lines are a first plane **402**, a second plane **404**, a third plane **406**, and a fourth plane **408**, all parallel to a yz-plane. The planes **402**, **404**, **406**, and **408** are at different depths from the left side (per the view of FIG. **4A**) of robotic mechanical digit **100** and a left section view at each of planes **402**, **404**, **406**, and **408** is shown in FIGS. **5A**, **5B**, **5C**, and **5D**, respectively. The fourth plane **408** is positioned at the center of mechanical digit **100** and a left section view at this plane is also shown in FIG. **6**. Similarly, a fifth plane **410** is shown by a broken line, and is also parallel to the yz-plane. The fifth plane **410** is positioned such that a center of the left cylinder **104b** sits on said plane. A left section view at the fifth plane **410** is shown in FIGS. **9A**, **9B**, and **9C**.

[0054] FIG. **4B** shows robotic mechanical digit **100** in the straight or neutral pose. Shown by a broken line is a sixth plane **412** parallel to the yx-plane and positioned such that respective centers of both the right cylinder **104a** and left cylinder **104b** are on the sixth plane **412**. Cross sectional views at the sixth plane **412** are shown in FIGS. **7** and **8**.

[0055] FIGS. **5A**, **5B**, **5C**, and **5D** show robotic mechanical digit **100** with section cuts at planes **402**, **404**, **406**, and **408** respectively. Visible in FIGS. **5A**, **5B**, **5C**, and **5D** are a set of rolling surfaces **501a**, **501b**, **501c**, **501d**, **501e**, **501f** (collectively either **501a-501f** or **501**), a first phalanx body **502**, a second phalanx body **504**, and a third phalanx body **506**, a set of phalangeal gears **507a**, **507b**, **507c**, **507d**, **507e**, **507f** (collectively either **507a-507f** or **507**), a first phalanx link **508**, a second phalanx link **510**, a first curl link **511**, a second curl link **512**, a set of pin joints **514a-j**, a first curl gear **516a**, and a second curl gear **516b**. Each of the phalanx bodies **502**, **504**, and **506**, the links **508**, **510**, **511**, and **512**, and each of the gears **516a** and **516b** is symmetrical across the yz-plane, and all features and connections described in FIGS. **5A**, **5B**, **5C**, and **5D** are also present on a right side of mechanical digit **100**.

[0056] As visible in FIG. **5A**, the flexPCB **118** (illustrated in FIGS. **5A**, **5B**, **5C**, and **5D** with a thick black line; for a planar view of the unfolded PCB, see FIGS. **10B** and **10C**) is coupled to the yaw carrier **110** at one end, threads between rolling surfaces **501a** and **501b** to a top of the first phalanx body **502**, threads between rolling surfaces **501c** and **501d** to a bottom of the second phalanx body **504**, threads between rolling surfaces **501e** and **501f** to a top of the third phalanx body **506**, wraps around a tip of the third phalanx body **506** and is fixed to the third phalanx body **506** at a bottom thereof. The rolling surfaces **501a** and **501b** form the first rolling surface joint **113**, the rolling surfaces **501c** and **501d** form the second rolling surface joint **115**, and rolling surfaces **501e** and **501f** form the third rolling surface joint **117**. The flexPCB **118** also includes paneling or wings that wraps or wrap around the sides of the first, second, and third phalanges. The paneling or wings are illustrated in FIGS. **10B** and **10C**.

[0057] The pin joint **514a** rotatably couples together the right and left pitch-yaw linkages **108a**, **108b**, the first curl gear **516a**, and the yaw carriage **110**. The pin joint **514b** rotatably couples together the right and left pitch-yaw linkages **108a**, **108b**, the second curl gear **516b**, and the first phalanx body **502**. The pin joint **514c** rotatably couples together the second curl gear **516b** and the first phalanx link **508**. The pin joint **514d** rotatably couples together the first curl link **511** and the first phalanx link **508**. The pin joint **514e** rotatably couples together the first curl link **511** and the first phalanx body **502**. The pin joint **514f** rotatably couples together the second phalanx link **510** and the first curl link **511**. The pin joint **514g** rotatably couples together the second phalanx body **504** and the first curl link **511**. The pin joint **514h** rotatably couples together the second phalanx link **510** and the second curl link **512**. The pin joint **514i** rotatably couples together the second phalanx body **504** and the second curl link **512**. The pin joint **514j** rotatably couples together the third phalanx body **506** and the second curl link **512**.

[0058] The rolling surfaces **501a**, **501b**, **501c**, **501d**, **501e**, and **501f** each have respective profiles

defined by arcs centered on pin joints **514a**, **514b**, **514e**, **514g**, **514i**, and **514j** respectively. Rolling surfaces **501a** and **501b**, rolling surfaces **501c** and **501d**, and rolling surfaces **501e** and **501f**, form respective pairs of rolling surfaces having, for example, equal radii. In the illustrated implementations, the radii are equal to half of the distance between their centers less a thickness of the flexPCB **118** such that, with the flexPCB **118** between them, the rolling surfaces can roll against one another without slippage or a change in length of the flexPCB **118**. Spaced inwardly from each of the rolling surfaces **501a**-**501f** is a respective phalangeal gear **507a**-**507f** centered at a respective pin joint. Phalangeal gears **507a** and **507b**, **507c** and **507d**, and **507e** and **507f** form respective pairs of gears having, for example, equal pitch circle radii and pitches, and each pair of gears is engaged with one another. Similarly, the first curl gear **516a** and the second curl gear **516b** have, for example, equal pitch circle radii and pitches, and are engaged with one another. Due to all of the above mechanical couplings, when the first curl gear is actuated such that it rotates clockwise (from the point of view of the left section view of FIGS. 5A, 5B, 5C, and 5D), the linkage created by the variety of links and gears curls the second and third phalange bodies **504**, **506** counterclockwise around the x-axis. This actuation is functional regardless of the pitch of the first phalanx body **502** (as visible in FIGS. 9A, 9B, and 9C) due to the freedom of the second curl gear **516b** to orbit around the first curl gear **516a** without rotating relative to the first phalanx body **502**.

[0059] FIG. 6 shows a sectional view along fourth plane **408** from FIG. 4A of robotic mechanical digit **100** in a fully curled, pitch-down pose. Visible in FIG. 6 are a back of the bottom cylinder **602**, a bottom piston **604** slidably received by the bottom cylinder **602** for translation along a translation axis, and a set of O-Ring seals **606**. Also shown are a bottom piston rod **608** directly coupled at a first end to the bottom piston **604** by a first spherical or ball joint **610a** and at a second end to the first curl gear **509a** by a second spherical or ball joint **610b**, a spring **612** which sits within the bottom cylinder **120** and pushes on the bottom piston **604**, and a bleed port **614**. Illustrated as a dark arrow is the movement of a hydraulic fluid **616** (e.g., an oil, such as mineral oil or peanut oil) from an external source through the bottom port **208** into a back of the bottom cylinder **602**. This fluid movement **616** applies a pressure on the bottom piston **604** and, assuming the pressure is greater than that applied by the spring **612** causes the bottom piston **604** to move within the bottom cylinder **120**, pushing the bottom piston rod **608** forwards, causing the first curl gear **509a** to rotate around its pin joint **514a**, and actuating the rest of the curl mechanism as described above. When the movement of the fluid **616** is relieved, reversed, or otherwise changed, the force applied by the spring **612** may be sufficient to move the bottom piston **604** backwards into the cylinder **120**, causing the curl mechanism to reverse. This reversed movement straightens the second and third phalanges **504**, **506** with respect to the first phalanx **502**. Due to the spherical or ball joints **610a**, **610b** at both connections of the bottom piston rod **608**, this actuation is capable of proceeding regardless of the rotation of the yaw carriage **110** around the z-axis. While illustrated using a spring **612**, some implementations may have ports to provide pressurized fluid at both a front and the back of the bottom cylinder **120**, allowing omission of the spring **612**, but somewhat complicating the overall structure and operation. The ports (e.g., **208**, **614**) may each have one or more valves associated therewith, for instance active valves that can be operated to selectively pass or block a passage of fluid therethrough, and/or passive valves, for instance check valves. The valve(s) may be positioned at the port(s) or remotely therefrom.

[0060] FIG. 7 shows a sectional view along sixth plane **412** from FIG. 4B of robotic mechanical digit **100** in the straight or neutral pose. Visible in FIG. 7 are a back of the right cylinder **702a**, a right piston **704a** slidably received by the right cylinder **702a** for translation along a first translation axis, a set of right O-Ring seals **706a**, the right piston rod **106a** directly coupled at a first end to right piston **704a** by a first right spherical or ball joint **708a** and at a second end to the right pitch-yaw linkage **108a** by a second right spherical or ball joint **710a**, a right spring **712a** which sits within the right cylinder **104a** and pushes on the right piston **704a**, a back of the left cylinder **702b**,

a left piston **704b** slidably received by the left cylinder **702b** for translation along a second translation axis, a set of left O-Ring seals **706b**, the left piston rod **106b** directly coupled at a first end to the left piston **704b** by a first left spherical or ball joint **708b** and at a second end to the left pitch-yaw linkage **108b** by a second left or ball spherical joint **710b**, and a left spring **712b** which sits within the left cylinder **104b** and pushes on the left piston **704b**. Due to the spherical or ball joints on both sides of each of the right and left piston rods **106a**, **106b**, this actuation is capable of proceeding regardless of the rotation of the yaw carriage **110** around the z-axis. While illustrated using a spring **712a**, **712b**, some implementations may have ports to provide pressurized fluid at both a front and the back of the right and/or left cylinders **702a**, **702b**, allowing omission of the spring, but somewhat complicating the overall structure and operation. The ports may each have one or more valves associated therewith, for instance active valves that can be operated to selectively pass or block a passage of fluid therethrough, and/or passive valves, for instance check valves. The valve(s) may be positioned at the port(s) or remotely therefrom.

[0061] FIG. **8** shows the sectional view along sixth plane **412** from FIG. **7** with portions of robotic mechanical digit **100** rotated counterclockwise about a yaw (or “z”) axis. This pose is actuated by a right fluid movement **802** (illustrated by a thick black arrow) moving from an external fluid reservoir through right fluid port **210a** and into the back of the right cylinder **702a**, and a left fluid movement **804** (illustrated by a thick black arrow) being expelled to an external fluid reservoir through left fluid port **210b**. Fluid movements **802** and **804** cause equal but opposite movements of the left and right pistons **704a** and **704b** causing a rotation of the yaw carriage **110** (and the attached robotic digit) around the pin joint **206**. The external fluid reservoir may comprise a source of fluid (e.g., liquid; gas), which may be pressurized, for instance via a compressor. One or more valves can be operated to control a flow, and direction of flow, of fluids.

[0062] FIGS. **9A**, **9B**, and **9C** show respective sectional views along fifth plane **410** from FIG. **4A** of various configurations of robotic mechanical digit **100**. In FIG. **9A**, robotic mechanical digit **100** is in a neutral pose, for instance at a neutral or default rotational position about a pitch axes. In FIG. **9B**, robotic mechanical digit **100** is in a pitched-up pose, for instance rotated counterclockwise about the pitch axis in relation to the view of FIG. **9B**. In FIG. **9C**, the robotic mechanical digit **100** is in a pitched-down pose, for instance rotated clockwise about the pitch axis in relation to the view of FIG. **9C**.

[0063] FIGS. **9A**, **9B**, and **9C** also illustrate a left bleed port **902b**, a first left connective strip **904b** of the flexPCB **118** that travels between a first left flexPCB rolling surface **906a** and a second left flexPCB rolling surface **906b**.

[0064] As noted, robotic mechanical digit **100** is illustrated in a pitched-up pose in FIG. **9B** relative to the neutral pose illustrated in FIG. **9A**. The upward pitch results from (a) a fluid movement **908** out of the back of the left cylinder **702b** through the left fluid port **210b**, causing the left piston **704b** to be pulled backwards (and/or pushed backwards by spring **712b**) in a negative direction along the y-axis, which, due to the spherical or ball joints **708b**, **710b** coupling the left piston **704b** to the left pitch-yaw linkage **108b**, rotates the left pitch-yaw linkage **108b** around pin joint **514a** which in turn causes the orbit of the first phalanx **112** around the pin joint **514a** and (b) an identical fluid movement in the right cylinder (not shown in FIG. **9B**).

[0065] Also as noted, robotic mechanical digit **100** is illustrated in a pitched-down pose in FIG. **9C** relative to the neutral pose illustrated in FIG. **9A**. The downward pitch results from (a) a fluid movement **910** into the back of the left cylinder **702b** through the left fluid port **210b**, causing the left piston **704b** to be pushed forwards in a positive direction along the y-axis, which, due to the spherical or ball joints **708b**, **710b** coupling the left piston **704b** to the left pitch-yaw linkage **108b**, rotates the left pitch-yaw linkage **108b** around pin joint **514a** which in turn causes the orbit of the first phalanx **112** around the pin joint **514a** and (b) an identical fluid movement in the right cylinder (not shown in FIG. **9C**).

[0066] As illustrated in FIGS. **9A**, **9B**, and **9C**, the first left connective strip **904b** travels between

the yaw carriage **110** and the first phalanx **112** by extending between the first left flexPCB rolling surface **906a** and the second left flexPCB rolling surface **906b**, and transferring from one to the other through the change in pose. The first left connective strip **904b** may be made of an easily bendable material, although not necessarily stretchable, for instance polyimide. The geometries and/or surface curvatures of the rolling surfaces **906a**, **906b** are compatibly designed such that there is no length change in the path the first left connective strip **904b** takes when the first phalanx **112** shifts into and between the neutral pose of FIG. 9A, the pitched-up pose of FIG. 9B, and the pitched-down pose of FIG. 9C. Thus, the first left connective strip **904b** advantageously does not experience any high longitudinal stress that may cause damage to the strip **904b**, and only experiences a bending stress, which the bendable nature of the connective strip **904b** is generally more able to accommodate without breaking.

[0067] FIG. 10A shows a robotic mechanical digit **1000** in a straight or neutral pose and without a membrane or artificial skin in accordance with the present systems, devices, and methods. Mechanical digit **1000** of FIG. 10A is substantially similar to mechanical digit **100** with the flexPCB **118** removed or omitted.

[0068] FIG. 10B shows a first side **1001a** of a flattened flexPCB **1001** that may be used, for example, as flexPCB **118** in mechanical digit **100**. FIG. 10C shows a second side **1001b** of the flattened flexPCB **1001** of FIG. 10A, the second side opposite the first side. The flexPCB **1001** can attach to and be routed through the various pieces of mechanical digit **1000** to produce robotic mechanical digit **100**, such as the flexPCB **118**.

[0069] The flexPCB **1001** comprises the following, as shown in FIGS. 10B and 10C: a set of connective strips (collectively **904**) comprising a first right connective strip **904a**, a first left connective strip **904b**, a second right connective strip **904c**, a second left connective strip **904d**, a third right connective strip **904e**, and a third left connective strip **904f**. The first left and right connective strips **904a** and **904b** each connect (e.g., physically couple) at a first end of a first phalanx panel or wing **1002**; the second left and right connective strips **904c** and **904d** each connect (e.g., physically couple) at and between a second end of the first phalanx panel or wing **1002** and a first end of a second phalanx panel or wing **1004**; and the third left and right connective strips **904e** and **904f** each connect (e.g., physically couple) at and between a second end of the second phalanx panel or wing **1004** and a first end of a third phalanx panel or wing **1006**. The connective strips **904** all carry power and communicative electrical lines to/from/between the various panels or wings **1002**, **1004**, **1006**. Each of the phalanx panels or wings **1002**, **1004**, **1006** comprises a respective set of sub panels or sub-wings that, when folded around the edges of their respective digit phalanx (e.g., **112**, **114**, **116**), cover the majority of the external surface area of the phalanx. Each of the phalanx panels or wings **1002**, **1004**, **1006** carries a plurality of tactile, force, or pressure sensors **1008** (only a few of which are indicated in the figures to reduce clutter). These sensors **1008** may be of a variety of sizes to achieve different tactile sensor densities at different parts of the digit **1000**. Due to the fact that the connective strips **904** move through the inter-phalanx joints (as described in previous figures), the placement of the sensors **1008** alternates between the first side **1001a** and the second side **1001b** in order to always be pointing outwards on the surface of the digit **1000**. The plurality of sensors **1008** electrically couple (optionally through an integrated circuit or microcontroller) to the electrical lines carried by the connective strips **904**, which terminate at a set of connector pads **1010a** and **1010b** on which sit a set of mechanical and electrical couplers **1012a** and **1012b** respectively.

[0070] FIG. 11A shows robotic mechanical digit **100** in a pitched-down pose actuated by an extension (outward travel from a neutral position) of both the right and left pistons **106a**, **106b** in accordance with the present systems, devices, and methods. FIG. 11B shows robotic mechanical digit **100** in a pitched-up pose actuated by a retraction (inward travel from a neutral position) of the both right and left pistons **106a**, **106b** in accordance with the present systems, devices, and methods. Rotation about the pitch axis without rotation about the yaw axis is actuated by

concurrent movements of the right piston **106a** along its translation axis and the left piston **106b** along its translation axis that are equal in speed, magnitude and direction with respect to one another along their respective translation axes. Conversely, rotation about the yaw axis with a rotation about the pitch axis is actuated by movements of right piston **106a** along its translation axis and left piston **106b** along its translation axis that are at least one of: not concurrent, not matched in speed, or not matched in magnitude, along their respective translation axes.

[0071] FIG. **12A** shows robotic mechanical digit **100** in a yaw-right pose actuated by an extension (outward travel from a neutral position) of the left piston **106b** and a retraction (inward travel from a neutral position) of the right piston **106a** in accordance with the present systems, devices, and methods. FIG. **12B** shows robotic mechanical digit **100** in a yaw-left pose actuated by an extension (outward travel from a neutral position) of the right piston **106a** and a retraction (inward travel from a neutral position) of the left piston **106b** in accordance with the present systems, devices, and methods. Rotation about the yaw axis without rotation about the pitch axis is actuated by concurrent movements of the right piston **106a** along its translation axis and the left piston **106b** along its translation axis that are equal in speed and magnitude but opposite in direction with respect to one another along their respective translation axes.

[0072] FIG. **12C** shows robotic mechanical digit **100** in a curled pose actuated by an extension (outward travel from a neutral position) of the bottom piston **604** in accordance with the present systems, devices, and methods.

[0073] FIG. **13A** shows a first portion of robotic mechanical digit **100**; FIG. **13B** shows a second portion of robotic mechanical digit **100**.

[0074] As illustrated in FIGS. **13A** and **13B**, the first right connection strip **904a** couples mechanically and electrically through the connector pad **1010a** to a right yaw carriage PCB **1302a** which extends around the yaw carriage **110** through a connection strip **1308** to a left yaw carriage PCB, not visible in the figures but similar in design to the right yaw carriage PCB **1302a** and coupling to the first left connection strip **904b**. Also coupled to the right yaw carriage PCB **1302a** is a yaw slack strip **1306** through a connector pad **1304**. The yaw slack strip **1306** carries power and communication for the flexPCB **118** and is sufficiently flexible to not break through the yaw motion of the yaw carriage **110**. The yaw slack strip **1306** terminates at the electrical connector port **202**, visible in FIG. **2**.

[0075] FIG. **14** shows a robotic mechanical hand **1400** comprised of a set of four (4) robotic mechanical digits in the form of mechanical fingers **1402**, **1404**, **1406**, and **1408** coupled to a palm **1410**. The robotic mechanical hand **1400** may also comprise a fifth mechanical digit in the form of a robotic mechanical thumb **1412** also coupled to the palm **1410**. The robotic mechanical thumb **1412** may be positioned and operable to be opposed to one or more of mechanical fingers **1402**, **1404**, **1406**, and **1408** to allow a pinching or grasping pose to be realized. The set of four robotic mechanical fingers may be of different sizes or of the same size as one another. There may be more or fewer such robotic mechanical fingers coupled to the palm **1410** to form such a robotic mechanical hand **1400**. Any or all of robotic mechanical fingers **1402**, **1404**, **1406**, and/or **1408** may be substantially similar to mechanical digit **100** as described throughout the present systems, devices, and methods.

[0076] While the embodiments illustrated and described in the above description comprise gear systems, linkages, and hydraulic pistons, these subsystems may be replaced by cables, compliant mechanisms, and/or rolling membrane pistons without significant changes to the operations and functionality of the embodiments, as those skilled in the relevant art will recognize.

[0077] The above description of illustrated embodiments, including what is described in the Abstract, is not intended to be exhaustive or to limit the embodiments to the precise forms disclosed. Although specific embodiments of and examples are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the disclosure, as will be recognized by those skilled in the relevant art.

[0078] For instance, the foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, schematics, and examples. Insofar as such block diagrams, schematics, and examples contain one or more functions and/or operations, it will be understood by those skilled in the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. In one embodiment, the present subject matter may be implemented via Application Specific Integrated Circuits (ASICs). However, those skilled in the art will recognize that the embodiments disclosed herein, in whole or in part, can be equivalently implemented in standard integrated circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more controllers (e.g., microcontrollers) as one or more programs running on one or more processors (e.g., microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of ordinary skill in the art in light of this disclosure.

[0079] In addition, those skilled in the art will appreciate that control mechanisms taught herein for controlling a robotic member are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment applies equally regardless of the particular type of signal bearing media used to actually carry out the distribution. Examples of signal bearing media include, but are not limited to, the following: recordable type media such as floppy disks, hard disk drives, CD ROMs, digital tape, and computer memory; and transmission type media such as digital and analog communication links using TDM or IP based communication links (e.g., packet links).

[0080] The various embodiments described above can be combined to provide further embodiments. To the extent that they are not inconsistent with the specific teachings and definitions herein, all of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, including but not limited to U.S. patent application Ser. No. 62/937,044 and U.S. provisional patent application Ser. No. 63/086,258 (404P1), with the present disclosure are incorporated herein by reference, in their entirety. Aspects of the embodiments can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments.

[0081] These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

Claims

1. A mechanical digit comprising: a carriage member supported for movement about a first axis; a first phalanx coupled to the carriage member and rotatable relative to the carriage member about a second axis transverse to the first axis; a first actuator having a first actuator output; a second actuator having a second actuator output; a first linkage having a first connection area coupled to the first actuator output, a second connection area coupled to the carriage member, and a third connection area coupled to the first phalanx; and a second linkage having a first connection area coupled to the second actuator output, a second connection area coupled to the carriage member, and a third connection area coupled to the first phalanx; wherein a difference in operation of the first actuator and the second actuator causes rotation of the carriage member about the first axis, and wherein a sameness in operation of the first actuator and the second actuator causes rotation of the first phalanx about the second axis.

2. The mechanical digit of claim 1, further comprising a base, wherein the carriage member is coupled to the base and movable relative to the base about the first axis.
3. The mechanical digit of claim 2, wherein the first actuator and the second actuator are coupled to the base.
4. The mechanical digit of claim 1, wherein the first linkage and the second linkage are disposed on opposite sides of the carriage member.
5. The mechanical digit of claim 1, further comprising: a second phalanx coupled to the first phalanx and rotatable relative to the first phalanx about a third axis parallel to the second axis; and a third actuator having a third actuator output coupled to the first phalanx, wherein operation of the third actuator rotates the second phalanx about the third axis.
6. The mechanical digit of claim 5, wherein the third actuator output is coupled to the first phalanx through a plurality of gears comprising: a first curl gear pivotably coupled to the carriage member and the first and second linkages, wherein the third actuator is coupled to the first curl gear; and a second curl gear pivotably coupled to the first phalanx and the first and second linkages, wherein the second curl gear is engaged with the first curl gear.
7. The mechanical digit of claim 6, wherein the first curl gear and the second curl gear are pivotably coupled to the first linkage and the second linkage.
8. The mechanical digit of claim 5, further comprising: a third phalanx coupled to the second phalanx and rotatable relative to the second phalanx about a fourth axis parallel to the third axis, wherein rotation of the second phalanx about the third axis causes rotation of the third phalanx about the fourth axis.
9. The mechanical digit of claim 8, wherein the first phalanx is coupled to the second phalanx through a first rolling surface joint, and wherein the second phalanx is coupled to the third phalanx through a second rolling surface joint.
10. The mechanical digit of claim 5, wherein the first actuator, the second actuator, and the third actuator are fluid cylinders.
11. The mechanical digit of claim 1, wherein the first connection area of the first linkage is coupled to the first actuator output through a first spherical joint, and wherein the second connection area of the second linkage is coupled to the second actuator output through a second spherical joint.
12. The mechanical digit of claim 1, wherein the second connection areas of the first linkage and the second linkage are pivotably coupled to the carriage member, and wherein the third connection areas of the first linkage and the second linkage are pivotably coupled to the first phalanx.
13. The mechanical digit of claim 1, wherein the first actuator and the second actuator are arranged in parallel.
14. The mechanical digit of claim 1, wherein the second axis is orthogonal to the first axis.
15. A robotic end effector comprising: a palm; and at least one mechanical digit comprising: a carriage member supported for movement about a first axis; a first phalanx coupled to the carriage member and rotatable relative to the carriage member about a second axis transverse to the first axis; a first actuator having a first actuator output; a second actuator having a second actuator output; a first linkage having a first connection area coupled to the first actuator output, a second connection area coupled to the carriage member, and a third connection area coupled to the first phalanx; a second linkage having a first connection area coupled to the second actuator output, a second connection area coupled to the carriage member, and a third connection area coupled to the first phalanx, wherein the first linkage and the second linkage are disposed on opposite sides of the carriage member; wherein a difference in operation of the first actuator and the second actuator causes rotation of the carriage member about the first axis, and wherein a sameness in operation of the first actuator and the second actuator causes rotation of the first phalanx about the second axis.
16. The robotic end effector of claim 15, wherein the least one mechanical digit further comprises a base coupled to the palm, wherein the carriage member is coupled to the base and movable relative to the base about the first axis, and wherein the first actuator and the second actuator are coupled to the base.

- 17.** The robotic end effector of claim 15, wherein the at least one mechanical digit further comprises: a second phalanx coupled to the first phalanx and rotatable relative to the first phalanx about a third axis parallel to the second axis; and a third actuator having a third actuator output coupled to the first phalanx, wherein operation of the third actuator rotates the second phalanx about the third axis.
- 18.** The robotic end effector of claim 17, wherein the at least one mechanical digit further comprises a third phalanx coupled to the second phalanx and rotatable relative to the second phalanx about a fourth axis parallel to the third axis, and wherein rotation of the second phalanx about the third axis causes rotation of the third phalanx about the fourth axis.
- 19.** The robotic end effector of claim 18, wherein the first phalanx is coupled to the second phalanx through a first rolling surface joint, and wherein the second phalanx is coupled to the third phalanx through a second rolling surface joint.
- 20.** The robotic end effector of claim 15, wherein the second axis is orthogonal to the first axis.
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