US008857874B2

(12) **United States Patent**
Ihrke et al.

(10) **Patent No.: US 8,857,874 B2**
(45) **Date of Patent: Oct. 14, 2014**

(54) **ROBOTIC FINGER ASSEMBLY**

(71) Applicants: **GM Global Technology Operations, Inc.**, Detroit, MI (US); **The United States of America as Represented by the National Aeronautics and Space Administration**, Washington, DC (US)

(72) Inventors: **Chris A. Ihrke**, Hartland, MI (US); **Lyndon Bridgwater**, Houston, TX (US); **Myron A. Diftler**, Houston, TX (US); **Douglas Martin Linn**, White Lake, MI (US); **Robert J. Platt, Jr.**, Houston, TX (US); **Brian Hargrave**, Dickenson, TX (US); **Scott R. Askew**, Houston, TX (US); **Michael C. Valvo**, League City, TX (US)

(73) Assignee: **GM Global Technology Operations LLC**, Detroit, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/826,206**

(22) Filed: **Mar. 14, 2013**

(65) **Prior Publication Data**

US 2013/0193704 A1 Aug. 1, 2013

Related U.S. Application Data

(62) Division of application No. 12/564,078, filed on Sep. 22, 2009.

(51) **Int. Cl.**
B25J 15/10 (2006.01)

(52) **U.S. Cl.**
USPC **294/106**; 901/28; 901/31

(58) **Field of Classification Search**
USPC 294/106, 111; 414/5, 7; 623/24, 57, 64; 901/21, 27, 28, 29, 31, 39; 74/490.04, 74/490.05, 490.06
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,865,376	A *	9/1989	Leaver et al.	294/111
5,501,498	A *	3/1996	Ulrich	294/106
6,517,132	B2 *	2/2003	Matsuda et al.	294/106
6,817,641	B1 *	11/2004	Singleton, Jr.	294/106
7,222,904	B2 *	5/2007	Matsuda	294/111
8,276,958	B2 *	10/2012	Ihrke et al.	294/111
8,562,049	B2 *	10/2013	Ihrke et al.	294/106
2006/0033462	A1 *	2/2006	Moridaira	318/568.12

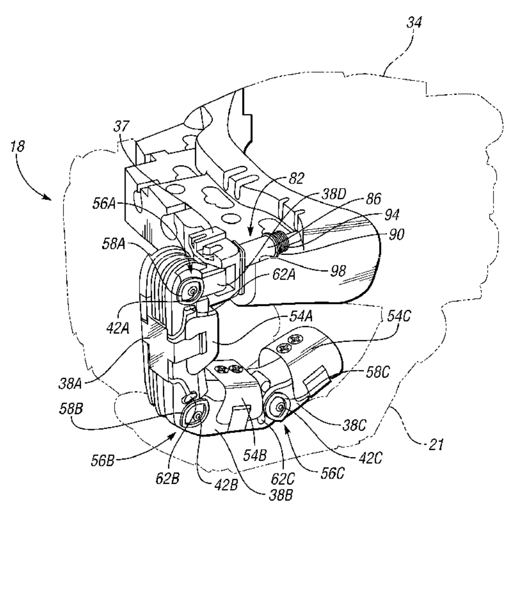
* cited by examiner

Primary Examiner — Paul T Chin
(74) *Attorney, Agent, or Firm* — Quinn Law Group, PLLC

(57) **ABSTRACT**

A robotic hand includes a finger with first, second, and third phalanges. A first joint rotatably connects the first phalange to a base structure. A second joint rotatably connects the first phalange to the second phalange. A third joint rotatably connects the third phalange to the second phalange. The second joint and the third joint are kinematically linked such that the position of the third phalange with respect to the second phalange is determined by the position of the second phalange with respect to the first phalange.

8 Claims, 10 Drawing Sheets



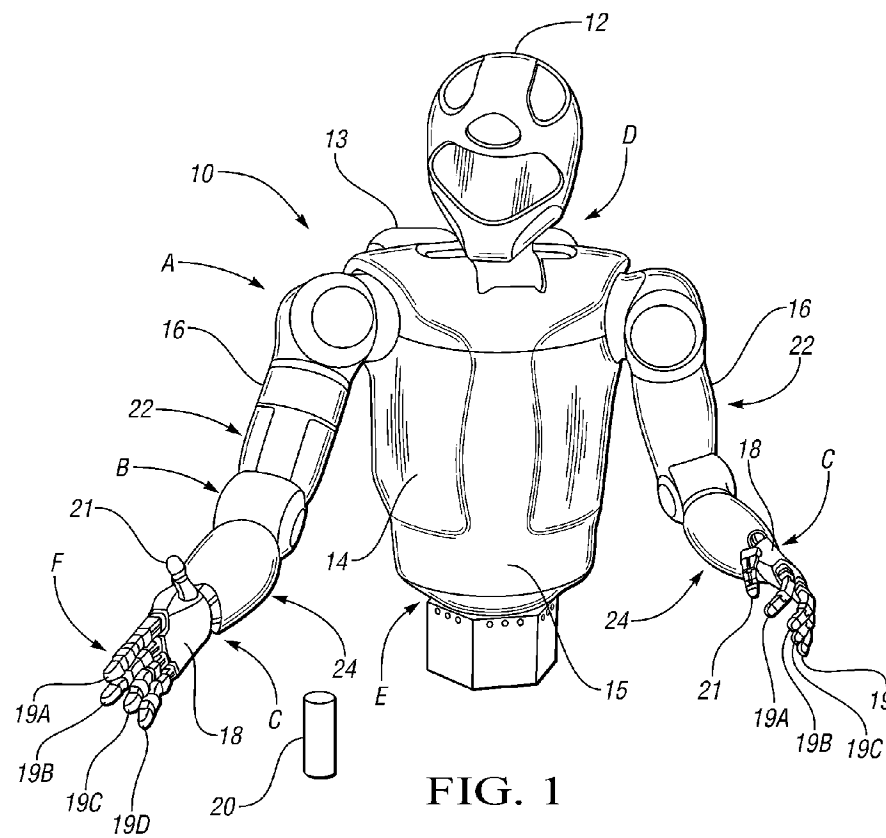

12
13
D
10
A
16
16
22
22
B
18
C
21
F
14
24
24
E
15
21
19A
19B
19C
19D
18
C
19A
19B
19C
19D
20

FIG. 1

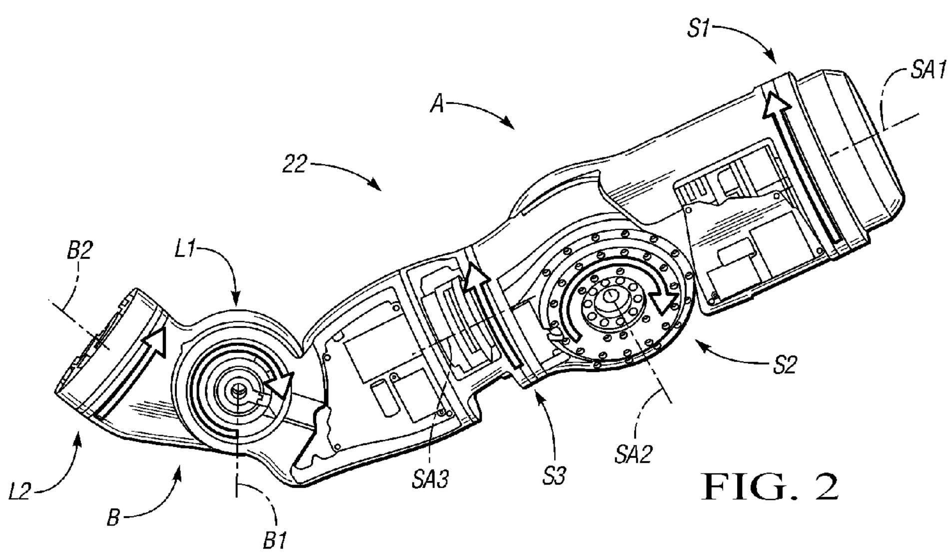

S1
SA1
A
22
B2
L1
S2
SA3
S3
SA2
L2
B
B1

FIG. 2

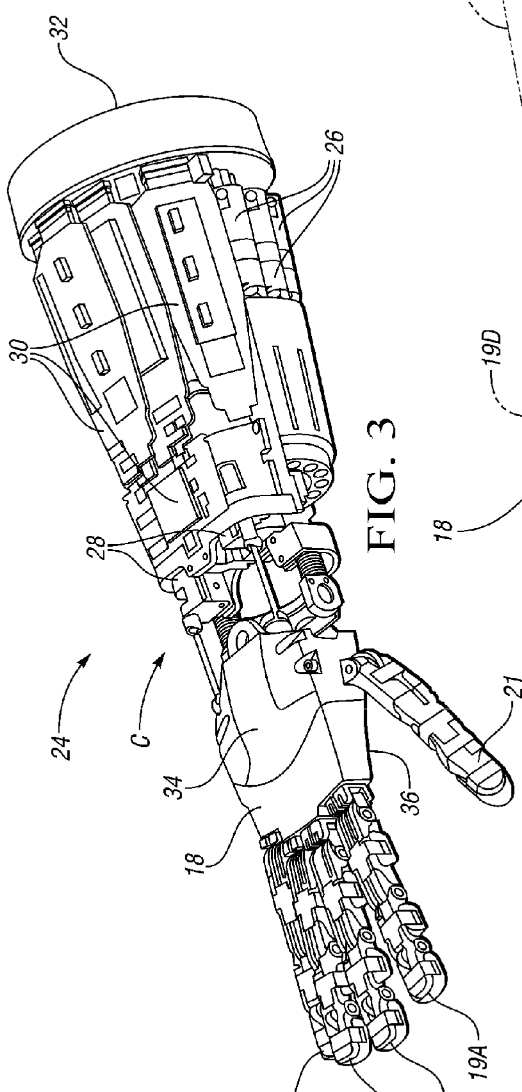

32
26
30
28
24
C
34
36
21
18
19D
19C
19B
19A

FIG. 3

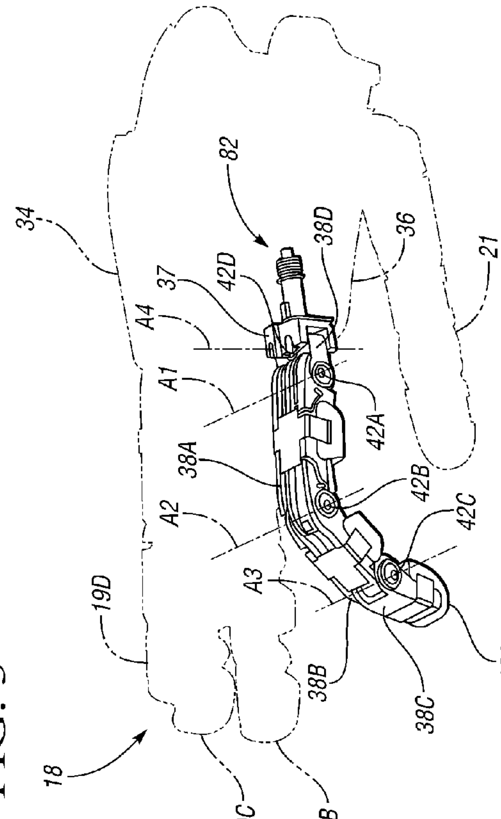

82
34
36
21
37
42D
38D
A4
A1
42A
38A
A2
42B
42C
A3
19D
38B
38C
19A
18
19C
19B

FIG. 4

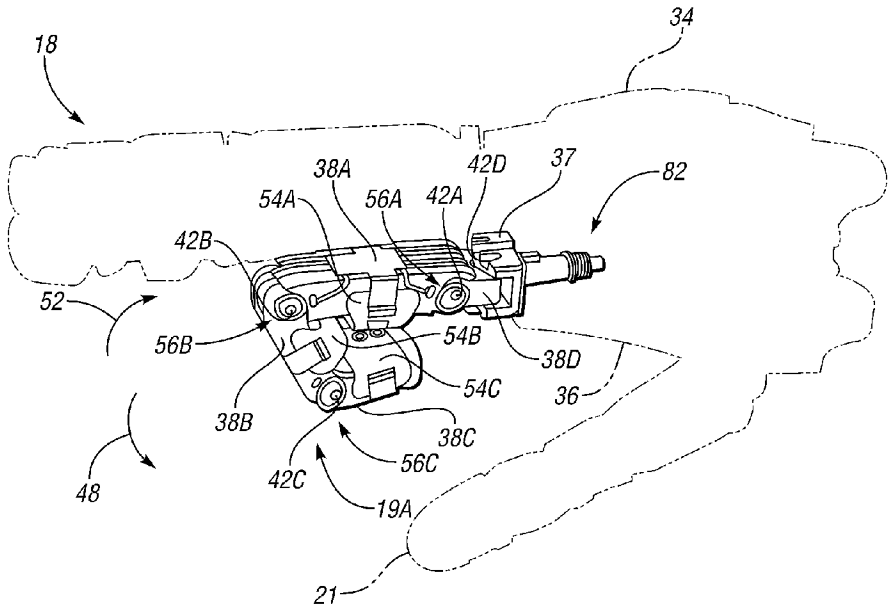

18
34
38A
42D
37
82
54A
56A
42A
42B
52
56B
54B
38D
54C
36
38B
38C
56C
42C
48
19A
21

FIG. 5

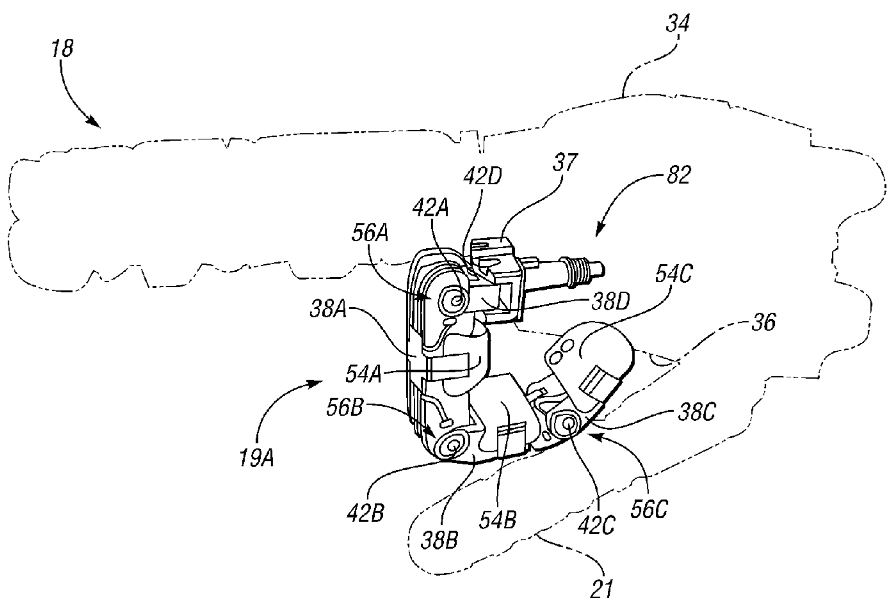

18
34
42D
37
82
42A
56A
54C
38D
38A
36
54A
19A
56B
38C
42B
38B
54B
42C
56C
21

FIG. 6

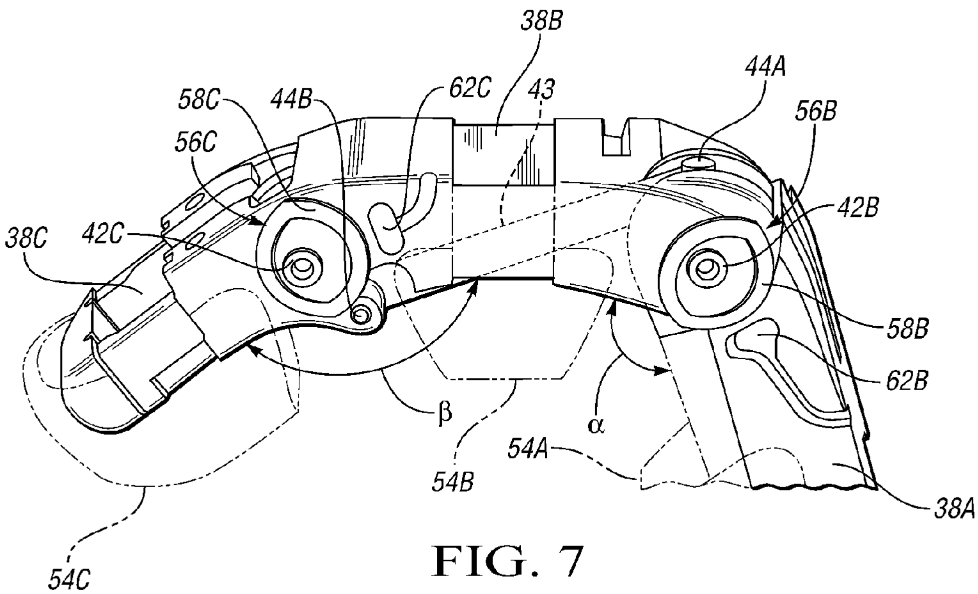

38B
44A
58C
44B
62C
43
56B
56C
42B
38C
42C
58B
62B
β
α
54A
54B
38A
54C

FIG. 7

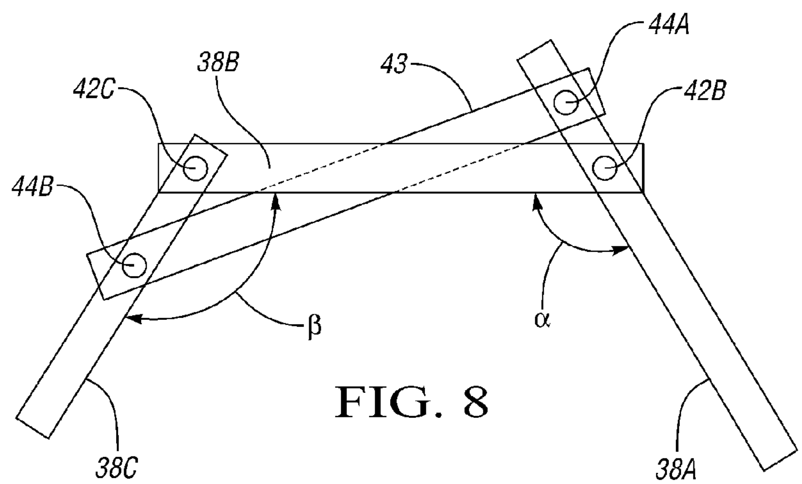

44A
42C
38B
43
42B
44B
β
α
38C
38A

FIG. 8

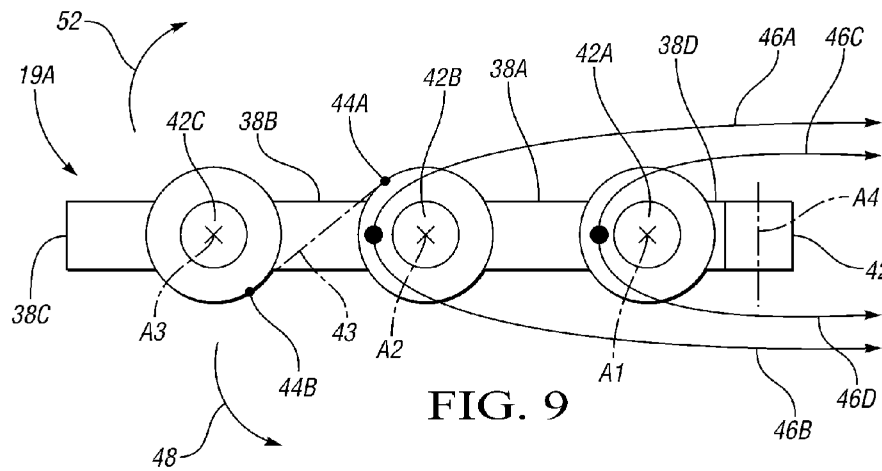

52
19A
42C
38B
44A
42B
38A
42A
38D
46A
46C
A4
42D
38C
A3
43
A2
A1
44B
46D
46B
48

FIG. 9

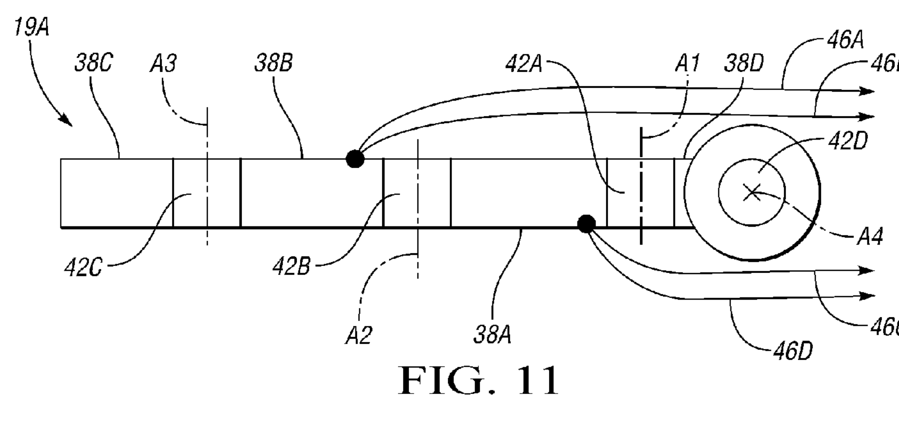

19A
38C
A3
38B
42A
A1
38D
46A
46B
42D
A4
42C
42B
A2
38A
46C
46D

FIG. 11

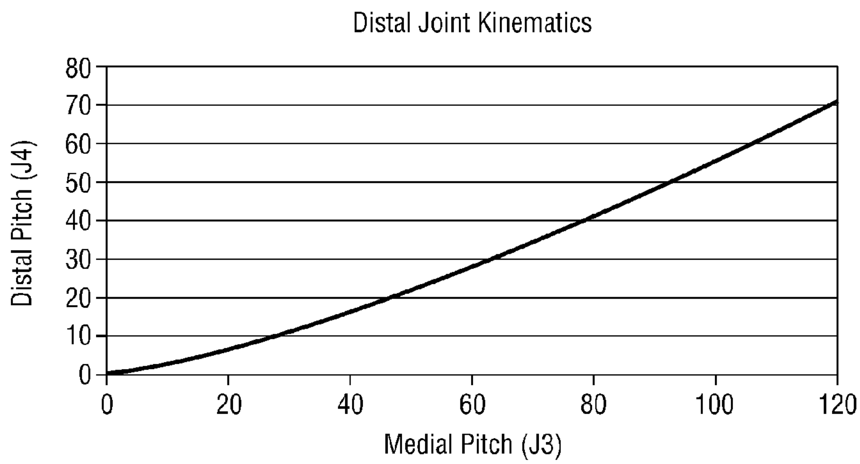

Distal Joint Kinematics
Distal Pitch (J4)
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Medial Pitch (J3)

FIG. 10

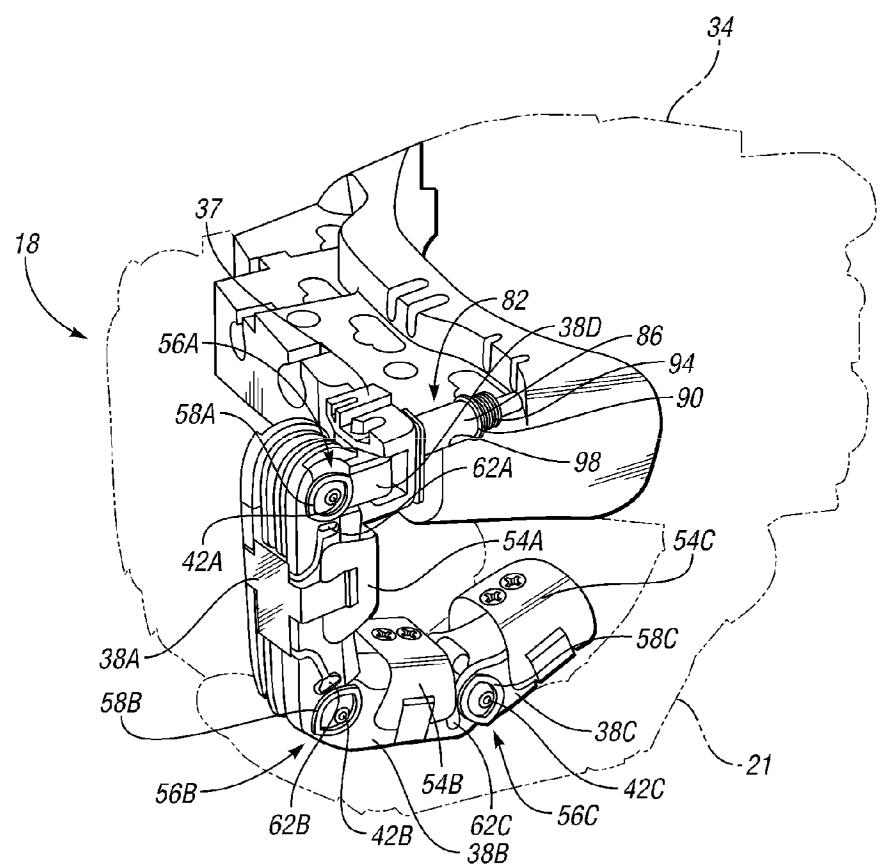

34
18
37
56A
58A
82
38D
86
94
90
98
62A
42A
54A
54C
38A
58C
58B
38C
21
56B
62B
42B
54B
62C
38B
56C
42C

FIG. 12

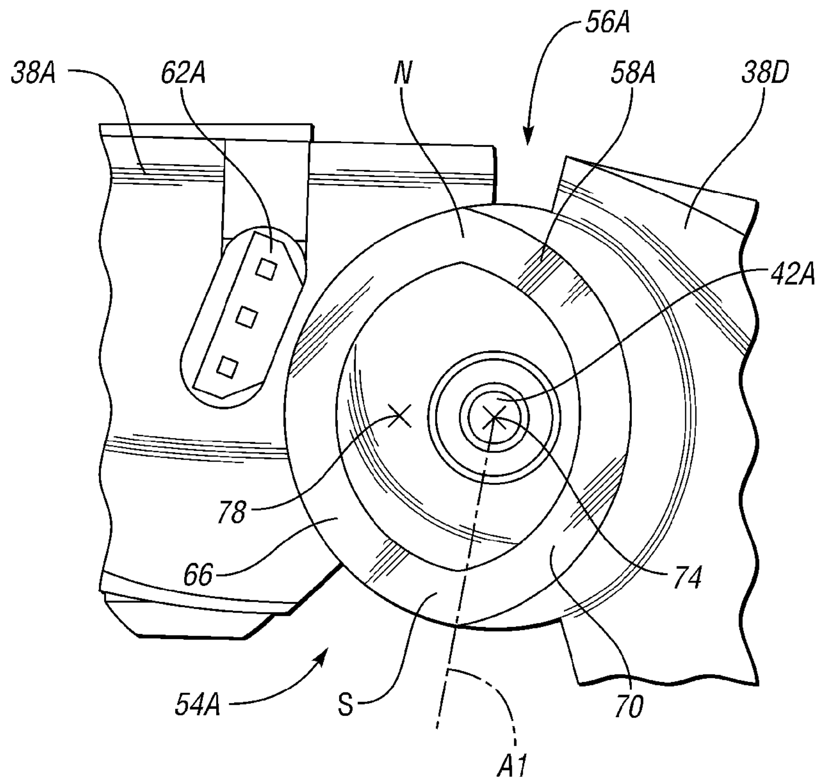


FIG. 13

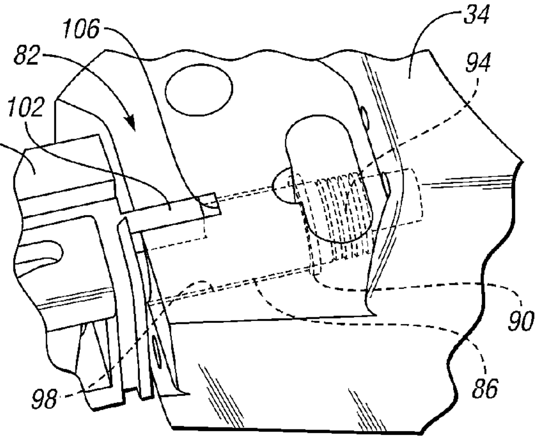


FIG. 14

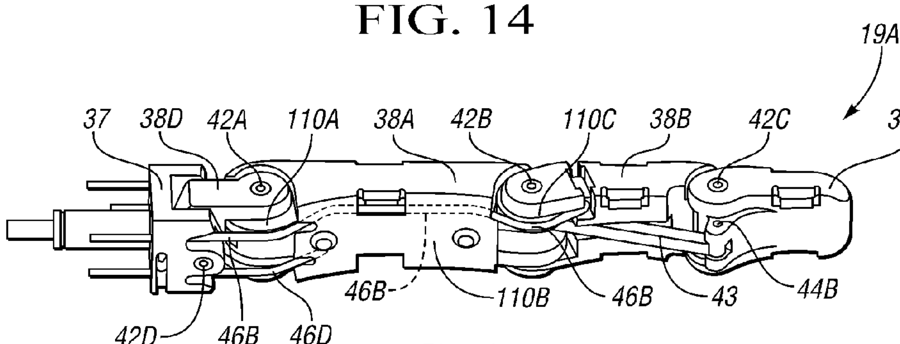


FIG. 15

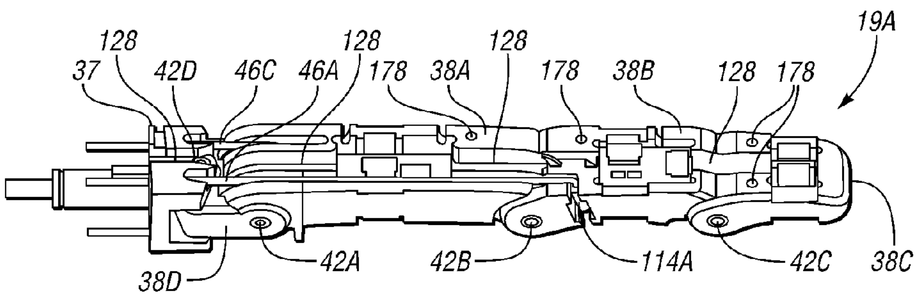


FIG. 16

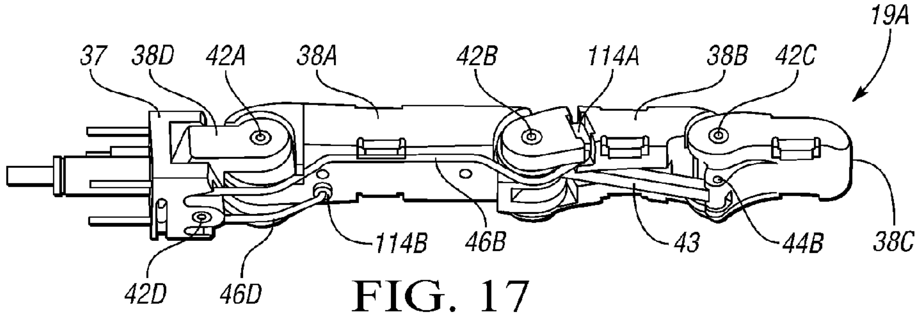


FIG. 17

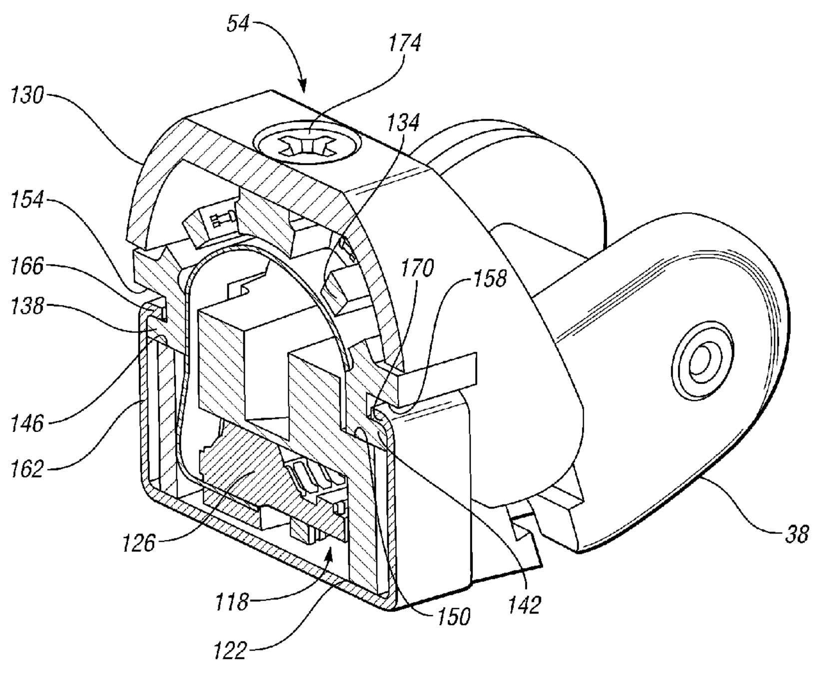


FIG. 18

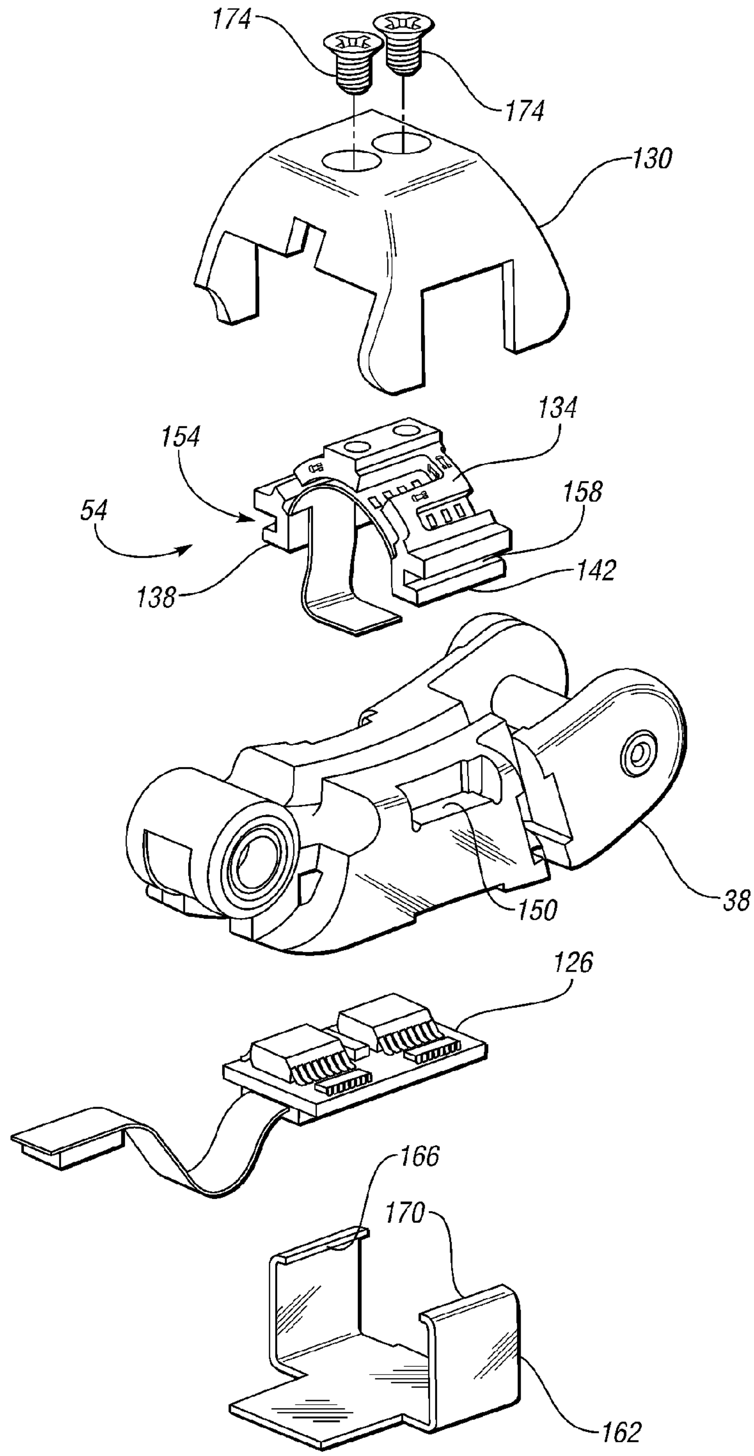


FIG. 19

ROBOTIC FINGER ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATION

This application is a divisional application of U.S. application Ser. No. 12/564,078, filed Sep. 22, 2009, and which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under NASA Space Act Agreement number SAA-AT-07-003. The government may have certain rights in the invention.

TECHNICAL FIELD

The present invention relates to robotic hands, and more particularly to robotic fingers.

BACKGROUND OF THE INVENTION

Typical robots are automated devices that are able to manipulate objects using a series of rigid links, which in turn are interconnected via articulations or motor-driven robotic joints. Each joint in a typical robot represents an independent control variable, also referred to as a degree of freedom (DOF). End-effectors are the particular links used for performing a task at hand, e.g., grasping a work tool or an object. Therefore, precise motion control of a robot may be organized by the level of task specification: object level control, i.e., the ability to control the behavior of an object held in a single or cooperative grasp of a robot, end-effector control, and joint level control. Collectively, the various control levels cooperate to achieve the required robotic mobility, dexterity, and work task-related functionality.

Humanoid robots in particular are robots having an approximately human structure or appearance, whether a full body, a torso, and/or an appendage, with the structural complexity of the humanoid robot being largely dependent upon the nature of the work task being performed. The use of humanoid robots may be preferred where direct interaction is required with devices or systems that are specifically made for human use. Due to the wide spectrum of work tasks that may be expected of a humanoid robot, different control modes may be simultaneously required. For example, precise control must be applied within the different spaces noted above, as well as control over the applied torque or force, motion, and the various grasp types.

SUMMARY OF THE INVENTION

A robotic hand assembly includes a base structure; a finger having first, second, and third phalanges; a first joint operatively connecting the first phalange to the base structure such that the first phalange is selectively rotatable with respect to the base structure about a first axis; a second joint operatively connecting the second phalange to the first phalange such that the second phalange is selectively rotatable with respect to the first phalange about a second axis; and a third joint operatively connecting the third phalange to the second phalange such that the third phalange is selectively rotatable with respect to the second phalange about a third axis.

The third joint is kinematically linked to the second joint such that the position of the third phalange with respect to the second phalange is determined by the position of the second phalange with respect to the first phalange. The kinematic linkage between the second and third joints replaces one of the degrees of freedom of a human finger while closely approximating the movement of a human finger.

The above features and advantages and other features and advantages of the present invention are readily apparent from the following detailed description of the best modes for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic perspective illustration of a dexterous humanoid robot having two hands;

FIG. **2** is a schematic perspective illustration of an upper arm for the dexterous humanoid robot of FIG. **1**;

FIG. **3** is a schematic perspective illustration of a lower arm for the dexterous humanoid robot of FIGS. **1** and **2**;

FIG. **4** is a schematic, perspective view of a finger of one of the hands of FIG. **1** in a first position;

FIG. **5** is a schematic, perspective view of the finger of FIG. **4** in a second position; and

FIG. **6** is a schematic, perspective view of the finger of FIGS. **4** and **5** in a third position;

FIG. **7** is a schematic, side view of a portion of the finger of FIG. **4**;

FIG. **8** is another schematic, side view of the portion of the finger of FIG. **7**;

FIG. **9** is a schematic, side view of the finger of FIG. **4** depicting tendon routing;

FIG. **10** is a graph depicting the position of one of the joints in the finger as a function of the position of another one of the joints in the finger;

FIG. **11** is a schematic, top view of the thumb of FIG. **4** depicting tendon routing;

FIG. **12** is a schematic, perspective view of the finger of FIG. **4** mounted to base structure by a shock mount;

FIG. **13** is a schematic, side view of a sensor assembly at a joint of the finger of FIG. **4**;

FIG. **14** is a schematic, perspective view of the shock mount of FIG. **12**;

FIG. **15** is another schematic, perspective view of the finger of FIG. **4**;

FIG. **16** is yet another schematic, perspective view of the finger of FIG. **4**;

FIG. **17** is yet another schematic, perspective view of the finger of FIG. **4**;

FIG. **18** is a schematic, perspective, cutaway view of a phalange and sensor assembly that is representative of the phalanges of the finger of FIG. **4**; and

FIG. **19** is a schematic, exploded view of the phalange and sensor assembly of FIG. **18**.

DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference to the drawings, wherein like reference numbers refer to the same or similar components throughout the several views, FIG. **1** shows a dexterous humanoid robot **10** adapted to perform one or more tasks with multiple degrees of freedom (DOF).

The humanoid robot **10** may include a head **12**, torso **14**, waist **15**, arms **16**, hands **18**, fingers **19**A-**19**D, and thumbs **21**, with various joints being disposed within or therebetween. The robot **10** may also include a task-suitable fixture or base (not shown) such as legs, treads, or another moveable or fixed base depending on the particular application or intended use of the robot. A power supply **13** may be integrally mounted to the robot **10**, e.g., a rechargeable battery pack carried or worn on the back of the torso **14** or another suitable energy supply.

According to one embodiment, the robot **10** is configured with a plurality of independently and interdependently-moveable robotic joints, such as but not limited to a shoulder joint assembly (arrow A), an elbow joint assembly (arrow B), a wrist joint assembly (arrow C), a neck joint assembly (arrow D), and a waist joint assembly (arrow E), as well as the various finger and thumb joint assemblies (arrow F) positioned between the phalanges of each robotic finger **19**A-**19**D and thumb **21**.

The arm **16** is divided into an upper arm **22** and a lower arm (or forearm) **24**. The upper arm **22** extends from the shoulder joint assembly (arrow A) to the elbow joint assembly (arrow B). Extending from the elbow joint (arrow B) is the lower arm **24**, hands **18**, fingers **19**, and thumbs **21**. For the purpose of simplification, as described herein, the upward direction is toward the head **12** and the downward direction is toward the waist **15**. Those skilled in the art will appreciate that since the robot **10** is intended to simulate a humanoid, the robot will be substantially symmetrical about a vertical plane bisecting the torso and head, and essentially include an identical symmetrical structure on both the left and right sides.

Referring to FIG. **2**, the upper arm **22** is illustrated. Although only one upper arm **22** for the arms **16** is shown, both the left and the right arms **16** operate in the same manner as described below. The upper arm **22** has a shoulder joint assembly (arrow A) that includes a first shoulder joint S**1** providing a first DOF, and second shoulder joint S**2** providing a second DOF, and a third shoulder joint S**3** providing a third degree of freedom. Together the first through third shoulder joints S**1**, S**2**, S**3** perform the movements that represent the movements a human shoulder can perform. Specifically, rotation of the first shoulder joint S**1** about a first shoulder axis SA**1** moves a second shoulder axis SA**2** for the second shoulder joint S**2** into a desired position. Based upon the position of the first shoulder joint S**1**, rotation of the second shoulder joint S**2** about the second shoulder axis SA**2** then moves the arm **16** up and down relative to the torso **14**, or forward and backward relative to the torso **14**. The third shoulder joint S**3** rotates the upper arm **22** about a third shoulder axis SA**3**. Rotation of the third shoulder joint S**3** rotates the upper arm **22** axially, i.e. rotation of the third shoulder joint S**3** rotates the elbow joint assembly (arrow B) to face upwards or downwards. Therefore, together the first shoulder joint S**1**, the second shoulder joint S**2**, and the third shoulder joint S**3** form the motions of a shoulder joint assembly (arrow A).

The upper arm **22** also includes an elbow joint assembly (arrow B) which includes a first elbow joint L**1** and a second elbow joint L**2**. The first elbow joint L**1** and second elbow joint L**2** each provide a degree of freedom. Together the first elbow joint L**1**, and the second elbow joint L**2** perform the movements that represent the movements a human elbow can perform. Rotation of the first elbow joint L**1** about a first elbow axis B**1** causes the upper arm **22**, below the elbow joint assembly (arrow B) to bend and straighten. Additionally, rotation of the second elbow joint L**2** about a second elbow axis B**2** causes the upper arm **22**, below the elbow joint assembly (arrow B) to rotate axially, i.e. rotation of the second elbow joint L**2** about the second elbow axis B**2** rotates the lower arm **24** and hand **18** (FIG. **1**) to face palm up or down.

FIG. **3** illustrates the lower arm **24**, including the wrist joint assembly (arrow C), the hand **18**, the fingers **19**A-**19**D, and thumb **21**. The lower arm **24** includes a plurality of finger (and thumb) actuators **26** and a plurality of wrist actuators **28**. Additionally, a plurality of controls **30** for the finger actuators **26** and the wrist actuators **28** are also supported on the lower arm **24**. The lower arm **24** is attached to a load cell **32** which is used to connect the lower arm **24** with the upper arm **22**. The hand **18** includes a base structure **34** that defines the palm **36** of the hand **18**. Fingers **19**A-**19**D and thumb **21** are movably mounted to the base structure **34** and selectively curl toward the palm **36** in order to grip an object, such as the one shown at **20** in FIG. **1**.

In the embodiment depicted, the hand **18** is comparable in size to that of a sixtieth to eight-fifth percentile human male hand. More specifically, in the embodiment depicted, the length of the hand **18** is 7.9 inches (eightieth percentile human); the breadth, or width, of the hand **18** is 3.6 inches (sixtieth percentile human); and the circumference of the hand (around the base structure) is 8.8 inches (eighty-fifth percentile human).

Referring to FIGS. **4**-**7**, finger **19**A corresponds in position and function to a human index finger. Finger **19**A includes a base member **37** operatively connected to the base structure **34** of the hand **18**. The finger **19**A also includes a plurality of rigid links, or phalanges **38**A-**38**D, and four joints **42**A-**42**D. Joint **42**A operatively connects proximal phalange **38**A to the base structure **34** such that the phalange **38**A is selectively rotatable with respect to the structure **34** about axis A**1**. Joint **42**B rotatably mounts phalange **38**B to phalange **38**A such that phalange **38**B is selectively rotatable with respect to phalange **38**A about axis A**2**. Joint **42**C rotatably mounts phalange **38**C to phalange **38**B such that phalange **38**C is selectively rotatable with respect to phalange **38**B about axis A**3**. Axes A**1**, A**2**, and A**3** are parallel to one another.

In the embodiment depicted, the proximal phalange **38**A is operatively connected to the base structure **34** by phalange **38**D, joint **42**D, and base member **37**. More specifically, joint **42**A rotatably mounts phalange **38**A to phalange **38**D; joint **42**D rotatably mounts phalange **38**D to the base member **37** such that phalange **38**D, and, correspondingly, phalanges **38**A-**38**C, are selectively rotatable with respect to the base member **37** and the base structure **34** about axis A**4**. Axis A**4** is perpendicular to axes A**1**, A**2**, and A**3**. Thus, joint **42**D permits rotation of the finger **19**A to the right and left.

Referring to FIGS. **7**-**8**, the finger **19**A includes a linkage **43**. One end of the linkage **43** is rotatably connected to phalange **38**A by joint **44**A such that the linkage **43** is selectively rotatably with respect to phalange **38**A about an axis that is parallel to axes A**1**, A**2**, and A**3**. The other end of the linkage **43** is rotatably connected to phalange **38**C by joint **44**B such that the linkage **43** is selectively rotatable with respect to phalange **38**C about an axis that is parallel to axes A**1**, A**2**, and A**3**. Accordingly, phalanges **38**A-**38**C and linkage **43** cooperate to define a four-bar linkage.

Referring to FIG. **9**, wherein like reference numbers refer to like components from FIGS. **1**-**8**, movement of the phalanges **38**A-**38**D about joints **42**A-**42**D is accomplished by robotic tendons **46**A-**46**D, i.e., flexible members such as cables. Each of the tendons **46**A-**46**D is operatively connected to a respective actuator (shown at **26** in FIG. **3**) in the forearm (shown at **24** in FIG. **3**). In an exemplary embodiment, the actuators **26** are electric motors operatively connected to the tendons **46**A-**46**D by drive mechanisms configured to convert the rotary motion of the motors to linear motion to drive the tendons **46**A-**46**D. The placement of the actuators and drive mechanisms in the forearm **24** and/or wrist contributes to the compactness of the hand **18**.

The routing of the tendons **46**A-**46**D with respect to the joints **42**A-D and the axes A**1**-A**4** enables the finger **19**A to be fully controlled through three degrees of freedom using only the four tendons **46**A-**46**D. Two opposing tendons **46**A, **46**B control the medial pitch joint **42**B, and two opposing tendons **46**C, **46**D control the proximal pitch joint **42**A. One end of tendon **46**B is operatively connected to phalange **38**B on one side of joint **42**B and axis A**2** such that tension in tendon **46**B causes rotation of phalange **38**B with respect to phalange **38**A about axis A**2** in a first direction **48**. One end of tendon **46**A is operatively connected to phalange **38**B on the opposite side of joint **42**B and axis A**2** from tendon **46**B such that tension in tendon **46**A causes rotation of phalange **38**B with respect to phalange **38**A about axis A**2** in a second direction **52** opposite the first direction **48**.

One end of tendon **46**D is operatively connected to phalange **38**A on one side of joint **42**A and axis A**1** such that tension in tendon **46**D causes rotation of phalange **38**A with respect to phalange **38**D about axis A**1** in the first direction **48**. One end of tendon **46**C is operatively connected to phalange **38**A on the opposite side of joint **42**A and axis A**1** from tendon **46**D such that tension in tendon **46**C causes rotation of phalange **38**A with respect to phalange **38**D about axis A**1** in the second direction **52**. Rotation of the phalanges in the first direction **48** causes the phalanges to rotate toward the palm **36**, as shown in FIGS. **5**-**6**, and thus rotation of the phalanges in the first direction **48** enables the hand **18** to grip an object. Rotation of the phalanges in the second direction **52** causes the phalanges to rotate away from the palm **36**, and thus causes the finger **19**A to release a grip on the object.

Referring again to FIGS. **7**-**8**, joint **42**C is kinematically linked to joint **42**B via linkage **43**, and thus the angular position of joint **42**C is dependent upon the angular position of joint **42**B. Accordingly, the rotational position of phalange **38**C with respect to phalange **38**B is dependent upon the rotational position of phalange **38**B with respect to phalange **38**A. More specifically, the angle β formed between phalanges **38**C and **38**B is determined by the angle α formed between phalanges **38**B and **38**A: decreasing α causes a corresponding decrease in β. An exemplary relationship between the rotational position of joint **42**C and joint **42**B is depicted in FIG. **10**.

Referring to FIG. **10**, the angle of joint **42**C is shown as a function of the angle of joint **42**B. It may be desirable for the function to be as linear as the design constraints of the finger **19**A will allow. The four bar linkage comprising phalanges **38**A-**38**C and linkage **43** is designed such that the linkage **43** is a straight line member between its end shafts, and is in tension during grasping. Linkage **43** in one embodiment is a rigid member; in another embodiment, linkage **43** is a compliant member, such as a spring, to achieve compliance of the distal pitch joint **42**C during grasping.

Accordingly, tendons **46**A and **46**B control the position of joint **42**C via their control of joint **42**B. A human finger is generally considered to have four independently controllable degrees of freedom. By kinematically linking joints **42**B and **42**C, finger **19**A effectively approximates the poses achievable by a human finger with only three independently controllable degrees of freedom, thereby eliminating the tendons that would be required to control joint **42**D independently.

Referring to FIG. **11**, wherein like reference numbers refer to like components from FIGS. **1**-**11**, there are no tendons dedicated to controlling the position of the yaw joint **42**D. Instead, tendons **46**A and **46**B are routed on one side of joint **42**D and axis A**4**, and tendons **46**C and **46**D are routed on another side of joint **42**D and axis A**4**. The balance of tension in these four tendons **46**A-**46**D is manipulated to control the position of joint **42**D and, correspondingly, the angular position of phalanges **38**A-**38**D with respect to the base structure **34**.

Referring to FIG. **12**, the finger **19**A includes at least two types of sensors. More specifically, the sensors of the finger **19**A include tactile load cells **54**A-**54**C, each of which is mounted to a respective phalange **38**A-**38**C. The finger **19**A also includes a plurality of joint position sensor assemblies **56**A-**56**C, each of which is configured to measure the absolute angular position of a respective one of the joints **42**A-**42**C and the relative angular position of a phalange relative to a connecting phalange. Each of the joint position sensor assemblies **56**A-**56**C includes a respective magnet **58**A-**58**C and a respective Hall effect sensor **62**A-**62**C.

Referring to FIG. **13**, sensor assembly **56**A is representative of sensor assemblies **56**B and **56**C, and thus magnet **58**A and sensor **62**A are representative of magnets **58**B, **58**C and sensors **62**B, **62**C, respectively. Magnet **58**A is rigidly mounted with respect to phalange **38**D, and sensor **62**A is rigidly mounted with respect to phalange **38**A. Magnet **58**A is characterized by two portions **66**, **70**. Portion **66** is a segment of a circle having a center point **74** on axis A**1**. Portion **70** is a segment of a circle having a center point at **78**. The north pole N of the magnet **58**A is disposed at one intersection of the portions **66**, **70**, and the south pole S of the magnet **58**A is disposed at the other intersection of the portions **66**, **70**. In the embodiment depicted, portion **66** has the same radius as portion **70**, and the concave sides of portions **66**, **70** face one another. The magnet **58**A circumscribes both center points **74**, **78**.

Sensor **62**A is positioned on phalange **38**A such that, as phalange **38**A rotates with respect to phalange **38**D about axis A**1**, the sensor **62**A maintains a constant distance from portion **66** of the magnet **58**A. The shape of the magnet **58**A and the placement of the sensor **62**A provide a linear relationship between angular position of the phalange **38**A with respect to phalange **38**D and the change in magnetic field that is read by sensor **62**A. In the embodiment depicted, sensor assembly **56**A generates an approximately linear signal over a 150-degree usable range of angular positions.

Magnet **58**A is mounted with respect to phalange **38**D and sensor **62**A is mounted with respect to phalange **38**A, and thus sensor assembly **56**A measures the rotational position of phalange **38**A with respect to phalange **38**D. Magnet **58**B is mounted with respect to phalange **38**B and sensor **62**B is mounted with respect to phalange **38**A, and thus sensor assembly **56**B measures the rotational position of phalange **38**B with respect to phalange **38**A. Magnet **58**C is mounted with respect to phalange **38**C and sensor **62**C is mounted with respect to phalange **38**B, and thus sensor assembly **56**C measures the rotational position of phalange **38**C with respect to phalange **38**B. A sensor assembly (not shown) substantially identical to sensor assemblies **56**A-**56**C measures the position of phalange **38**D with respect to base member **37** as phalange **38**D rotates about axis A**4**.

In the embodiment depicted, the range of motion of joint **42**A (proximal pitch) is −10° to 95°; the range of motion of joint **42**B (medial pitch) is 0° to 120°; the range of motion of joint **42**C (distal pitch) is 0° to 70°; and the range of motion of joint **42**D (yaw) is −20° to 20°.

Referring to FIGS. **12** and **14**, finger **19**A is mounted to the base structure **34** by a shock mount **82**. The shock mount **82** includes a keyed shaft **86**, a retainer ring **90**, and a spring **94**. The cylindrical shaft **86** is slidingly engaged within a cylindrical cavity **98** defined by the base structure **34**. The rectangular key **102** extends within a rectangular portion **106** of cavity **98** to prevent rotation of the shaft **86** with respect to the structure **34**. The retainer ring **90** is larger than the cavity **98** and thus retains the shaft **86** inside the cavity **98**. The spring **94** biases the shaft **86** outward and absorbs shocks that may be exerted on the finger **19**A.

It should be noted that, although the tendons **46**A-**46**D are depicted in FIGS. **9** and **11** as being external to the phalanges **38**A-**38**D, each of the tendons is routed through a respective internal guide channel. In the embodiment depicted, tendons **46**A-**46**D are braided polymers. Referring to FIG. **15**, the finger **19**A includes inserts, such as the ones shown at **110**A, **110**B, **110**C, where sliding friction of the tendons **46**A-**46**D occurs. The inserts **110**A, **110**B, **110**C are softer and weaker than the structural material of the phalanges **38**A-**38**D, and are selectively replaceable. In one embodiment, the tendons **46**A-**46**D comprise Vectran® and the inserts **110**A, **110**B, **110**C are bronze.

Referring to FIGS. **16** and **17**, the finger **19**A is configured to accommodate, for each pair of opposing tendons, a respective bidirectional tendon terminator **114**A, **114**B. More specifically, tendon **46**A extends on the non-palmar, or dorsal, side of axes A**1** and A**2**, and is mounted to phalange **38**B via tendon terminator **114**A. Tendon **46**B extends on the palmar side of axes A**1** and A**2**, and is mounted to phalange **38**B via tendon terminator **114**A. Similarly, tendon **46**C extends on the non-palmar side of axis A**1** and is mounted to phalange **38**A by tendon terminator **114**B. Tendon **46**D extends on the palmar side of axis A**1** and is mounted to phalange **38**A by tendon terminator **114**B.

Referring to FIG. **18**, a phalange **38** is shown in a cutaway, perspective view. Phalange **38** is representative of phalanges **38**A-**38**C, and sensor **54** is representative of sensors **54**A-**54**C. Phalange **38** defines a chamber **118** that is characterized by an opening **122**. Compact electronics **126** are contained within the chamber **118**. The functions of the electronics **126** include providing power to the sensors, collecting analog sensor data, converting analog signals to digital signals, multiplexing digital signals, and communicating data to upstream electronics. Referring again to FIG. **16**, the finger **19**A includes a central channel **128** that extends the length of the finger **19**A to accommodate the wiring required to connect the sensors, the compact electronics, and the upstream electronics.

Referring to FIGS. **18** and **19**, sensor **54** includes a sensor cover **130** and a sensor assembly **134**. The sensor assembly **134** generates sensor signals in response to loads applied to the sensor cover **130**, and transmits the sensor signals to the electronics **126**. The sensor assembly **134** is generally C-shaped, and is characterized by a flange **138**, **142** at each end. Each flange **138**, **142** abuts a respective shoulder **146**, **150** formed by the phalange **38**. The flanges **138**, **142** of the sensor assembly **134** also partially define respective slots **154**, **158**.

A C-shaped clip **162** includes a flange **166**, **170** at each end. The clip **162** extends across opening **122** to enclose the chamber **118** and the electronics **126** contained therein. Each flange **166**, **170** engages a respective one of the slots **154**, **158** to secure the clip **162** to the sensor assembly **134**, and to retain the sensor assembly **134** to the phalange **38**. The cover **130** is mounted to the sensor assembly **134** by screws **174**.

Referring again to FIG. **16**, the finger **19**A is designed to accommodate a glove or skin-like covering (not shown) for protection from the environment and to provide grip surfaces to the tactile sensors that are appropriate for a specific task. The finger **19**A includes a plurality of threaded attachment holes **178** designed to secure the glove or skin-like covering to the finger, preventing slippage at the critical locations.

While the best modes for carrying out the invention have been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention within the scope of the appended claims

The invention claimed is:

1. A robotic hand assembly comprising:

a base structure;

a finger having first, second, and third phalanges;

a first joint operatively connecting the first phalange to the base structure such that the first phalange is selectively rotatable with respect to the base structure about a first axis;

a second joint operatively connecting the second phalange to the first phalange such that the second phalange is selectively rotatable with respect to the first phalange about a second axis; and

a third joint operatively connecting the third phalange to the second phalange such that the third phalange is selectively rotatable with respect to the second phalange about a third axis;

a first tendon being operatively connected to the second phalange such that tension in the first tendon urges the second phalange to rotate about the second axis in a first direction;

a second tendon being operatively connected to the second phalange such that tension in the second tendon urges the second phalange to rotate about the second axis in a second direction;

a third tendon being operatively connected to the first phalange such that tension in the third tendon urges the first phalange to rotate about the first axis in the first direction;

a fourth tendon being operatively connected to the first phalange such that tension in the fourth tendon urges the first phalange to rotate about the first axis in the second direction;

wherein the third joint is kinematically linked to the second joint such that the position of the third phalange with respect to the second phalange is determined by the position of the second phalange with respect to the first phalange.

2. The robotic hand assembly of claim **1**, further comprising a linkage that is rotatably mounted with respect to the first phalange and rotatably mounted with respect to the third phalange to kinematically link the third joint and the second joint.

3. The robotic hand assembly of claim **2**, wherein the linkage includes a spring.

4. The robotic hand assembly of claim **1**, further comprising a fourth phalange rotatably connected to the first phalange by the first joint; and

a fourth joint operatively connecting the fourth phalange to the base structure such that the fourth phalange is selectively rotatable with respect to the base structure about a fourth axis.

5. The robotic hand assembly of claim **4**, wherein the fourth axis is substantially perpendicular to the first, second, and third axes.

6. The robotic hand assembly of claim **5**, wherein the first and second tendons are routed on a first side of the fourth axis; and

wherein the third and fourth tendons are routed on a second side of the fourth axis.

7. The robotic hand assembly of claim **1**, further comprising at least one insert;

wherein at least one of the first, second, third, and fourth tendons contacts the insert; and

wherein the insert is softer or weaker than the phalanges.

8. The robotic hand assembly of claim **1**, further comprising a shock mount that operatively connects the finger to the base structure.

* * * * *