US009272425B2

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

(10) **Patent No.: US 9,272,425 B2**
(45) **Date of Patent: Mar. 1, 2016**

(54) **TWISTED STRING ACTUATOR SYSTEMS**

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(73) Assignee: **SRI International**, Menlo Park, CA (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.: **14/745,668**

(22) Filed: **Jun. 22, 2015**

(65) **Prior Publication Data**

US 2015/0343647 A1 Dec. 3, 2015

Related U.S. Application Data

(63) Continuation of application No. 14/458,283, filed on Aug. 13, 2014, which is a continuation of application

(Continued)

(51) **Int. Cl.**

B25J 15/00 (2006.01)
B25J 15/08 (2006.01)
F16H 21/40 (2006.01)

(52) **U.S. Cl.**

CPC ***B25J 15/08*** (2013.01); ***B25J 15/0028*** (2013.01); ***F16H 21/40*** (2013.01); *Y10T 74/20323* (2015.01)

(58) **Field of Classification Search**

CPC B25J 15/083; B25J 15/0009; B25J 9/104; B25J 17/00; B25J 15/0085; B25J 15/08; B25J 19/00; B25J 15/0028; B25J 15/0233; B25J 15/0226; B25J 15/0213; H02N 13/00; Y10S 294/907; Y10S 901/39; F16H 21/40; Y10T 74/20323

USPC 294/106, 111, 198, 213, 200, 907; 901/38, 39, 36; 623/63, 64

See application file for complete search history.

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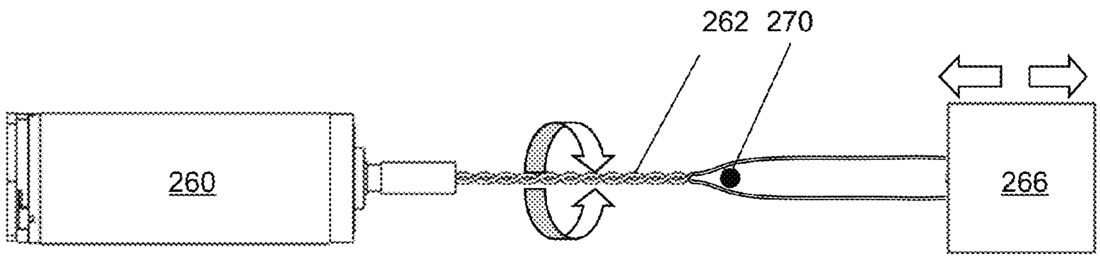
Primary Examiner — Gabriela Puig
(74) *Attorney, Agent, or Firm* — Schmeiser, Olsen & Watts LLP

(57) **ABSTRACT**

A twisted string actuator system includes a motor generating rotary motion of a rotor and a twisted string comprised of a pair of cords. One end of the twisted string is attached to the rotor and an opposite end of the twisted string is coupled to a load. The cords are twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string. A cord guide is fixedly disposed between the cords. The first and second sections of the twisted string are on a first side and second side, respectively, of the cord guide. Rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide while pulling a portion of the pair of cords from the second side of the cord guide into the first side.

20 Claims, 26 Drawing Sheets



Related U.S. Application Data

No. 14/005,092, filed as application No. PCT/US2012/029860 on Mar. 21, 2012, now Pat. No. 8,833,826.

(60) Provisional application No. 61/466,900, filed on Mar. 23, 2011, provisional application No. 61/466,902, filed on Mar. 23, 2011, provisional application No. 61/454,945, filed on Mar. 21, 2011, provisional application No. 61/454,948, filed on Mar. 21, 2011.

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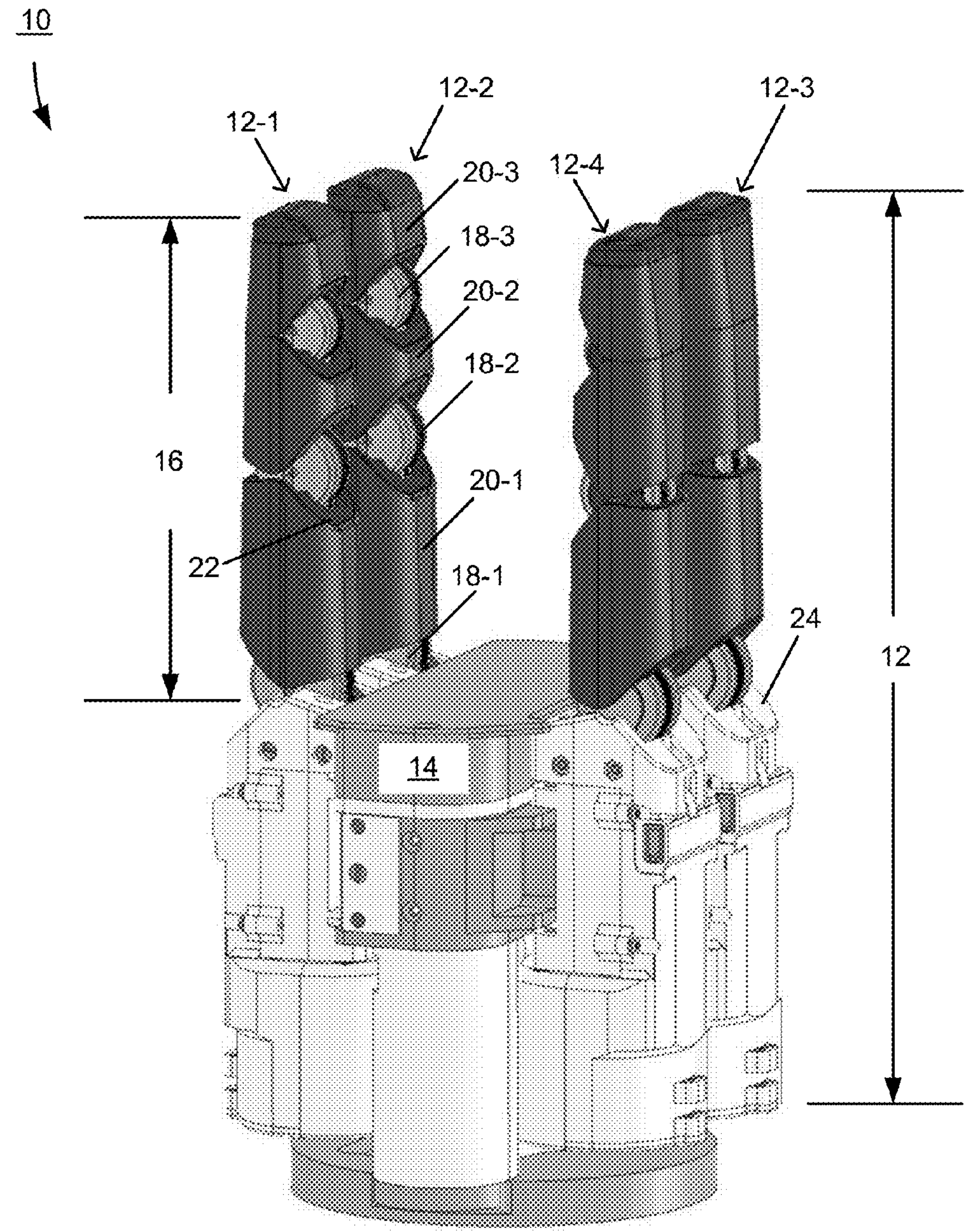


FIG. 1

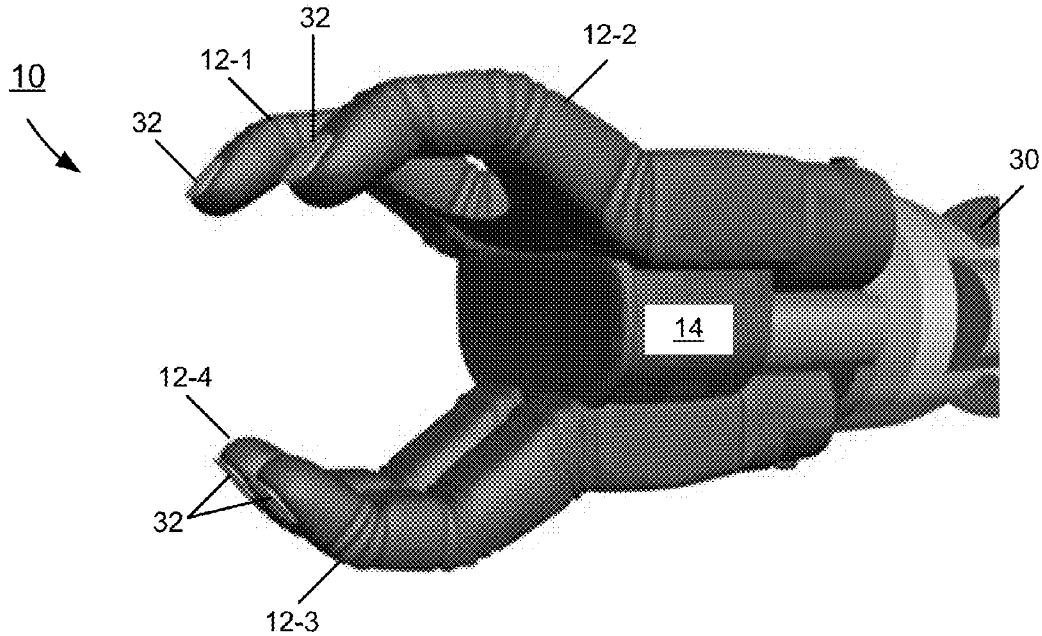
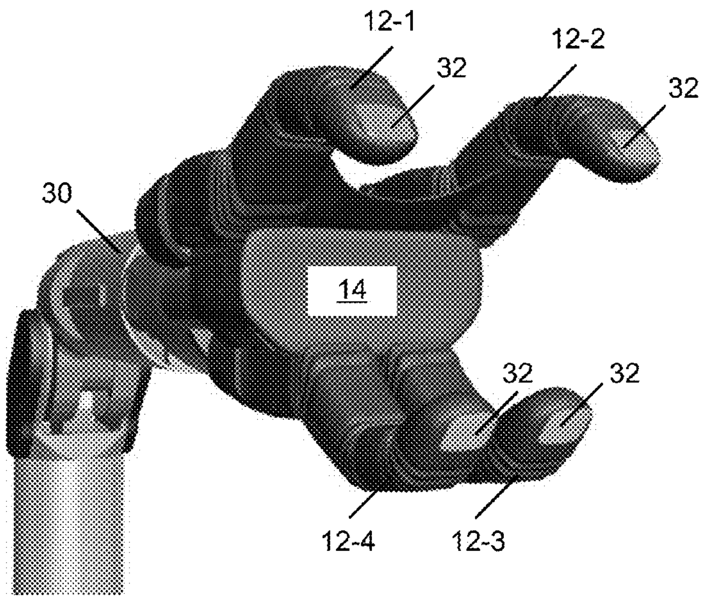


FIG. 2



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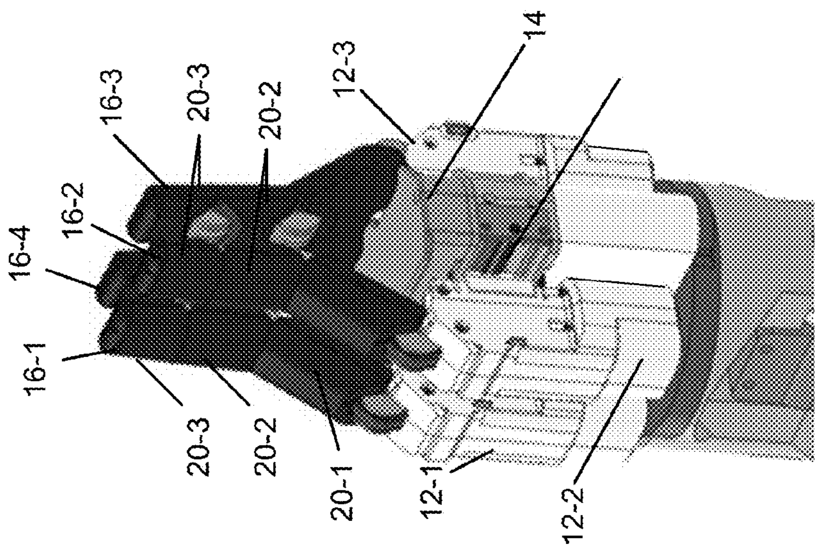

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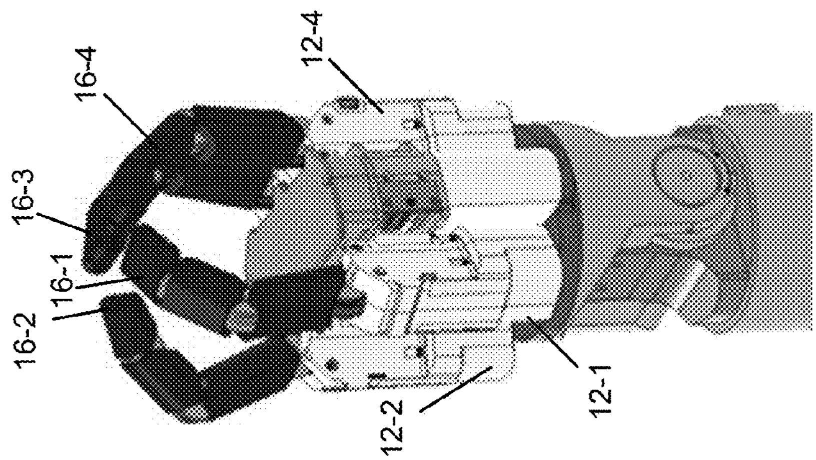

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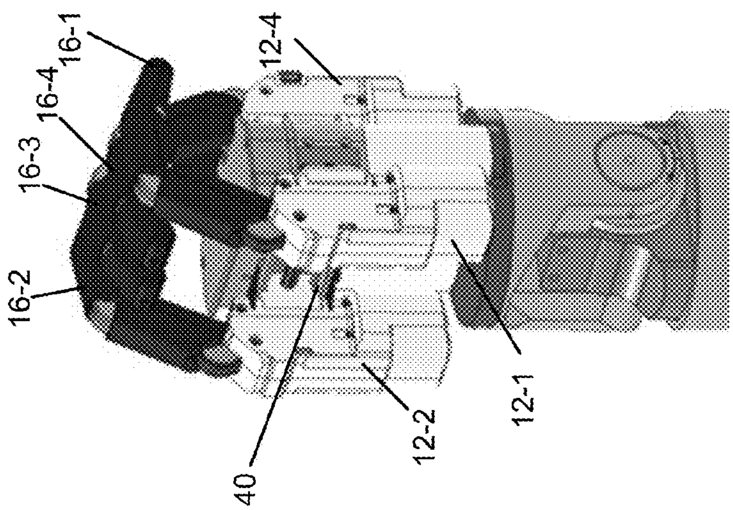

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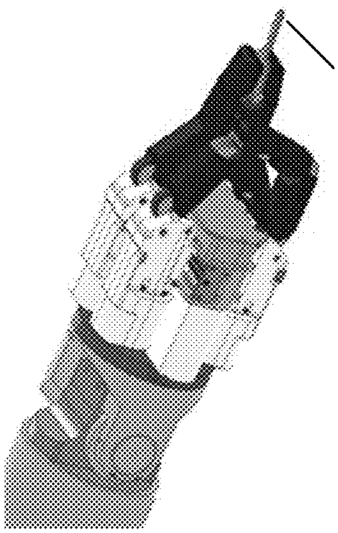
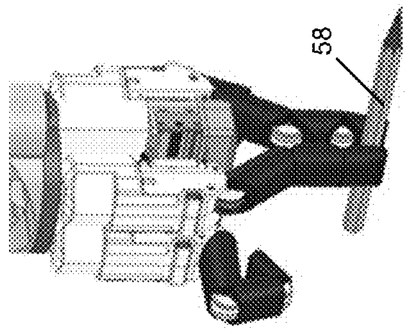


FIG. 10



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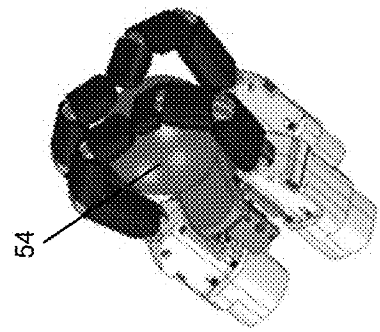

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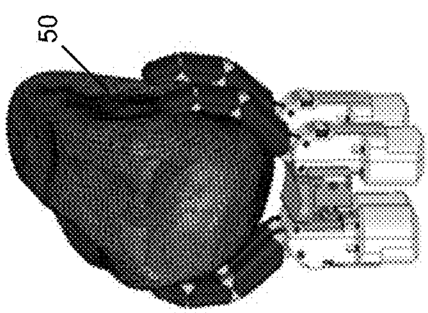

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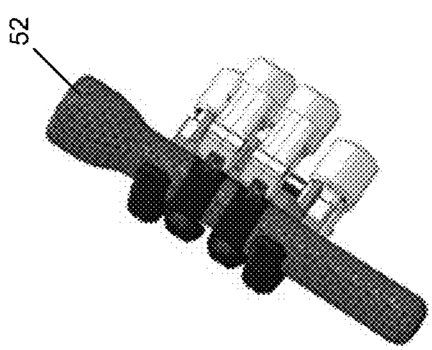

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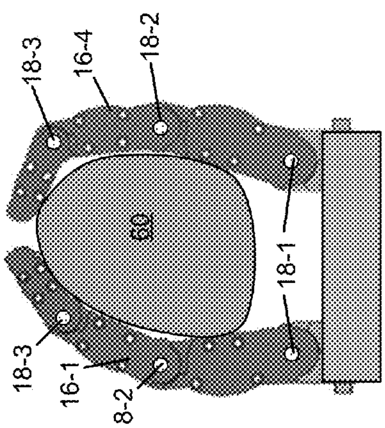


FIG. 12A

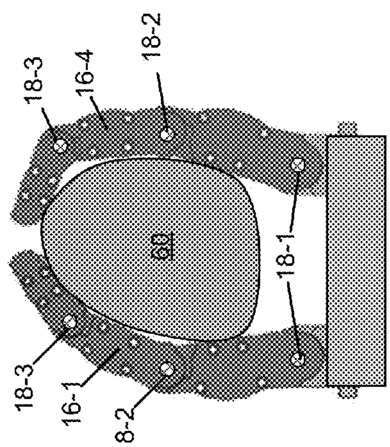


FIG. 12B

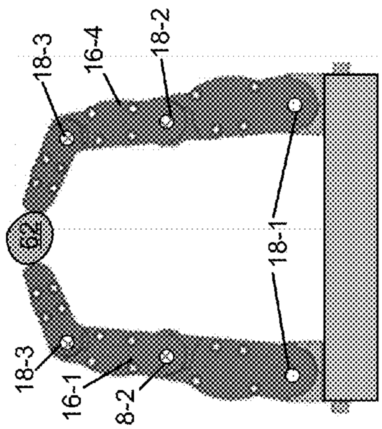
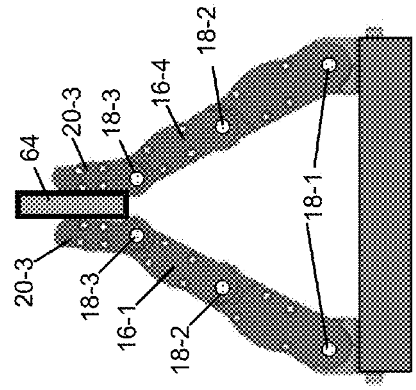


FIG. 13



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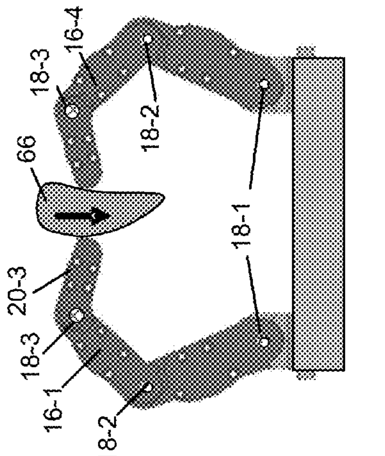
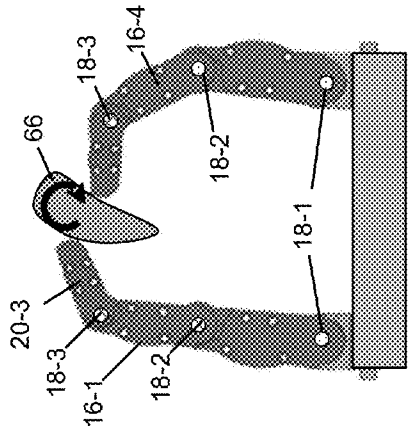


FIG. 15A



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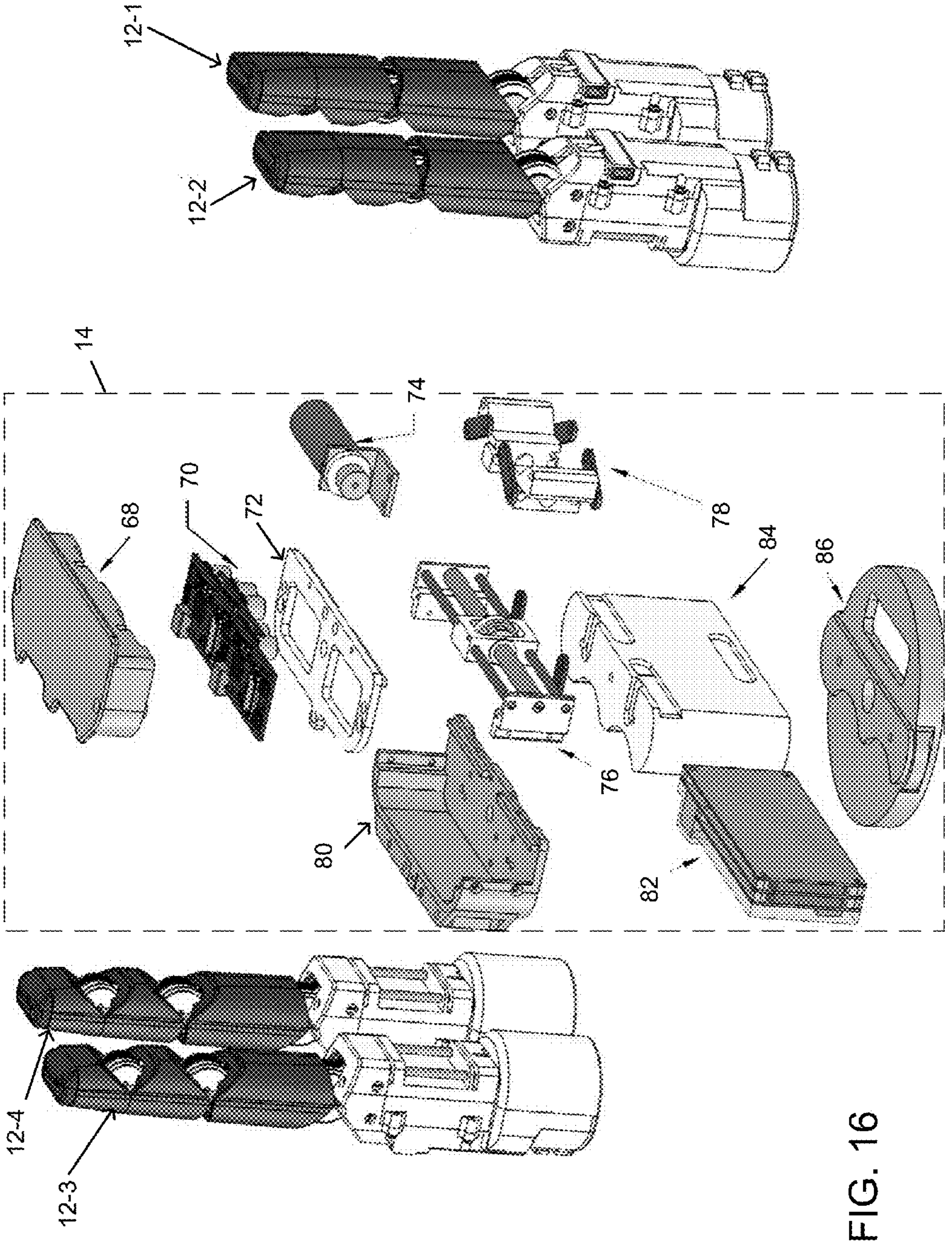

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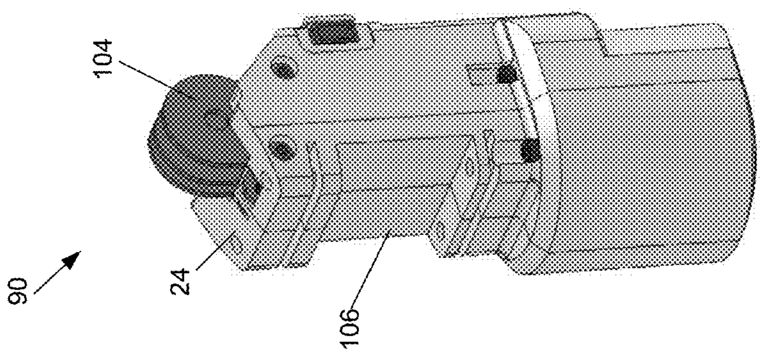
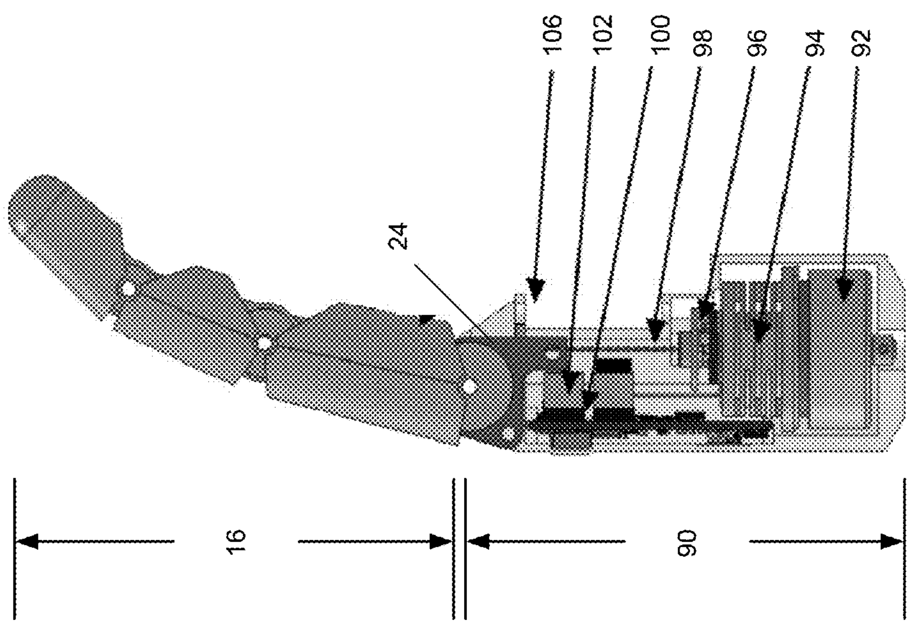


FIG. 18



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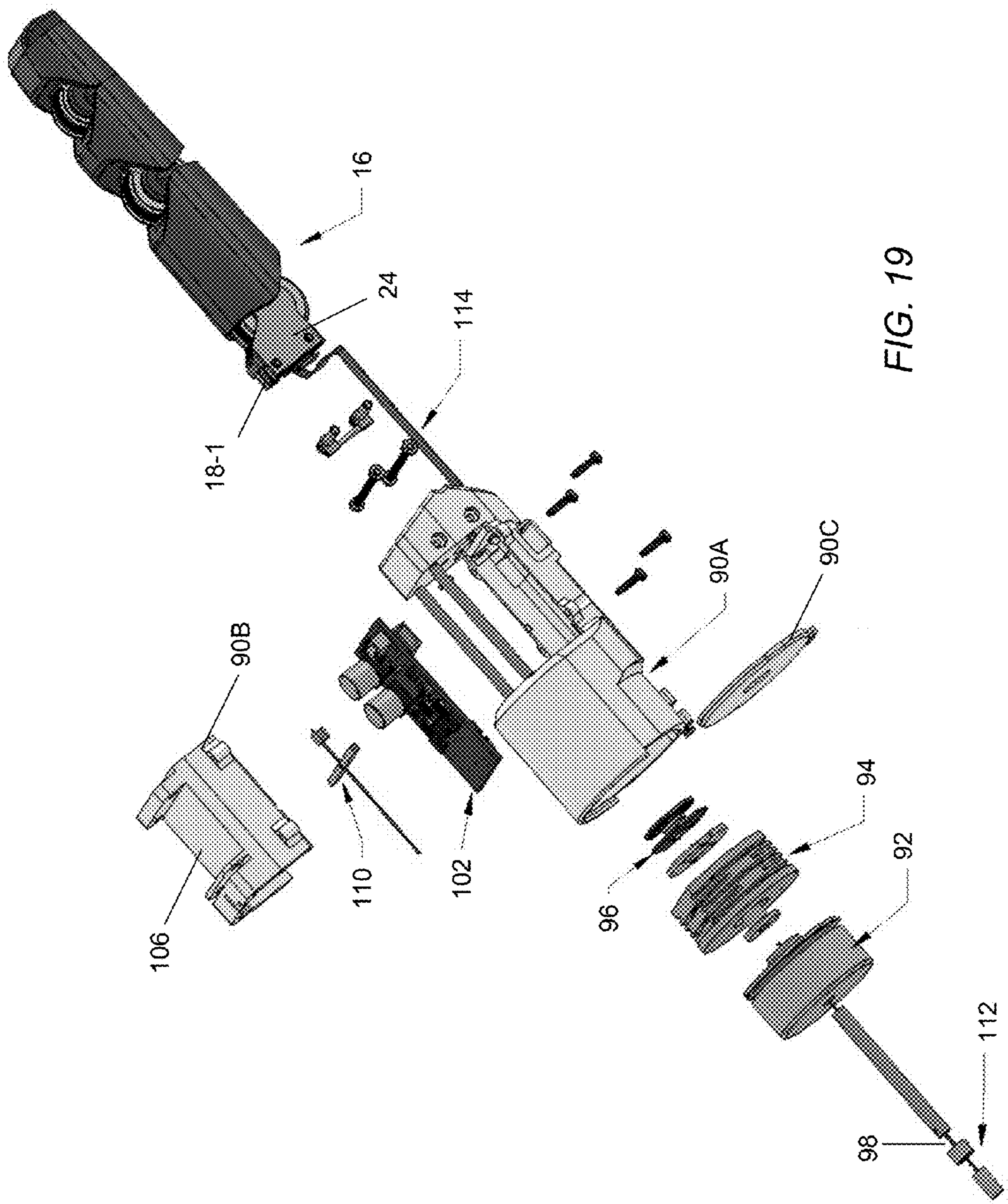

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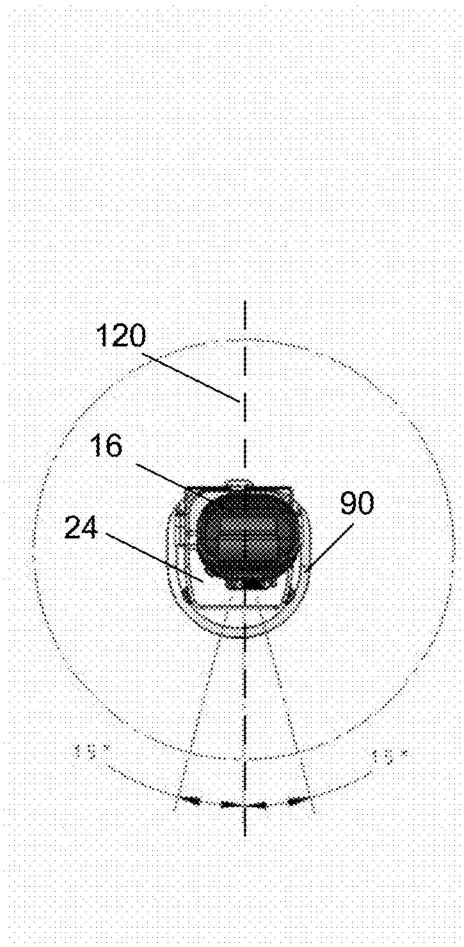

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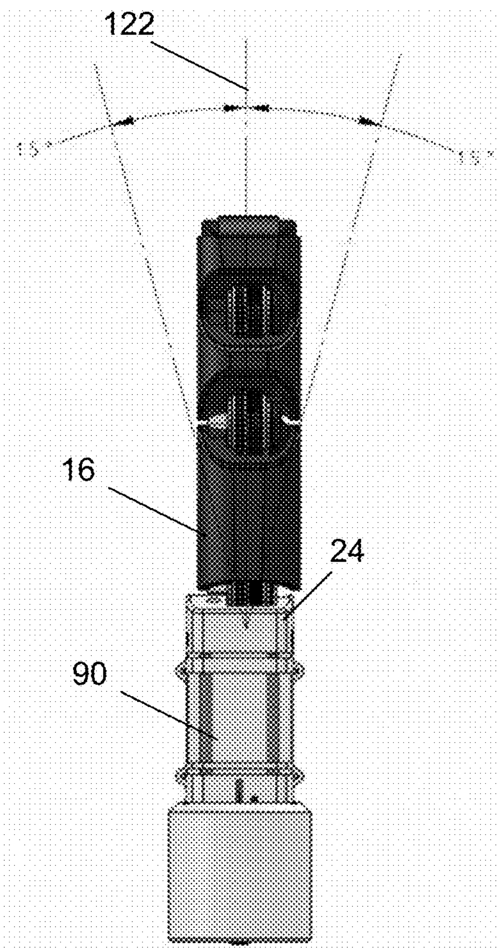

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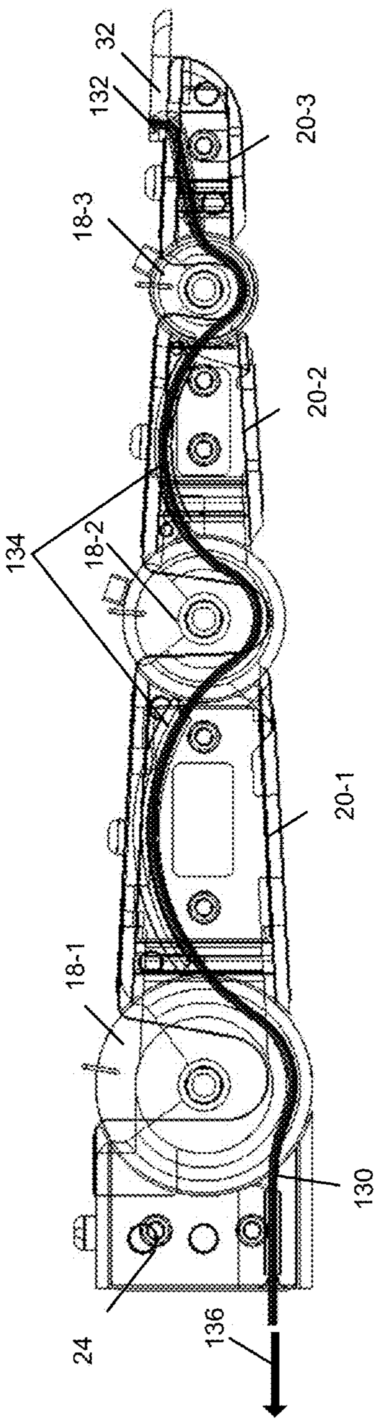
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132
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18-1
130
24
136

FIG. 22

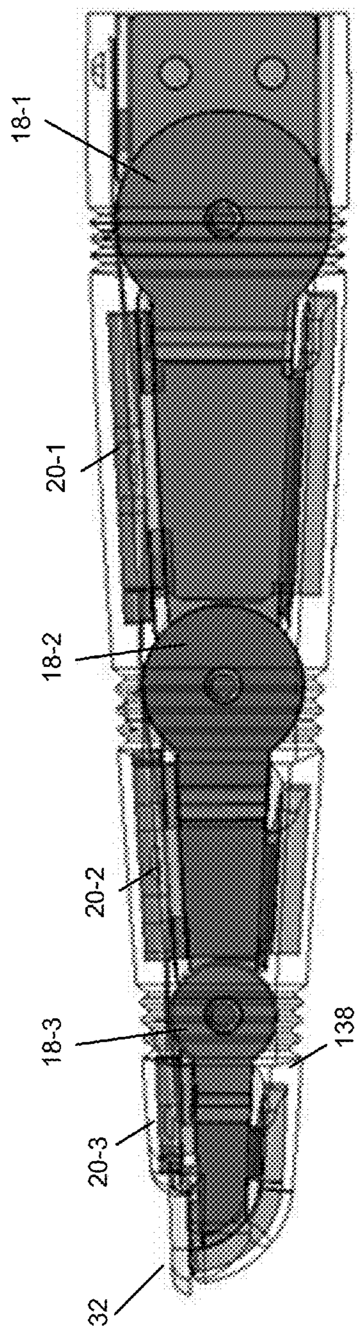
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FIG. 23

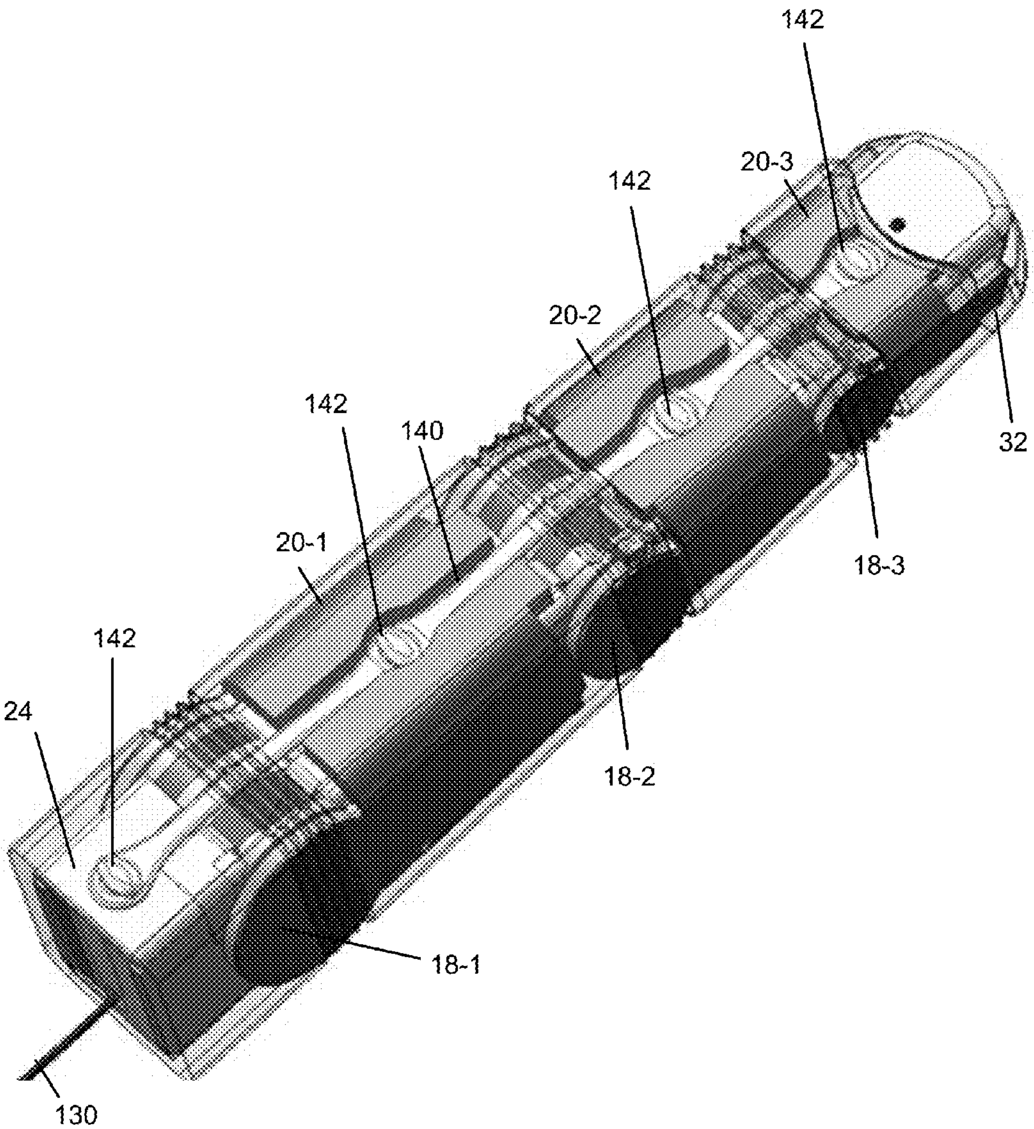


FIG. 24

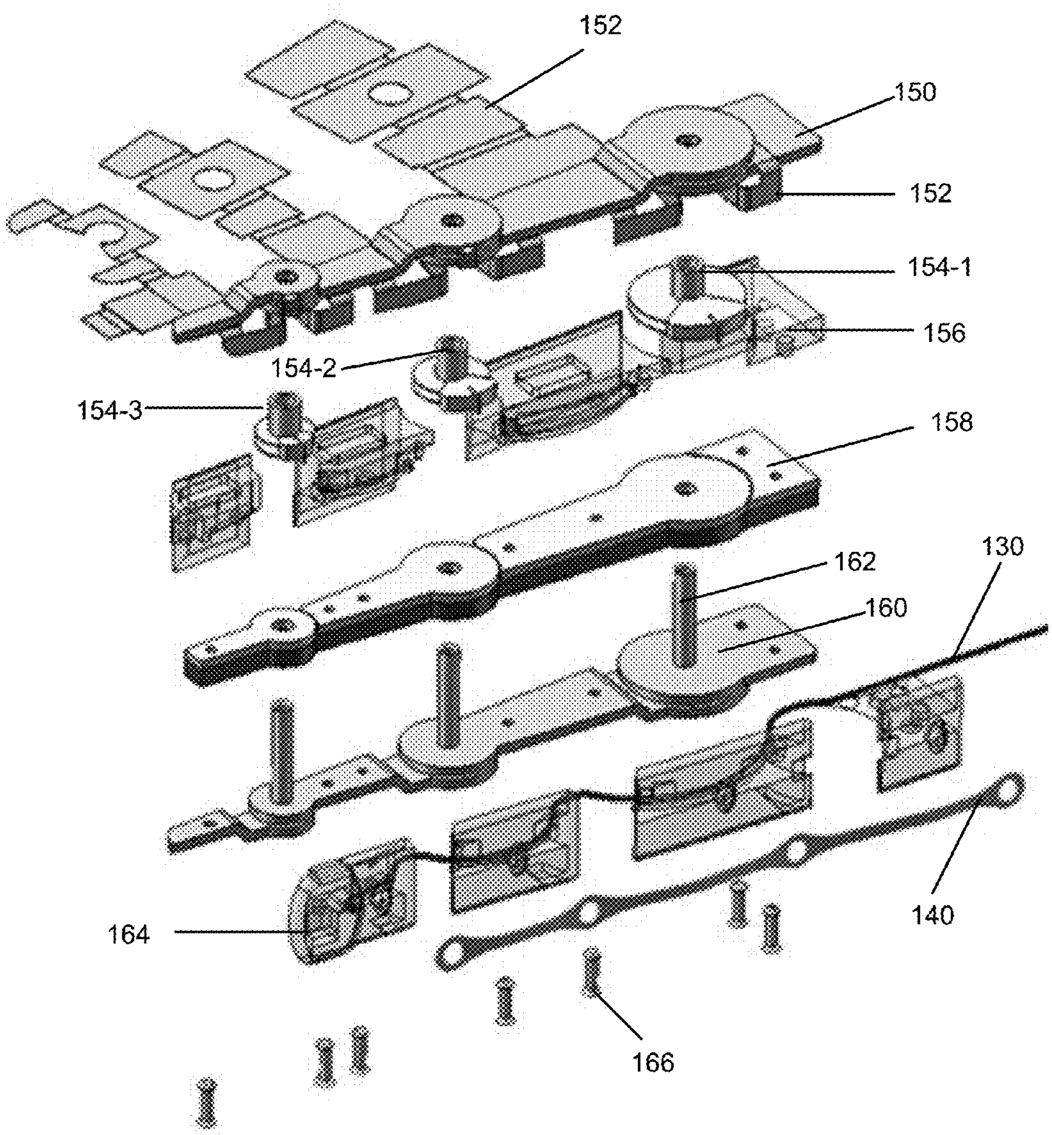


FIG. 25

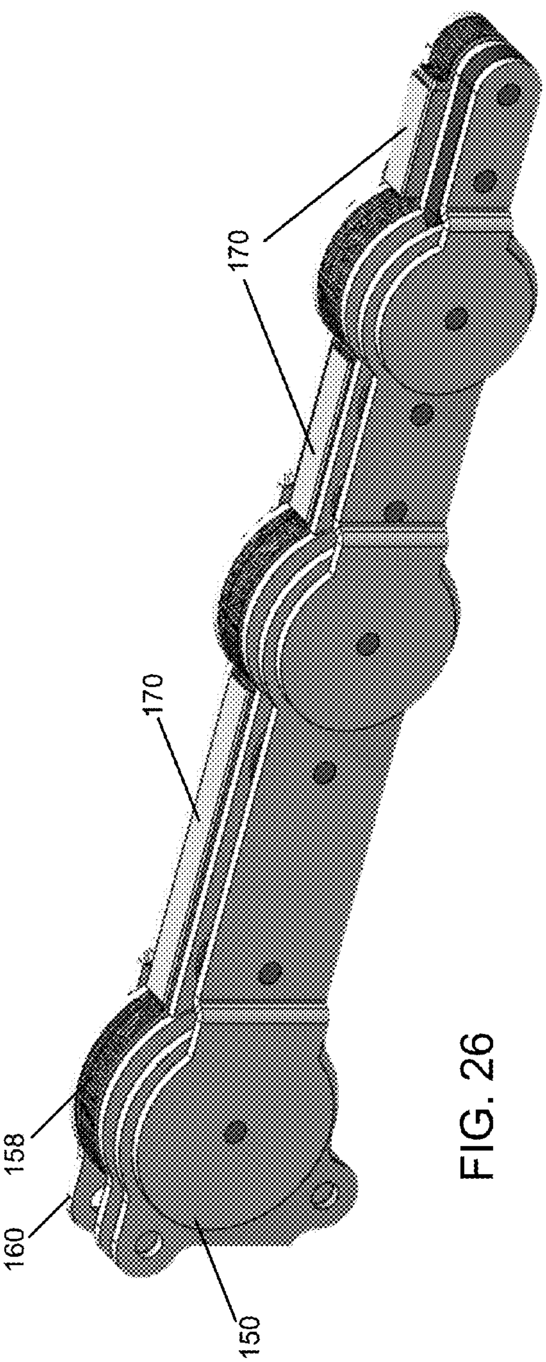


FIG. 26

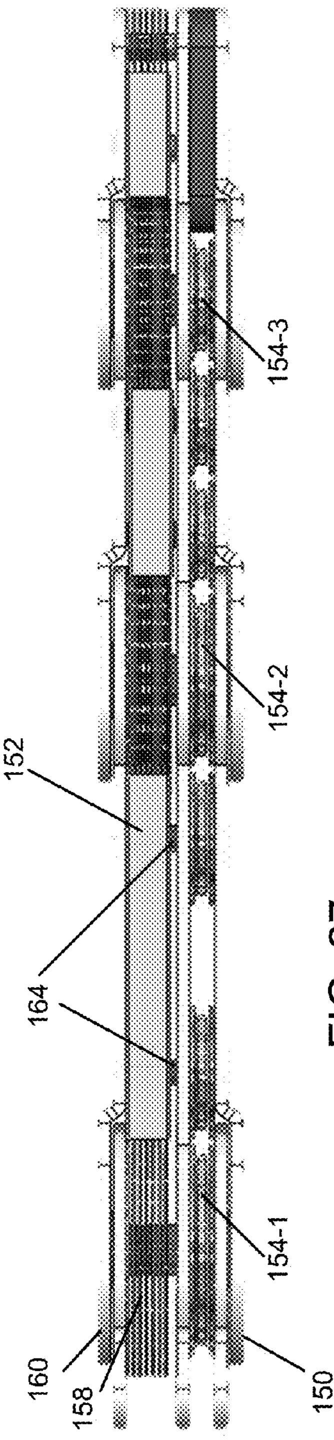


FIG. 27

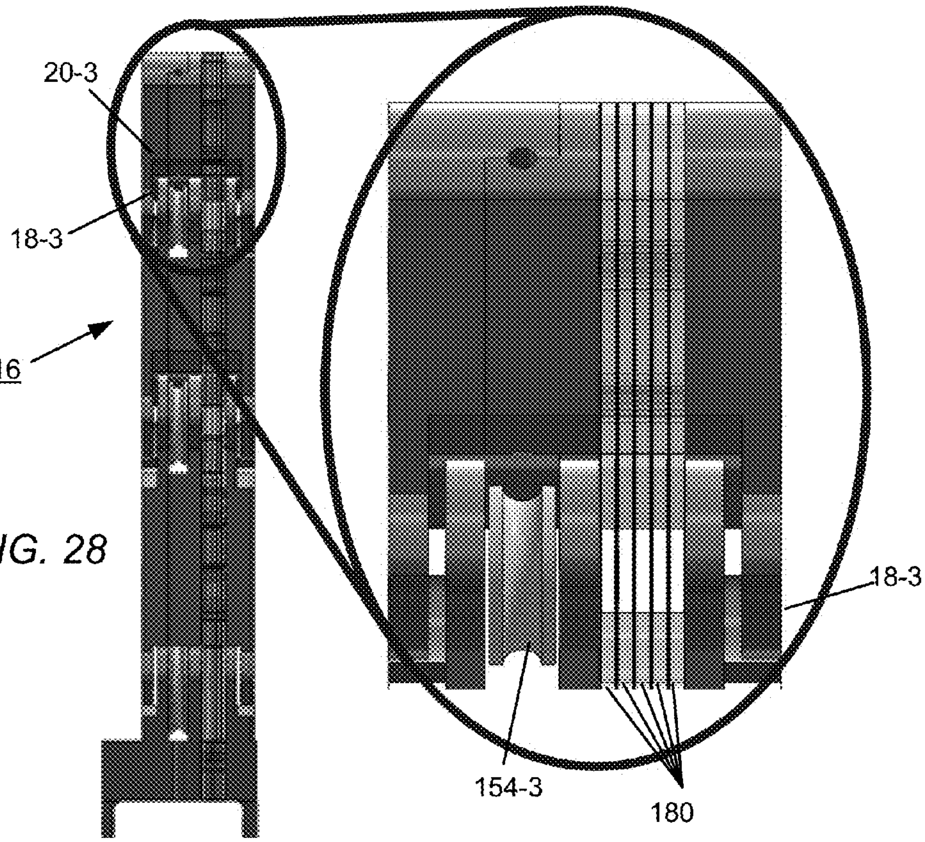
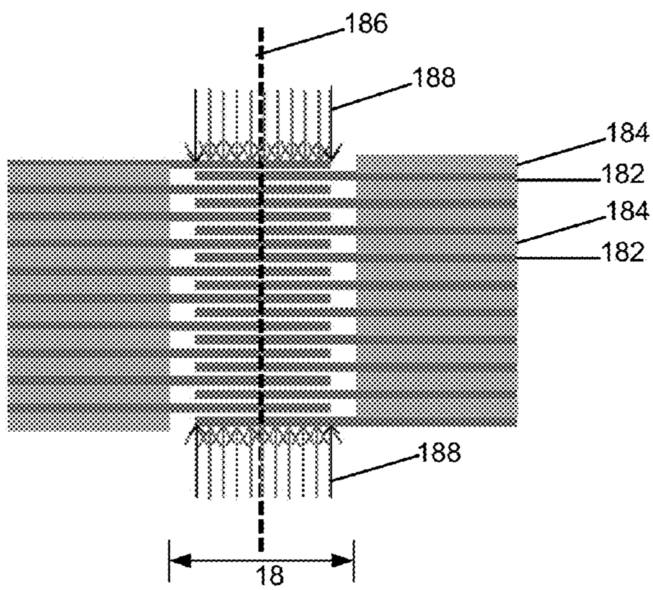


FIG. 28



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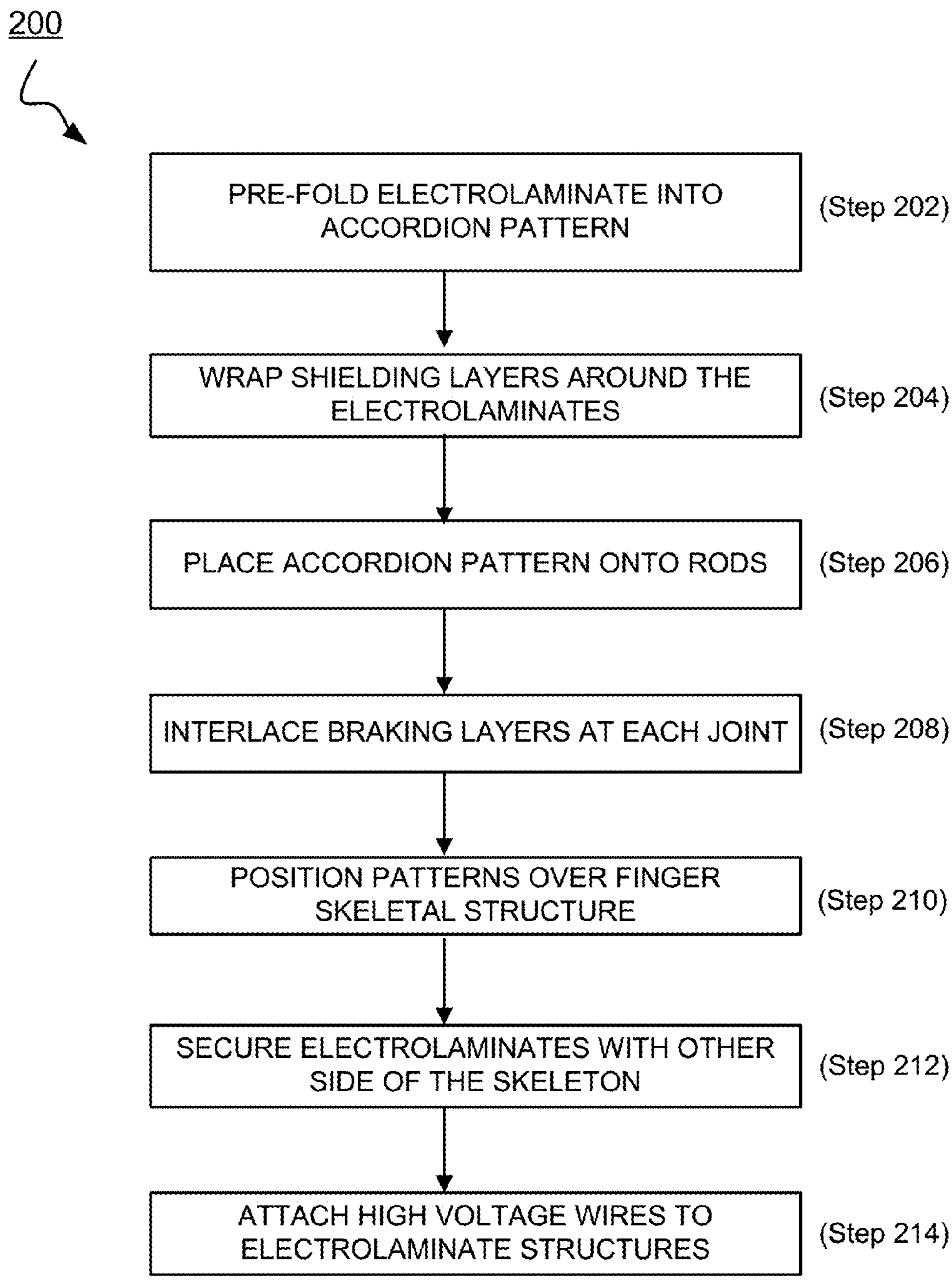

200
PRE-FOLD ELECTROLAMINATE INTO ACCORDION PATTERN
(Step 202)
WRAP SHIELDING LAYERS AROUND THE ELECTROLAMINATES
(Step 204)
PLACE ACCORDION PATTERN ONTO RODS
(Step 206)
INTERLACE BRAKING LAYERS AT EACH JOINT
(Step 208)
POSITION PATTERNS OVER FINGER SKELETAL STRUCTURE
(Step 210)
SECURE ELECTROLAMINATES WITH OTHER SIDE OF THE SKELETON
(Step 212)
ATTACH HIGH VOLTAGE WIRES TO ELECTROLAMINATE STRUCTURES
(Step 214)

FIG. 30

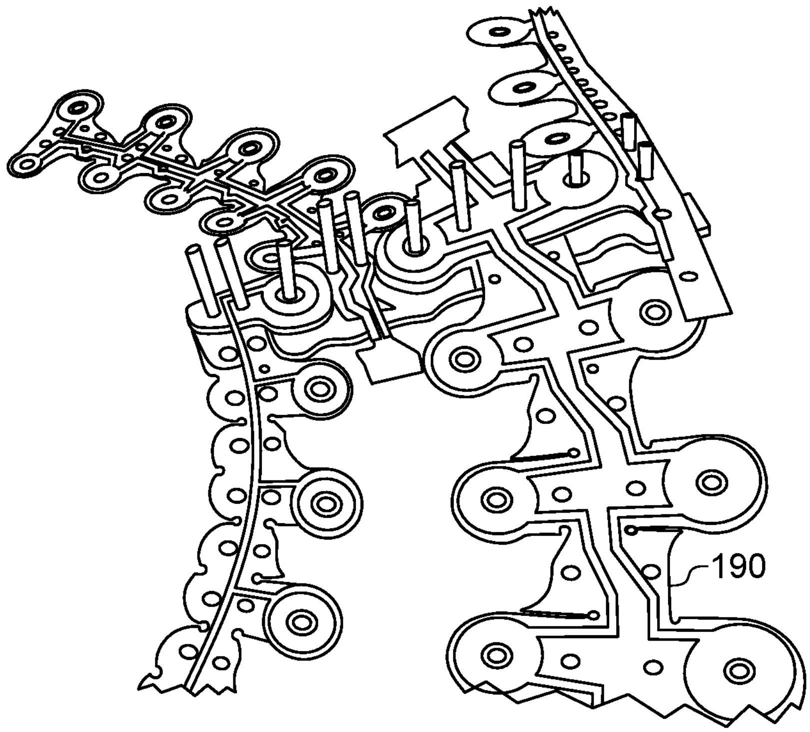


FIG. 31A

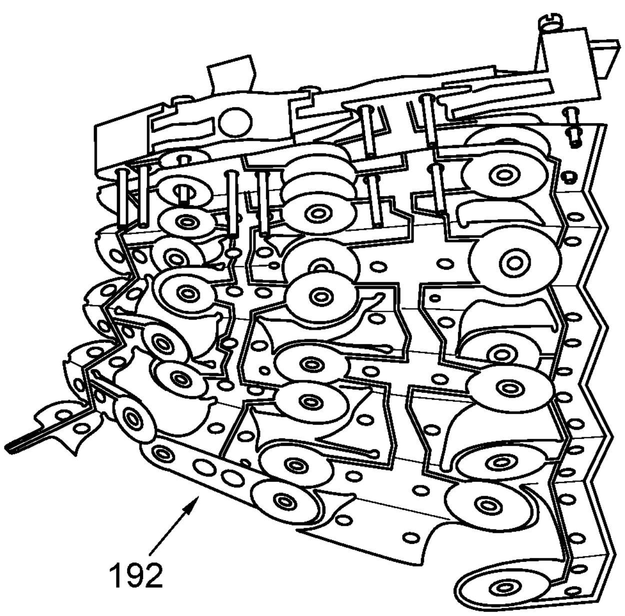


FIG. 31B

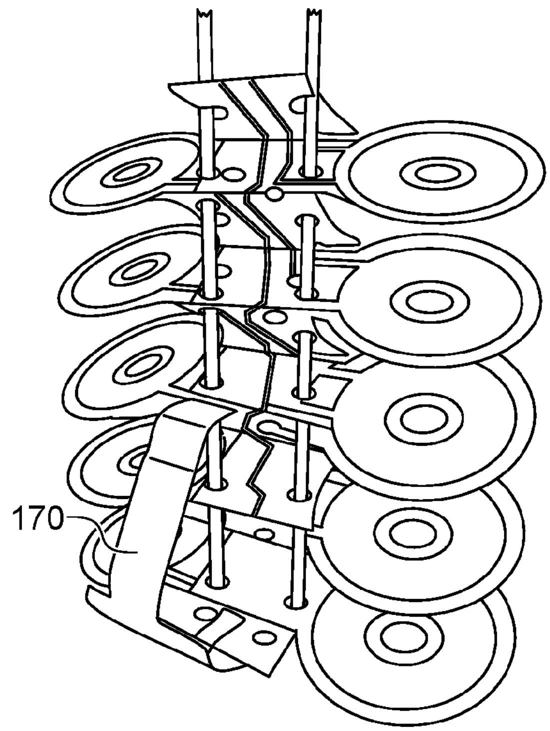


FIG. 31C

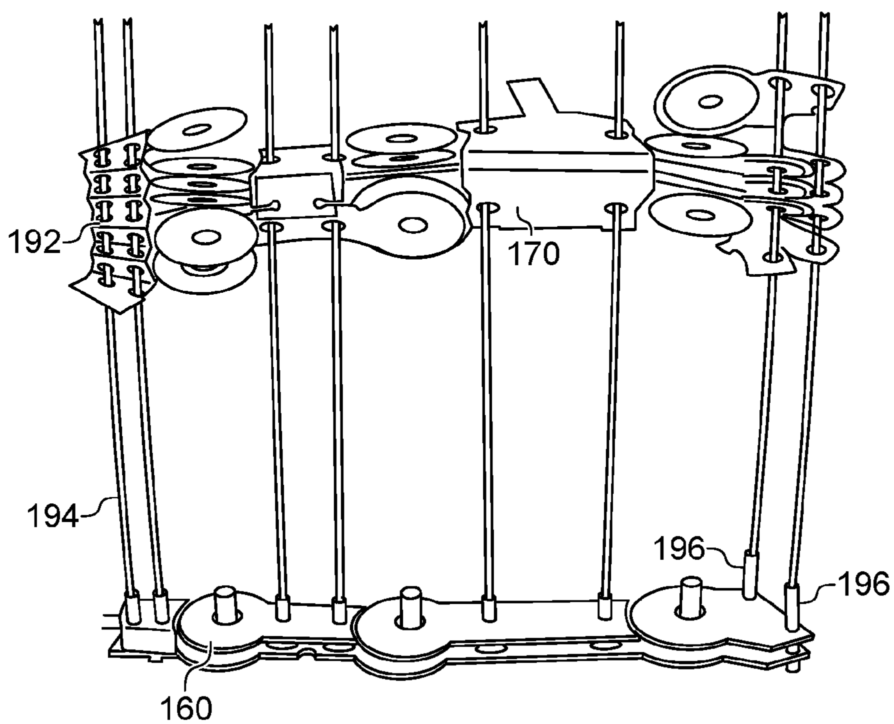


FIG. 31D

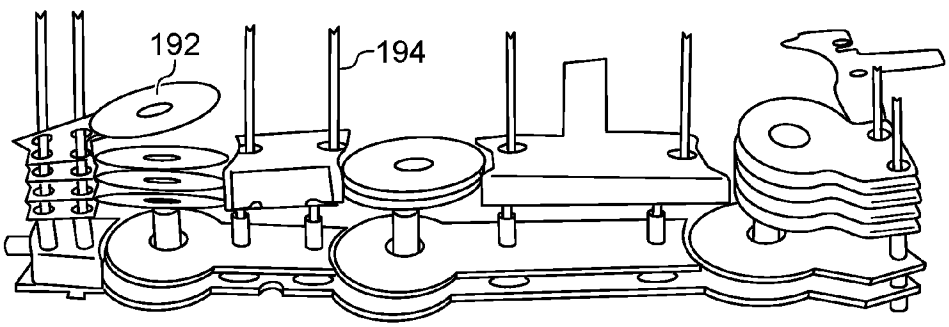


FIG. 31E

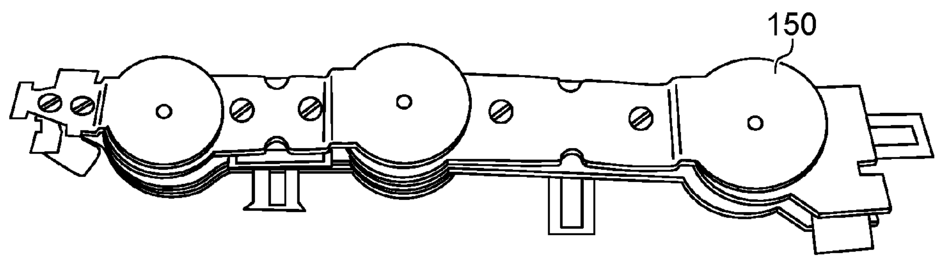


FIG. 31F

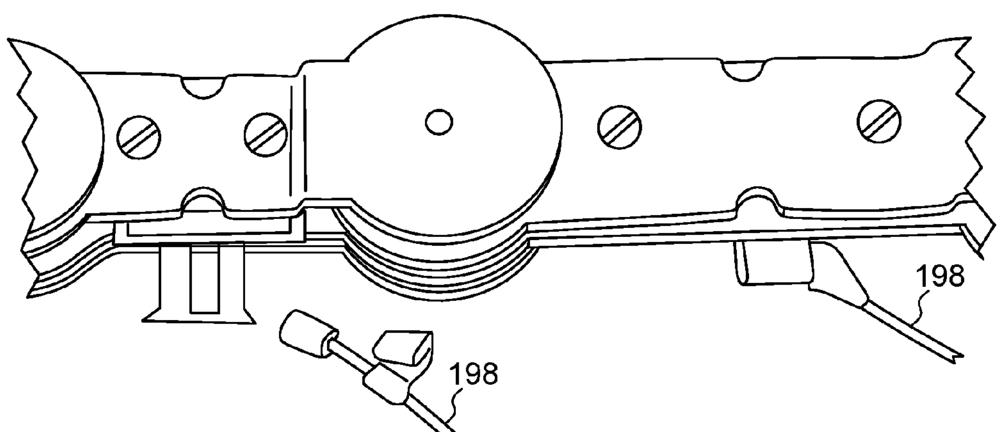
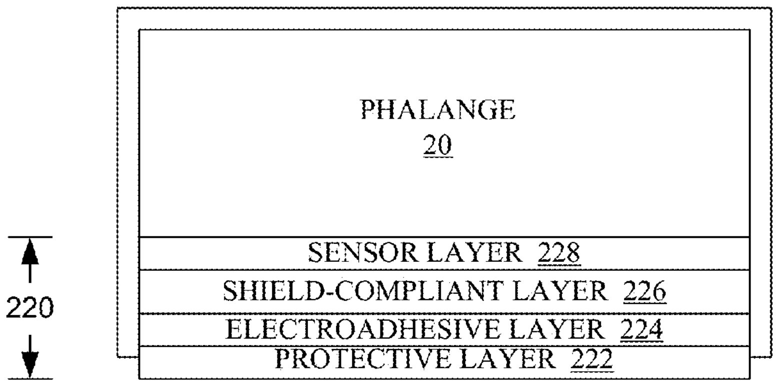


FIG. 31G


PHALANGE
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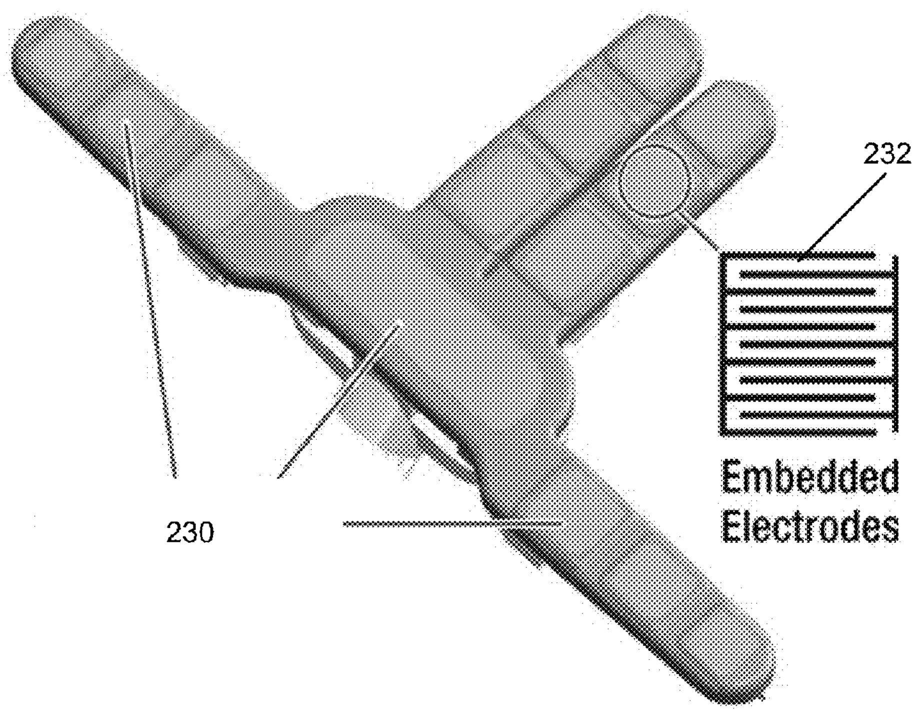
SHIELD-COMPLIANT LAYER 226
ELECTROADHESIVE LAYER 224
PROTECTIVE LAYER 222
220

FIG. 32


232
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Electrodes
230

FIG. 33

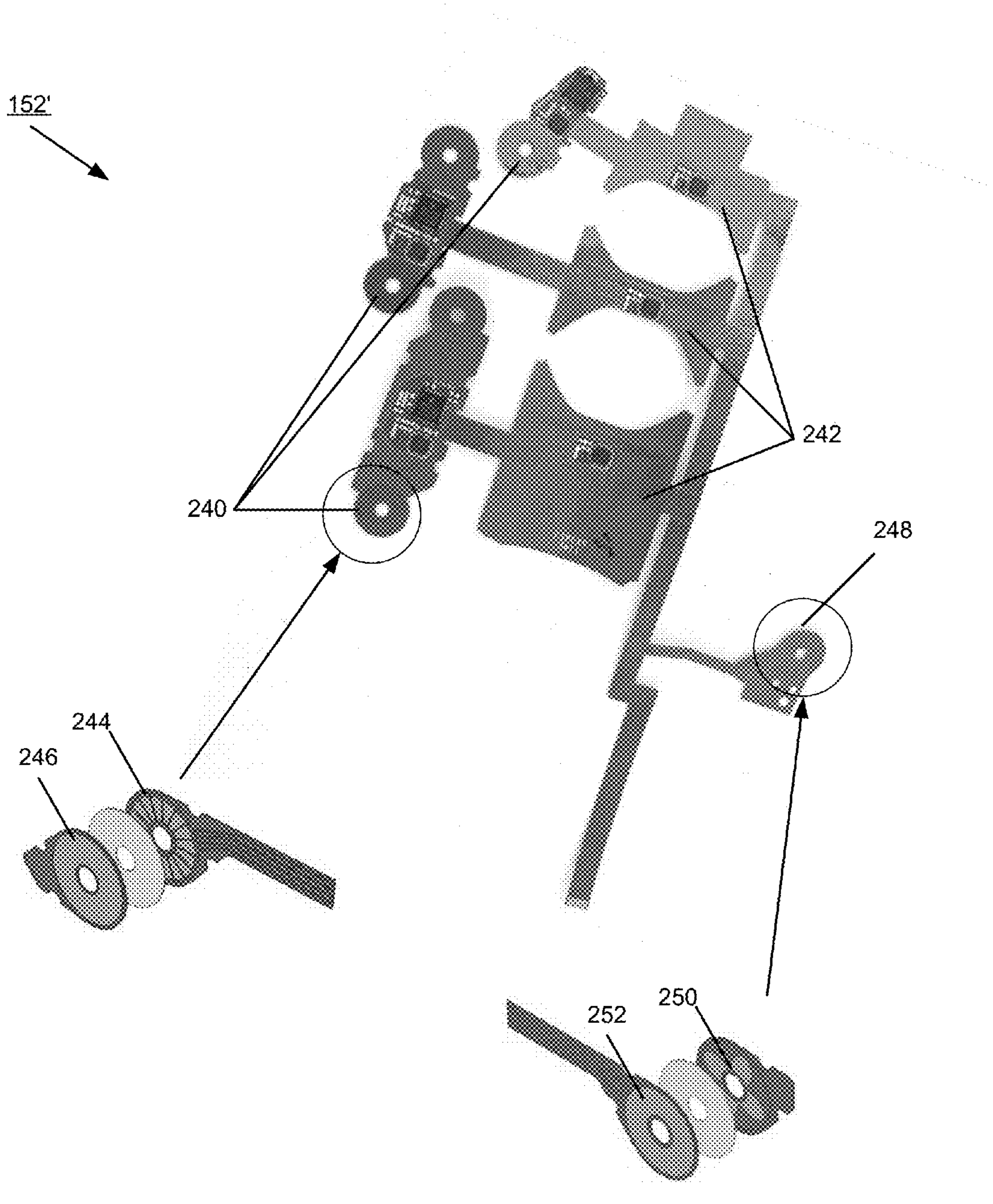


FIG. 34

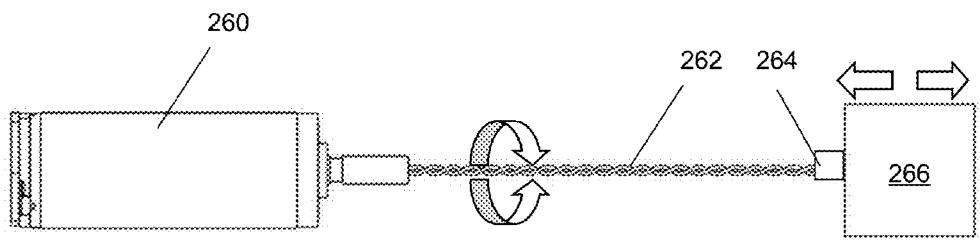


FIG. 35

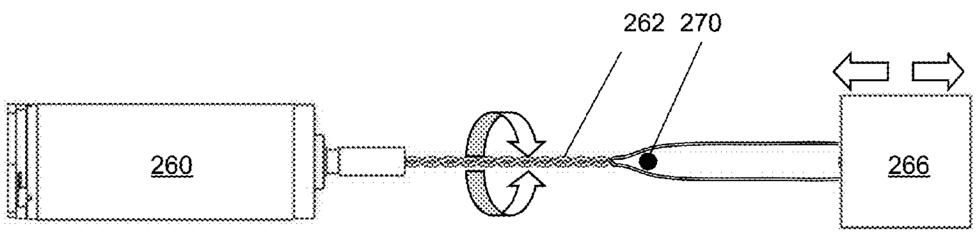
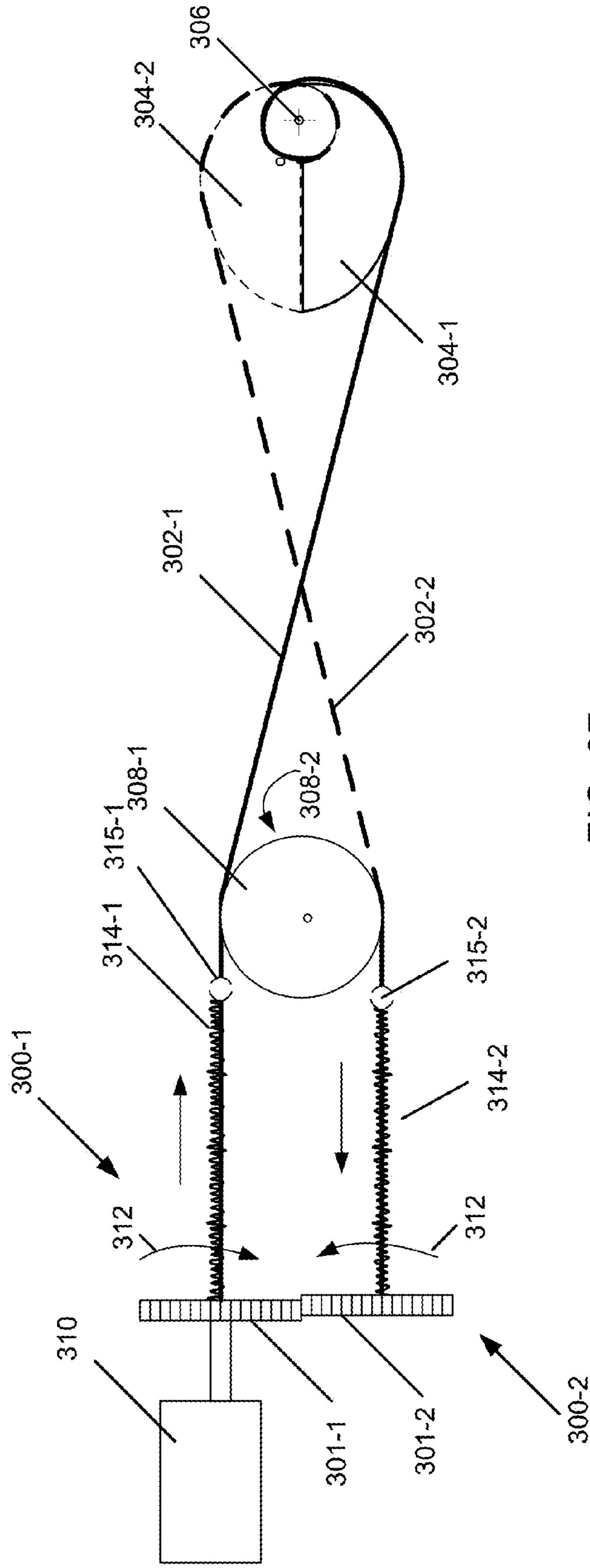


FIG. 36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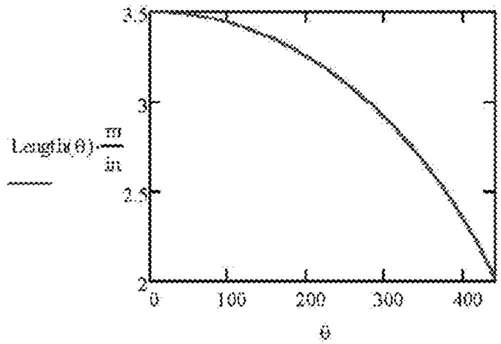
300-2

FIG. 37

FIG. 38



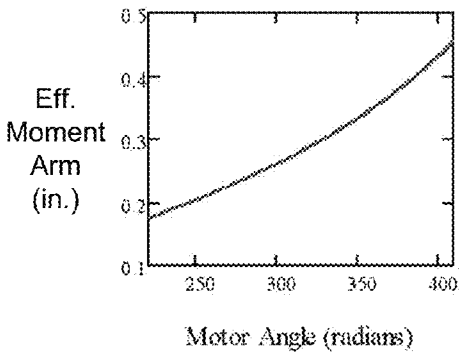


FIG. 39

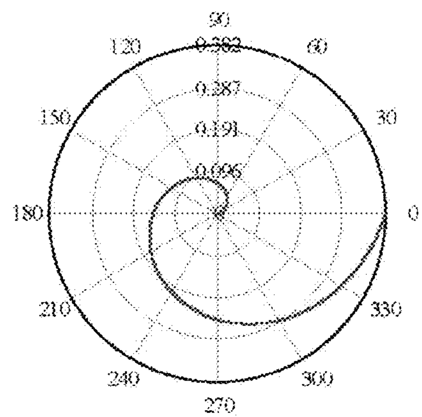


FIG. 40

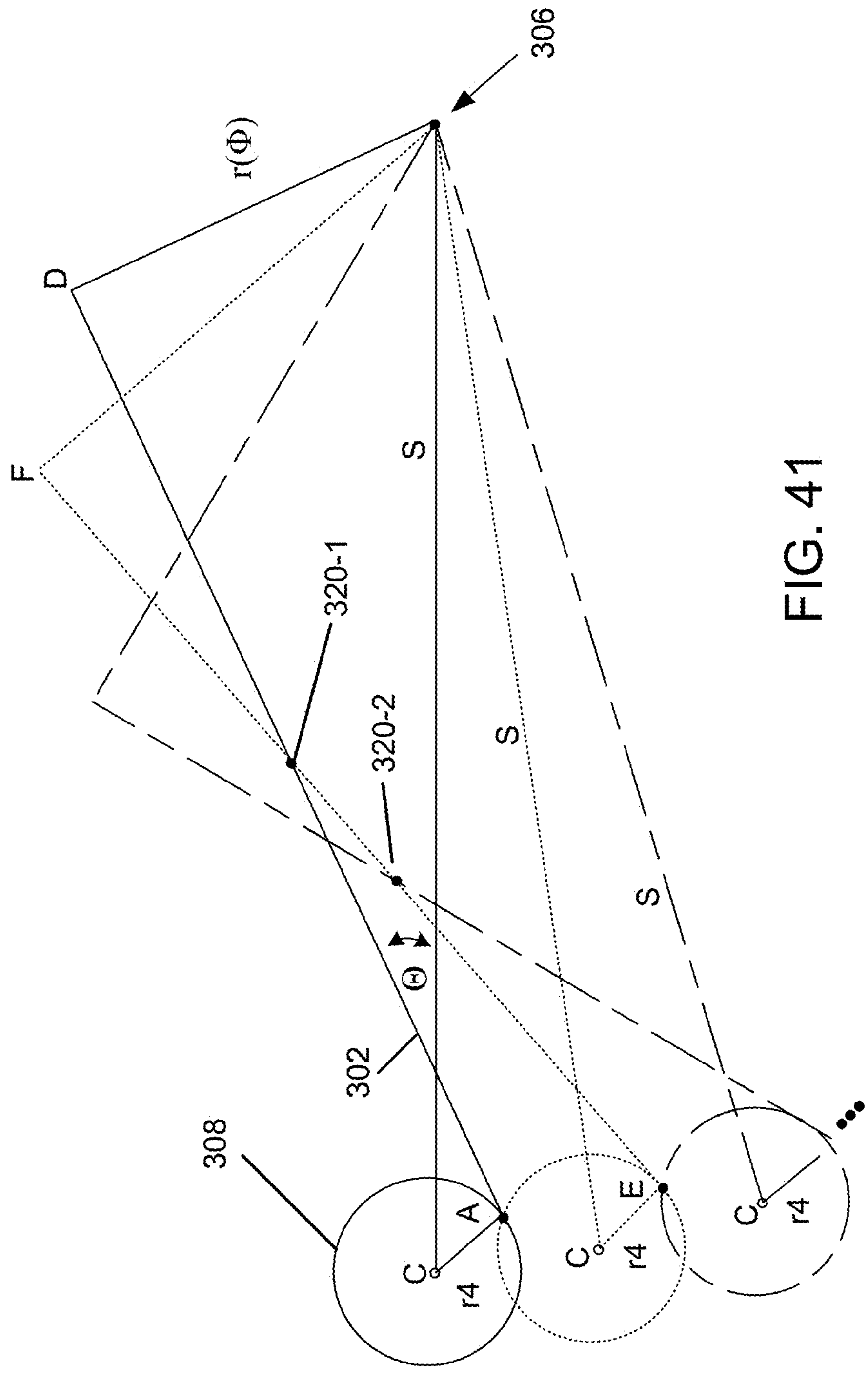


FIG. 41

$$X(\Phi) := \frac{\left|\begin{bmatrix} \left|\begin{pmatrix} x1(\Phi) & y1(\Phi) \\ x2(\Phi) & y2(\Phi) \end{pmatrix}\right| & x1(\Phi) - x2(\Phi) \\ \left|\begin{pmatrix} x3(\Phi) & y3(\Phi) \\ x4(\Phi) & y4(\Phi) \end{pmatrix}\right| & x3(\Phi) - x4(\Phi) \end{bmatrix}\right|}{\left|\begin{pmatrix} x1(\Phi) - x2(\Phi) & y1(\Phi) - y2(\Phi) \\ x3(\Phi) - x4(\Phi) & y3(\Phi) - y4(\Phi) \end{pmatrix}\right|} \quad m$$

$$Y(\Phi) := \frac{\left|\begin{bmatrix} \left|\begin{pmatrix} x1(\Phi) & y1(\Phi) \\ x2(\Phi) & y2(\Phi) \end{pmatrix}\right| & y1(\Phi) - y2(\Phi) \\ \left|\begin{pmatrix} x3(\Phi) & y3(\Phi) \\ x4(\Phi) & y4(\Phi) \end{pmatrix}\right| & y3(\Phi) - y4(\Phi) \end{bmatrix}\right|}{\left|\begin{pmatrix} x1(\Phi) - x2(\Phi) & y1(\Phi) - y2(\Phi) \\ x3(\Phi) - x4(\Phi) & y3(\Phi) - y4(\Phi) \end{pmatrix}\right|} \quad m$$

FIG. 42

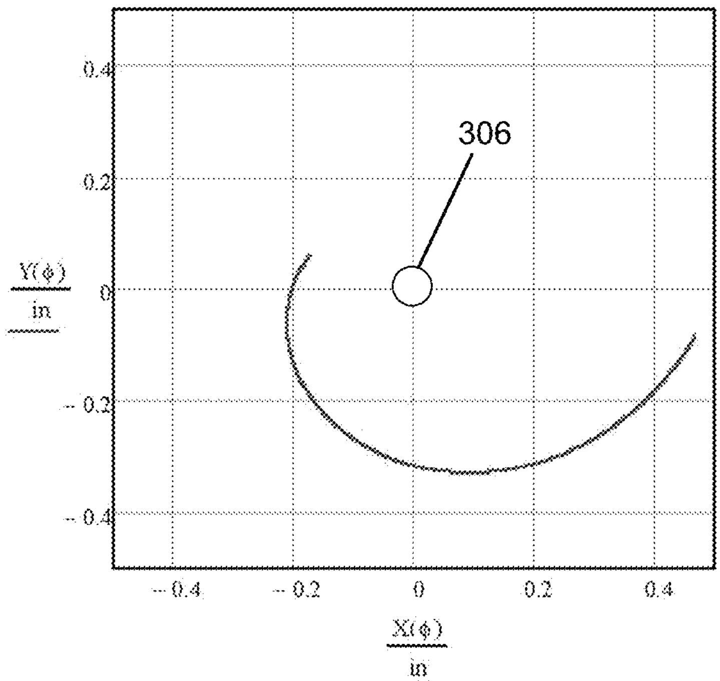


FIG. 43

TWISTED STRING ACTUATOR SYSTEMS

RELATED APPLICATIONS

This application is a continuation application of U.S. application Ser. No. 14/458,283 filed Aug. 13, 2014, titled "Multilayer Electrolaminate Braking System," which is a continuation application of U.S. application Ser. No. 14/005,092 filed Oct. 18, 2013, titled "Mobile Robotic Manipulator System," now U.S. Pat. No. 8,833,826, issued Sep. 16, 2014, which is the national stage of International Application No. PCT/US2012/029860, filed Mar. 21, 2012, designating the United States, which claims priority to and the benefit of the filing date of U.S. provisional application No. 61/454,945, filed on Mar. 21, 2011, titled "Improved Twisted String Actuator—I", U.S. provisional application No. 61/454,948, filed on Mar. 21, 2011, titled "A Modular Robotic Appendage—"A Finger"", U.S. provisional application No. 61/466,900, filed on Mar. 23, 2011, titled "Improved Twisted String Actuator—II", and U.S. provisional application No. 61/466,902, filed on Mar. 23, 2011, titled "A Mobile Robotic Manipulator System", the entireties of which applications are incorporated by reference herein.

GOVERNMENT RIGHTS IN THE INVENTION

This invention was made with government support under Contract No. W91-CRB-10-C-0139 awarded by the US Army. The government has certain rights in this invention.

FIELD OF THE INVENTION

The invention relates generally to robotic manipulator systems. More specifically, the invention relates to robotic appendages.

BACKGROUND

Many applications can benefit from the use of dexterous robotic hands that are capable of performing human-like tasks, such as grasping and manipulating a wide variety of objects. To achieve such versatility, the development of such robotic hands has turned to the use of underactuated fingers because underactuated fingers can self-adapt to wrap around objects, especially unknown objects. Although effective for power grasps, however, underactuation may perform poorly in precision grasps, in which the positions of the fingertips need to be controlled accurately, and where contact points are limited to distal links.

SUMMARY

In one aspect, the invention relates to a robotic finger assembly comprising a finger skeleton with one or more joints, a motor generating rotary motion of a rotor, and a twisted string comprised of a pair of cords. One end of the twisted string is attached to the rotor and an opposite end of the twisted string is coupled to the finger skeleton. The cords are twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string. A cord guide is fixedly disposed between the cords. The first section of the twisted string is on a first side of the cord guide, and the second section of the twisted string is on a second side of the cord guide. Rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide while pulling a portion of the pair of cords from the second side of the cord guide into the first side of the cord guide.

In another aspect, the invention relates to a robotic finger assembly comprising a finger skeleton with a pair of pulleys having a common axis of rotation, each pulley having a non-circular shape, a motor for generating rotary motion of a rotor, and first and second twisted string actuators each including a twisted string coupled at one end to the rotor and attached at an opposite end to one of the non-circular pulleys. The twisted string actuators are configured to operate in an antagonistic manner such that one twisted string actuator lengthens the twisted string of that twisted string actuator while the other twisted string actuator shortens the twisted string of that twisted string actuator in response to rotary motion produced by the motor. The non-circular shape of the pulleys is adapted to keep both twisted strings in tension throughout a range of the rotary motion produced by the motor.

In yet another aspect, the invention relates to a twisted string actuator system comprising a motor for generating rotary motion of a rotor, a pair of cams having a common axis of rotation, each cam having a non-circular shape, and first and second twisted string actuators each including a twisted string coupled at one end to the rotor and attached at an opposite end to one of the non-circular cams. The twisted string actuators are configured to operate in an antagonistic manner such that one twisted string actuator lengthens the twisted string of that twisted string actuator while the other twisted string actuator shortens the twisted string of that twisted string actuator in response to rotary motion produced by the motor. The non-circular shape of the cams is adapted to keep both twisted strings in tension throughout a range of the rotary motion produced by the motor.

In still another aspect, the invention relates to a twisted string actuator system including a motor generating rotary motion of a rotor and a twisted string comprised of a pair of cords. One end of the twisted string is attached to the rotor and an opposite end of the twisted string is coupled to a load. The cords are twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string. A cord guide is fixedly disposed between the cords. The first section of the twisted string is on a first side of the cord guide and the second section of the twisted string is on a second side of the cord guide. Rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide while pulling a portion of the pair of cords from the second side of the cord guide into the first side of the cord guide.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of this invention may be better understood by referring to the following description in conjunction with the accompanying drawings, in which like numerals indicate like structural elements and features in various figures. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. **1** is a diagram of an embodiment of robotic manipulator (or hand) having four finger modules.

FIG. **2** is a side view of one embodiment of the robotic manipulator.

FIG. **3** is a front view of the embodiment of the robotic manipulator of FIG. **2**.

FIG. **4** is a view of an embodiment of the robotic manipulator with the finger modules in an opposed configuration.

FIG. **5** is a view of an embodiment of the robotic manipulator with the finger modules in a spherical configuration.

FIG. **6** is a view of an embodiment of the robotic manipulator with the finger modules in an interlaced configuration.

FIG. **7** is a view of an embodiment of the robotic manipulator with underactuated fingers grasping an object.

FIG. **8** is a view of an embodiment of the robotic manipulator with underactuated fingers grasping a flashlight.

FIG. **9** is a view of the robotic manipulator with the fingers grasping a sphere.

FIG. **10** is a view of an embodiment of the robotic manipulator with the fingers using a precision grasp to pinch a key.

FIG. **11** is a view of an embodiment of the robotic manipulator with the fingers using a precision grasp to hold a pencil.

FIG. **12**A and FIG. **12**B are diagrams of example modes of operation for fingers grasping an object.

FIG. **13** is a diagram showing the use of selective locking of the joints of two opposing fingers to perform a precision grasp on a spherical object.

FIG. **14** is a diagram showing the use of selective locking of the joints of two opposing fingers to perform a precision grasp on a flat object.

FIG. **15**A and FIG. **15**B are diagrams showing the use of selective locking of the joints of two opposing fingers to hold, manipulate, and re-grasp an object.

FIG. **16** is an exploded view of one embodiment of the robotic manipulator including four finger modules and a palm assembly.

FIG. **17** is a side view of an embodiment of a finger module including a finger assembly mounted to an actuator module.

FIG. **18** is a view of an embodiment of the actuator module of FIG. **17**.

FIG. **19** is a diagram of an exploded view of one embodiment of the finger module including the finger assembly and the actuator module.

FIG. **20** is a diagram illustrating an example of a measure of rotational compliance of the finger assembly.

FIG. **21** is a diagram illustrating an example of a measure of lateral compliance of the finger assembly.

FIG. **22** and FIG. **23** are opposite side views of an embodiment of a finger assembly.

FIG. **24** is a bottom view of the embodiment of the finger assembly of FIG. **22** and FIG. **23**.

FIG. **25** is an exploded view of one embodiment of the finger assembly.

FIG. **26** is an isometric view of one embodiment of the internal structure of the finger assembly.

FIG. **27** is an edge view of the internal structure of the finger assembly.

FIG. **28** is a side view of an embodiment of the finger assembly with its distal joint shown in detail.

FIG. **29** is a diagrammatic view of an embodiment of a multilayer electrolaminate structure.

FIG. **30** is a flow diagram of an embodiment of a process for assembling a brake subsystem of the finger assembly.

FIG. **31**A-FIG. **31**G are pictorial illustrations of example steps of the assembly process described in FIG. **30**.

FIG. **32** is a diagrammatic representation of a multilayer skin covering a phalange of the finger assembly.

FIG. **33** is a diagram of an embodiment of a skin layer comprised of electroadhesive pads and embedded electrodes.

FIG. **34** is an image of an embodiment of a sensor assembly integrated into a single flex circuit board.

FIG. **35** is a diagram illustrating a conventional twisted-string actuator.

FIG. **36** is a diagram illustrating a twisted string actuator with a pin or pulley.

FIG. **37** is a diagram illustrating an embodiment of antagonistic string actuators with non-circular cams.

FIG. **38** is a graph illustrating an example length of the cord that is twisted for each angular position of the motor.

FIG. **39** is an example graph of the effective moment arm for each angular position of the motor.

FIG. **40** is an example graph illustrating the effective moment arm in polar coordinates.

FIG. **41** is a diagram illustrating an example process of determining a shape of the non-circular cam radius.

FIG. **42** shows equations for computing an example shape of the non-circular cam.

FIG. **43** is a graph illustrating an example shape of the non-circular cam.

DETAILED DESCRIPTION

Embodiments of robotic manipulators (or simply robotic hands) described herein employ selective underactuation, compliant force control, and multimodal tactile, position, and force sensing. Underactuation, when applied a mechanical device, signifies that the device has fewer actuators than degrees of freedom. Controllable selective underactuation, as described below, enable a robotic hand to grasp unknown objects using a power grasp, and then to switch to a precision grasp in order to perform operations requiring fine control of fingertip position and force. In general, a power grasp involves the palm and fingers in combination to secure an object firmly in the hand, whereas a precision grasp involves the fingertip regions to control the pose of an object precisely. With controllable selective underactuation, a robotic hand can employ a combination of power and precision grasps to hold, manipulate, and reposition an object, a process referred to as re-grasping.

The capabilities of the robotic hand extend from the capabilities designed into its individual underactuated fingers. In brief overview, the joints of each underactuated finger can lock and unlock independently in response to an electrical signal. This selective locking of joints allows a single actuator to multiplex the flexing of the finger joints. For example, each underactuated finger can passively wrap around an object of unknown shape to cooperate in a power grasp, and then selected joints of the fingers can be locked so the fingers can cooperate in a pincer to perform a precision grasp. A transmission integrated into each underactuated finger is back-driveable and has built-in elasticity, making the robotic hand resistant to shock and overload.

Grasping surfaces (i.e., skin) of the fingers can be fitted with electroadhesive pads to control adhesion and generate friction forces that overcome slippage and enhance the hand's grasping capabilities, yet without having to exert a gripping force that could crush or damage the object. The skin is abrasion-resistant and controllably compliant; the finger can be "soft" when making contact with objects of unknown shape and structure, and firm to control its precision precisely after making contact. Sensor assemblies integrated in the skin can sense contact pressure, slippage, and vibration. Fingers can detect contact points, grasping and pinching forces, the stability of the object, and slippage. These abilities enable manipulation and re-grasping of objects by rolling and sliding objects between fingertips. Other sensor devices can be incorporated into the finger to sense other types of parameters, for example, temperature and pressure.

FIG. **1** is a diagram of an embodiment of a robotic hand **10** having four finger modules **12-1**, **12-2**, **12-3**, **12-4** (generally, **12**) coupled to a palm assembly **14**. Each finger module **12** comprises a finger assembly (or simply finger) **16** with a proximal joint **18-1**, an intermediate joint **18-2**, and a distal joint **18-3**. The proximal joint **18-1** couples a proximal phalange **20-1** to a finger mount **24**, the intermediate joint **18-2** couples an intermediate phalange **20-2** to the proximal phalange **20-1**, and the distal joint **18-3** couples a distal phalange **20-3** (also called the fingertip) to the intermediate phalange **20-2**. The finger mount **24** is part of an actuator module, described in detail below. Each finger **16** has multilayer skin **22**. The palm assembly **14** can also be covered in a 'skin' adapted for grasping objects.

Each finger **16** can flex forward or backward at any of the joints and has three degrees of freedom (DOF); although the finger can have fewer or more DOFs, depending upon the particular application. As described in more detail below, a single actuator controls all three degrees of a finger, with selective locking of the joints allowing the single actuator to multiplex the flexing of the joints, individually, or in groups. By locking and unlocking the joints in rapid succession, the joints can appear to move and be controlled simultaneously.

In this embodiment, the finger modules **12-1**, **12-2** are movably coupled to one side of the palm assembly **14**, and the other finger modules **12-3**, **12-4** are fixed in position to the opposite side of the palm assembly **14**. The finger modules **12-1**, **12-2** can move together or apart. Fixing the location of the other finger modules **12-3**, **12-4**, makes their locations known and predictable, which is advantageous for precision grasps involving pinching by opposing finger modules (e.g. **12-1** and **12-4**).

Although described herein with reference to robotic hands with four fingers, the principles can extend to those embodiments with fewer or more than four.

FIG. **2** and FIG. **3** show a side view and front view, respectively, of one embodiment of the robotic hand **10** extending from a forearm **30**. Each finger **16** has a protective fingernail **32** at its fingertip. The fingernails of opposing fingers can be used to grasp small edges.

FIG. **4**, FIG. **5**, and FIG. **6** show the robotic hand **10** in three different configurations. In FIG. **4**, the fingers **16-1**, **16-2** are directly opposed to the fingers **16-3**, **16-4** (finger **16-1** being directly opposite finger **16-4**; finger **16-2** being directly opposite to finger **16-3**). In this configuration, the finger modules **12-1**, **12-2** are together, adjacent to each other, approximately midway along the side of the palm assembly **14**. The fingers **16** are bent so that the distal phalanges **20-3** and intermediate phalanges **20-2** of the fingers **16-1** and **16-4** are parallel to each other; as are the distal **20-3** and intermediate phalanges **20-2** of the fingers **16-2** and **16-3**. The finger modules **12-1**, **12-2** are disposed in a track **40** along which the finger modules **12-1**, **12-2** can travel laterally along the side of the palm assembly **14**. This lateral movement capability of the finger modules **12-1**, **12-2** makes the anatomy of the robotic hand **10** dynamically reconfigurable.

In FIG. **5**, the fingers **16-1**, **16-2** are spatially apart from each other and arched toward the other fingers **16-3**, **16-4**, which arch back toward the fingers **16-1**, **16-2**. The arrangement produces a spherical pose among the fingers **16**. In FIG. **6**, the fingers **16-1**, **16-2** are spatially apart from each other at opposite ends of the track **40** and bent forward. The other fingers **16-3** and **16-4**, fixed in their positions on the opposite side of the palm assembly **14**, are also bent forward, extending in the opposite direction of and coming in between the bent fingers **16-1** and **16-2**, producing an interlaced arrangement among the fingers **16**.

FIG. **7** through FIG. **11** show different grasps of which the robotic hand **10** is capable. The different grasps presented are merely illustrative examples; many other types of grasps are possible. In FIG. **7**, the underactuated fingers are executing a power grasp of an irregularly shaped object **50**. FIG. **8** shows the underactuated fingers in an interlaced configuration grasping a flashlight **52**. FIG. **9** shows the fingers in a spherical configuration grasping a sphere **54**. Two of the fingers use a power grasp to pinch a key **56** in FIG. **10**, whereas, in FIG. **11**, two fingers use a precision grasp to pinch a pencil **58**.

FIG. **12**A and FIG. **12**B show the use of selective locking of the joints of two opposing fingers **16-1** and **16-4** to alter a grasp of an object **60**. In FIG. **12**A, with all of the joints **18-1**, **18-2**, **18-3** (generally, **18**) unlocked, the fingers conform to the shape of the object **60**, and the robotic hand **10** performs a power grasp. Initially, the fingers **16** can close about the object until a finger detects light contact with the object. When a finger detects contact, its proximal joint **18-1** can be locked, while the remaining intermediate and distal joints of the finger remain unlocked. The intermediate and distal joints can continue to flex without increasing the contact force applied to the object. Accordingly, the contact with the object causes minimal disturbance of the object. Subsequently, the intermediate joint **18-2** can be locked, for example, after contact is detected on the intermediate phalange **20-2**, while the distal joint **18-3** remains unlocked. By locking the proximal and intermediate joints **18-1**, **18-2**, force can be transferred force to distal joint **18-3**, and the finger **16** has thus progressed from being underactuated with three degrees of freedom to having a single degree of freedom. After each finger makes contact sufficient to establish a grasp of the object, all joints can be locked to stiffen the grasp, as shown in FIG. **12**B.

FIG. **13** shows the use of selective locking of the joints of two opposing fingers **16-1** and **16-4** to perform a precision grasp on a spherical object **62**, which is held between the fingertips. In the execution of this grasp, the proximal joints **18-1** of both fingers are unlocked, while the intermediate joints **18-2** and distal joints **18-3** of both fingers **16-1**, **16-4** are locked, which effectively locks their distal phalanges **20-3**.

FIG. **14** shows the use of selective locking of the joints of two opposing fingers **16-1** and **16-4** to perform a precision grasp on a flat object **64**. The distal phalanges **20-3** of the opposing fingers can hyperextend to form a flat gripper, which provides a simple way of grasping small objects. To hold the object, all of the joints can be unlocked.

FIG. **15**A and FIG. **15**B show the use of selective locking of the joints of two opposing fingers **16-1** and **16-4** to hold, manipulate, and re-grasp an object **66**. In FIG. **15**A, the robotic hand has the object in a precision grasp, with the proximal joints **18-1** and intermediate joints **18-2** of both fingers being unlocked, while the distal joints **18-3** of both fingers are locked. As shown in FIG. **15**B, in an attempt to rotate the object **66**, the distal phalange **20-3** of the finger **16-1** pushes upwards against the object **66** and then locks its intermediate joint **18-2**, momentarily holding the finger **16-1** in this present position so that the other finger **16-4** can make the next move to further the rotation. By multiplexing incremental acts of flexing, locking, unlocking, and combinations thereof, the fingers can cooperate to manipulate and re-grasp objects held by the fingers **16** of the hand **10**.

FIG. **15**A and FIG. **15**B are just one example of how the robotic hand **10** can re-grasp an object. Numerous other techniques are possible, for instance, using three fingers to hold an object in a power grasp, while a fourth finger moves the object held in the power grasp. For example, the robotic hand **10** can use three fingers to hold a flashlight in a power grasp, and a fourth finger to rotate the flashlight to find and press its on/off button.

FIG. **16** shows an exploded view of one embodiment of the robotic hand **10** including the four finger modules **12-1**, **12-2**, 12-3, 12-4 and the palm assembly 14. All finger modules 12 are modular in construction; they are interchangeable, and can either be fixed or movably coupled to the palm assembly 14. In one embodiment, the palm assembly 14 includes a palm 68, a motor-and-hand controller PCB (printed circuit board) stack 70, a divider 72, a finger-spreader motor 74, a finger-spreader actuator 76, two finger-spreader blocks 78, a finger-module mount 80, high-voltage electronics 82, a base housing 84, and an arm adapter 86.

The arm adapter 86 couples the robotic hand 10 to a robotic forearm, for example, a GFE Barrett Arm (not shown). The base housing 84 attaches to the raised surface of the arm adapter 86. The high-voltage electronics 82 are housed within the base housing 84 and distribute power to the finger modules 12, motor-and-hand controller stack 70, and finger-spreader motor 74. In particular, the high-voltage electronics 82 include multiple switchable channels of high voltage (±1 kV) used to selectively lock and unlock joints 18, as described in more detail below.

The finger-spreader actuator 76 mounts to the open side of the finger module mount 80, and the finger module mount 80 connects to the top surface of the base housing 84. The finger-spreader motor 74 resides within a compartment defined by the side wall of the finger module mount 80 and the finger-spreader actuator 76. The finger-spreader motor 74 is operably coupled to move the finger-spreader actuator 76. The finger modules 12-3, 12-4 attach to the exterior of the side wall of finger module mount 80. Each finger-spreader block 78 couples one of the other finger modules 12-1, 12-2 to the finger-spreader actuator 76.

The palm 68 houses the motor-and-hand controller stack 70 and attaches to the top of the finger-module mount 80, the divider 72 serving as a gasket between the palm 68 and finger-module mount 80. The motor-and-hand controller stack 70 controls operation of the finger-spreader motor 74 in response to control commands, and interfaces with the finger modules 12 and the high-voltage electronics 82. Control signals sent from the motor-and-hand controller stack 70 to the high-voltage electronics 82 control the use of electroadhesion in the skin of the fingers and switch high voltage (e.g., +1 kV; −1 kV) among the electrolaminate brakes used to selectively lock and unlock the finger joints 18.

FIG. 17 shows an embodiment of a finger module 12 including the finger assembly 16 mounted to an actuator module 90. The actuator module 90 provides a backdriveable, twisted-string transmission with built-in compliance and low backlash. Although shown to be integrated into the finger module 12, in other embodiments, the twisted-string transmission of the actuator module 90 can be implemented in or mounted on a forearm connected to the robotic hand 10.

The actuator module 90 houses a motor 92, a machined spring 94, a motor encoder 96, a twisted string 98, a Hall Effect sensor 100, and a sensor circuit board 102 with a controller (e.g., 80 MIPS DSP). The motor 92 is, in one embodiment, a brushless DC motor (e.g., 15 W) with a high gear ratio (i.e., greater than 50:1). The motor encoder 96 tracks the position of the motor 92. The twisted string 98 is coupled by the finger mount 24 to the drive tendon 130. The twisted string 98 can be a KEVLAR, Spectra, or Vectran cable. The Hall Effect sensor 100 measures compression of the twisted string 98 to provide a force feedback signal, and the controller and sensor board 102 includes a force/current sensor that can measure actuator torque.

In brief overview, the actuator module 90 translates rotary motion of the motor 92 to linear motion of a tendon 130 (FIG. 22) within the finger 16. The motor 92 twists the twisted string 98. Twisting motion in one direction causes the length of the twisted string 98 to shorten, which causes a pull of the tendon 130 through the finger, causing the finger to actuate. The finger 16 flexes accordingly depending on which joints are locked and unlocked. Twisting in the other direction releases compression on the twisted string 98; and the spring return 140 (FIG. 24) urges the finger 16 to extend in a manner depending on which joints are presently locked and unlocked.

With a backdriveable transmission, the actuator module 90 can be responsive to external disturbances and maintain the force exerted on the finger below a certain level. If active force control is used to backdrive the transmission, sensors measure external forces exerted on the finger 16, and provide feedback. In response to this feedback, the actuator module 90 actively causes the motor 92 to move the finger in a manner as though the external forces were pushing the finger. Thus, the finger does not wholly resist the external forces, but moves with them. Alternatively, the transmission can be passively backdriveable without a sensor or a closed feedback loop buy using a low gear ratio (below 1:50) and having high efficiency.

FIG. 18 shows an embodiment of the actuator module 90 of FIG. 17. The actuator module 90 has disc-shaped plates 104 that interleave with and couple to plates of a finger assembly 16, to form the proximal joint 18-1 (FIG. 1) of the finger assembly 16. One side of the actuator module 90 has a notch 106 adapted to mount to one side of the palm assembly 14 (either to a rail on the side wall of the finger module mount 80 (FIG. 16) or to the finger-spreader blocks 78 (FIG. 16)).

FIG. 19 shows an exploded view of one embodiment of a finger module 12 including the finger assembly 16 and the actuator module 90 (exploded into three pieces: a plastic housing 90A, a palm assembly mount 90B with the notch 106, and a cover 90C). Also shown are the motor 92, the machined spring 94, the motor encoder 96, the sensor board 102, a forced-sensor assembly 110, and a twisted string assembly 112 with the twisted string 98. In addition, a flat flex electrical circuit 114 extends from the actuator module 90 to the proximal joint 18-1. The flex circuit 114 contains the communication bus for the position and tactile sensors in the fingers.

FIG. 20 and FIG. 21 show examples of mechanical compliance provided by the finger mount 24 used to join the finger assembly 16 to the actuator module 90. FIG. 20 shows to what degree the finger assembly 16 can be twisted relative to the actuator module 90. In this example, the finger module 20 is designed for ±15 degrees of twisting with respect to axis 120. FIG. 21 shows a measure of lateral compliance of the finger assembly 16 relative to the actuator module 90. Measured with respect to the axis 122, the finger assembly can tilt ±15 degrees. A flexure feature in the proximal joint 18-1 in the finger mount 24 at the base of the finger assembly 16 provides the rotational compliance. When an object is grasped with multiple fingers, the rotational and lateral compliance of the fingers can ensure that the fingers passively align and balance the normal forces exerted on the object.

FIG. 22 and FIG. 23 show opposite side views of an embodiment of the finger assembly 16. In FIG. 22, the finger assembly 16 includes a single cable (referred to as the tendon) 130 extending the length of the finger assembly. The tendon 130 runs from the finger mount 24 (not shown), routes around each joint 18-1, 18-2, 18-3, passes through each phalange 20-1, 20-2, and 20-3, and terminates near the fingertip 32 at an anchor point 132, to which the tendon 130 is fixed. The route of the tendon 130 through the finger 16 around the joints 18 and phalanges 20 runs tangent to pulley surfaces and passes through arcuate channels 134; the route is smooth, having no sharp corners. To bend the finger 16, force is applied to the tendon 130 in the direction indicated by arrow 136. The shape assumed by the finger **16** in response to the applied force depends on which joints **18** are locked and unlocked (and on any object currently in the grasp). FIG. **23** shows the side of the finger **16** opposite the tendon **130**. In FIG. **23**, the finger **16** has a thin protective outer skin **138**, with accordion-like folds at the joints **18** to allow for bending.

FIG. **24** shows a bottom view of the embodiment of the finger assembly **16** with a spring return **140** extending from the finger mount **24** to the distal phalange **20-3**. The spring return **140** couples to the finger mount **24** and to each phalange **20-1**, **20-2**, and **20-3** at anchor points **142**. The spring return **140** generally opposes the tendon **130** and urges the finger **16** to extend (straighten). Although a single tendon is being used to flex the finger, with a spring return **140** to urge the finger **16** back to its extended position, other embodiments can omit the spring return and use a single tendon in a loop configuration around the pulleys, or use multiple tendons.

FIG. **25** shows an exploded view of one embodiment of various components in the finger assembly **16**. The components include a stamped sheet metal skeleton **150**, a flex circuit **152** pre-bonded to the skeleton **150**, injection molded cable pulleys **154-1**, **154-2**, and **154-3** (generally, **154**), a first portion of an injection molded core **156**, a brake subsystem **158**, a stamped sheet metal skeleton **160** with hollow pins **162**, a second portion of the injection molded core **164** with the tendon **130** pre-inserted, the elastic spring return **140**, and rivets **166**.

When the finger **16** is fully assembled, the flex circuit **152** folds around each phalange **20**. The tendon **130** runs over the cable pulleys **154**. The two portions of the injection molded core **156**, **164** attach to each other to contain the tendon **130**. The spring return **140** attaches to anchor points **142** of the exterior side of the second portion of the injection molded core **164**.

The brake subsystem **158** provides the ability to lock and unlock joints. The brake subsystem **158** is shown here as a pre-assembled unit. Alternatively, the brake subsystem **158** can be assembled on the skeleton. The hollow pins **162** extend through openings in the brake subsystem **158**, the pulleys **154**, and skeleton **150**. The ends of the hollow pins **162** are flared to secure the assembly. The rivets **166** secure the skeleton **160** to the brake subsystem **158**.

FIG. **26** shows an isometric view and FIG. **27** shows an edge view of the internal structure of the finger **16** after assembly. The multi-layer internal structure includes the brake subsystem **158** sandwiched between the two sheet metal skeletons **150**, **160**. Segments of the brake subsystem **158** are wrapped in a shielding layer **170**. The shielding layer **170** shields sensors (i.e., in the flex circuit **152**) from possible interference from the high-voltage locking and unlocking actuation of the joints **18**.

FIG. **28** shows an example of the finger assembly **16**, with its distal joint **18-3** shown in detail. The distal joint **18-3** includes the cable pulley **154-3** and a multilayered composite structure **180** made of electrolaminate materials. In general, electrolaminates change from compliant and spring-like to essentially rigid, using electrostatic clamping to control the connectivity between different materials in the layered composite structure. The electrolaminate structure can withstand slip under pressure. The maximum force that the composite electrolaminate structure **180** can withstand is a function of the properties of the clamping surfaces, the applied voltage, and the total clamping area. Typical maximum clamping pressures are about 0.4 Mpa (70 psi).

The multilayered composite electrolaminate structure **180** can be fabricated as a monolithic sheet **190** (FIG. **31**A) with individual attachment points to each joint (or set of joints) that can be locked. The multilayered composite electrolaminate structure **180** includes passive (voltage-off) compliant elements that operate to oppose the actuator tendon **130** and provide an extensional force for each joint **18**. The multilayered composite electrolaminate structure **180** can be shielded by locating the ground planes on the outermost electrodes, or by encircling the electrolaminate structure **180** in a conductive elastomeric sheath.

FIG. **29** shows a diagrammatic representation of a multilayer electrolaminate structure **180** to illustrate the stiffening operation of a joint **18**. The multilayer electrolaminate structure **180** includes a plurality of brake layers **182** interleaved with spacer layers **184**. The joint **18** rotates about axis **186**. In response to an electrical signal (i.e., high voltage) to lock this joint **18**, the pressure distribution on the multilayer structure **180** occurs on both sides of the structure as illustrated by arrows **188**. Rather than concatenate segments of the multilayer electrolaminate structure **180** end-to-end, the multilayer electrolaminate structures **180** can be overlapped at the joint **18** to allow individual joint locking. Each segment of multilayer electrolaminate structure **180** is independently drivable; locking can be applied to the distal joint only, to the intermediate joint only, to the proximal joint only, to any two joints concurrently, or to all joints concurrently.

The multilayer electrolaminate structure **180** generates pressure through electrostatics, and is capable of producing high locking torques (e.g., approximately 4-12 lb-in for an electrolaminate stiffener having 5 layers, a 0.25 to 0.50 inch diameter, and 0.25 inch total thickness, and weighing 2.5 g). Power consumption can be less than a tenth of a Watt (e.g., 0.06). All forces are internal; hence the brake subsystem **158** does not require an external rigid structure to apply the braking force. After the applied voltage is removed, the multilayer electrolaminate structure **180** releases its grip in approximately 10 ms to 500 ms. The release time can determine how quickly one can multiplex locking and unlocking among the joints **18** of a finger **16**.

FIG. **30** shows a flow diagram of an embodiment of a process **200** for assembling the brake subsystem **158** of the finger assembly **16**. In the description of the process **200**, reference is made to FIGS. **31**A-**31**G to provide pictorial illustrations of some of the steps of the process **200**. At step **202**, an electrolaminate sheet **190** (FIG. **31**A) is pre-folded into an accordion pattern **192** (FIG. **31**B). Shielding layers **170** (FIG. **31**C) are wrapped (step **204**) around the electrolaminates. The accordion pattern **192** is placed (step **206**) onto rods **194** (FIG. **31**D), the rods **194** aligning with mounting features **196** on the finger skeleton **160**. The brake layers **182** are interlaced (step **208**) at each joint **18** and the accordion pattern **192** is lowered (step **210**) onto the skeleton. The electrolaminates are secured (step **212**) with the other side of the skeleton **150**. High voltage wires **198** are attached (step **214**) to the electrolaminates, to carry a voltage to each joint **18** that causes the corresponding multilayer electrolaminate structure of that joint to stiffen.

FIG. **32** shows a representation of the multilayer skin **220** covering a phalange **20** of the finger assembly **16**. The multilayer skin **220** includes a protective outer layer **222**, an electroadhesive layer **224**, a shield-compliant layer **226**, and a sensor layer **228**. The protective outer layer **222** wraps around the finger **16** to protect its internal components from external elements, such as dust, moisture, and chemicals. The protective outer layer **222** is made of a compliant and abrasion-resistant material, for example, polyurethane or latex. The material provides high friction, tear resistance, stretchability, and overall durability. The protective outer layer **222** is replaceable should it become worn from use.

The electroadhesive (EA) layer **224** is an electrically controllable skin layer capable of adhering to many materials surfaces, producing the effect of variable skin friction. This friction can assist in gripping objects to overcome slippage and enhance grasping capability. The EA layer **224** enables grasping objects of various sizes, with lower grasping forces, by controlling traction and sliding. The EA layer **224** can clamp on many types of materials, including, but not limited to, glass, wood, metal, concrete, drywall, brick, and granite. The clamping forces vary with the material. In addition, the EA layer **224** consumes almost no power (e.g., 0.02 mW/N of weight supported). The EA layer **224** can be detachable without affecting the mechanical grasping capabilities of the finger. The detachability enables use of the EA layer **224** whenever the EA layer **224** is appropriate for the task.

In one embodiment, the EA layer **224** is implemented with electroadhesive pads **230** (FIG. **33**) with embedded electrodes **232** (FIG. **33**). The EA layer **224** can be fabricated with a polymer, using a deposition technique, such as spray patterning. The electrode pattern can be fabricated from silicone or vulcanized rubber. A thin layer of abrasion-resistant polymer is deposited over the patterned electrodes to embed the electrodes. Although shown in FIG. **33** to be implemented on the phalanges of the fingers and on the palm, the EA layer **224** can also be folded into the joints.

High voltage (low current) applied to the electrodes induces electrostatic charges on the skin surface, which introduces anti-slip forces along an object surface. These anti-slip forces (or shear or traction forces) are decoupled from normal forces, enabling independent control of the normal and shear forces. This independent control is particularly advantageous for purposes of re-grasping an object. The selective modulation and enhancement of the skin friction (without the need for high grasping forces and tolerances) can be used in cooperation with object manipulations. Electroadhesion is described in more detail in U.S. Pat. No. 7,553,363, U.S. application Ser. No. 12/830,239, and U.S. application Ser. No. 12/762,260, the entireties of which are incorporated by reference herein.

The shield-compliant layer **226** is an electrically conducting layer integrated into one side of the EA layer **224** to mitigate interference with the various sensors of the tactile sensor layer **228** by the operation of the EA layer **224**.

The sensor layer **228** is comprised of a sensor assembly of tactile pressure sensors, vibrotactile sensors, and finger-joint position sensors for sensing contact pressures, slippage, and vibration at fingertips. Other types of sensors can be integrated into the sensor layer, including but not limited to shear sensors and temperature sensors. In one embodiment, the sensor layer is integrated into a single flex circuit board (e.g., flex circuit **152** of FIG. **25**) that conforms to the grasping surfaces of the finger **16**. For sensing contact and sliding, the fingertip **32** has an accelerometer.

FIG. **34** shows an embodiment of a sensor assembly integrated into a single flex circuit board **152'** (the prime (') here signifying an alternative embodiment of the flex circuit **152** shown in FIG. **25**). Each finger **16** has the flex circuit board **152'**, which extends to all finger joints **18** and phalanges **20**. Position sensors **240** and tactile (pressure) sensors **242** are printed onto the flex circuit board **152**. The position sensors **240** are embedded in the joints **18**; the tactile sensors **242** are on the phalanges **20**. Types of position sensors include, but are not limited to, capacitive sensors, Hall-Effect sensors, inductive sensors, and potentiometers. Preferably, the position sensor **240** includes a rotary capacitive sensor array **244**, as shown in FIG. **34**, with a built-in shield layer **246**. The shield layer **246** mitigates interference from the operation of the brake subsystem **158** on the performance of the position sensor **240**.

The flex circuit board **152'** can further include a position sensor **248** having a sensor array **250** and built-in shield **252**. The sensor **248** provides the position of each joint.

FIG. **35** shows a diagram generally illustrating a conventional twisted-string actuator **260**, in which two cords **262** twist about one another, or about a core, to form a helical section that shortens as the input (motor) is rotated. One end of this pair of cords **262** is attached to the input rotating shaft (from a motor) and the other end is connected to a sliding mechanism **264** that prevents this other end from twisting. This sliding component **264** is then attached to the output **266** of the actuator **260**, for example, a tendon or other similar linear output. The length of cord **262** between the sliding and rotating ends of the twisting section is fixed and prescribed by the designer.

In FIG. **36**, the sliding component **264** is eliminated and, in its place, a fixed pin **270** or pulley is used. The distance between the rotating input shaft (of the motor) and the pin **270** is constant and fixed by the designer. As the actuator input (motor) **260** is rotated, the cords **262** between the actuator input **260** and the fixed pin **270** twist, shortening and pulling additional untwisted string past the fixed pin or pulley into the twisted region. In this manner, the length of the string that is twisted is no longer fixed, but increases as the actuator input shaft rotates. Because a greater length of cord is available to be twisted, a greater number of twists can be supported before exceeding the limit of the critical helix angle, given by

$$\text{Alpha-max}=\arctan(\text{number of cords}\times\text{radius of cord}/\text{pi}\times\text{radius of helix}),$$

after which knotting occurs. For a two-cord actuator, this critical helix angle is about 32.5 degrees, where a 90-degree helix angle describes an untwisted actuator. The use of the pin **270** (or pulley) increases the effective stroke of the actuator, allowing the cords **262** to foreshorten by 86% of its original length, compared to 46% of a fixed length cord, before this limit is reached. The length of the actuator at the maximum helix angle, alpha max is:

$$\text{Linit}/\cos(\text{pi}-\text{alpha max})-\text{Linit}$$

where Linit is the distance between the fixed pin or pulley and the rotating input. Therefore, percent foreshortening is:

$$(\text{Linit}/\cos(\text{pi}-\text{alpha max})-\text{Linit}/\text{Linit}=0.86$$

Further, in the conventional twisted string actuator **260** of FIG. **35**, the output **266** is nonlinear. Furthermore, when a pair of twisted string actuators is used in an antagonistic manner, for example, to move a lever, or arm, around a pivot point, or joint, one actuator lengthens while the opposite one shortens, each in a non-linear manner. Therefore, if two tendons connected to the twisted string actuators were used to actuate a robot joint by wrapping the tendons around a circular pulley at that joint, the tension in the tendons would change when the joint is moved. In some joint positions the tendons would be slack and the position of the joint would not be known and not be controlled.

To linearize the output action of a set of opposing, antagonistic, twisted string actuators **300-1**, **300-2** (generally, **300**), a non-circular pulley can be used, as shown in FIG. **37**. Each tendon **302-1**, **302-2** is fixed to a non-circular cam **304-1**, **304-2**, respectively, which share a common axis **306** of rotation (enters into the plane of the FIG. **37** at crosshairs). In FIG. **37**, cam **304-1** is above the cam **304-2**. Each of the tendons

302-1, **302-2** passes around an idler pulley **308-1**, **308-2**, respectively (in FIG. **37**, idler pulley **308-1** is above idler pulley **308-2**). The tendon **302-1** is connected to the upper cam **304-1**; the tendon **302-2** crosses below the tendon **302-1** and is connected to the lower cam **304-2**.

A motor **310** turns the string actuator **300-1**, which has gears **301-1** that mesh with the gears **301-2** of the other twisted string actuator **300-2**. The twisted string actuators **300** are antagonistic; the motor **310** operates to turn them **300** in operate directions (as indicated by arrows **312**); alternatively, the motor **310** operates to turn them **300** in the same direction, but the twisted string sections **314-1**, **314-2** are twisted in opposite directions. In one embodiment, a fixed pin (or pulley) **315-1**, **315-2** can be disposed between the cords of each twisted string **314-1**, **314-2**, respectively, to increase the length of cord that is available for twisting, as described in connection with FIG. **36**.

The specific shape of each cam **304-1**, **304-2** is determined algebraically. In the embodiment shown, each cam **304-1**, **304-2** has a shape of a nautilus; the cams **304** oppose each other (i.e., a mirror image of each other). In this way, both tendons remain in proper tension as the actuator system moves through its designed range of operation.

Consider that the length of a cord **302** that will be twisted, L, is equal to 3.5 in., the diameter of 60 lb. test spectra cord, d, is equal to 013·in.; the radius of the cord, r, is equal to d/2, and θ is the angular position of the motor **310**.

As the cord **302** twists, its length depends on the angular position of the motor **310**, given by the equation Length(θ):=L cos(asin((θ·r)/L)). The change in this length is given by the equation dLdθ(θ):=((θ*r^2)/(L*sqrt(1−(θ^2·r^2)/L^2)). FIG. **38** is a graph showing the shortening length of the twisted cord as a function of the angular position of the motor **310**.

Consider, for illustration purposes, that the cam **304** rotates 1/60th of a full rotation for each full rotation of the motor **310** (i.e., Ratio:=60), where the rotation of the cam, called OutputRotation, is equal to 360 deg/Ratio. The effective radius of the cam is given by the equation r_2:=Ratio*((θ*r^2)/(L*sqrt(1−(θ^2·r^2)/L^2)). FIG. **39** shows the effective moment arm of the cord **302** around the axis **306** (i.e., perpendicular distance from the axis **306** of rotation to the line of the cord) as a function of the angle of the motor. FIG. **40** is a graph, in polar coordinates, of the effective moment arm as a function of the angle of the motor.

Consider further, for illustration purposes, that the radius of the idler pulley **308**, r_4, is equal to 0.6113 in., and that the distance, S, between the center, C, of the idler pulley **308** and the cam axis **306** is equal to 2.0 in.

FIG. **41** graphically illustrates an algorithm by which to determine algebraically the shape of the cams **304**. In brief overview, the algorithm finds the angle θ between the line connecting the center of the cam and the idler pulley for each angle ϕ. Phi, ϕ, is the range variable, and represents the orientation (angle) of the output cam. r(ϕ) is the instantaneous radius of action, which is at a right angle to where the cord **302** tangentially contacts the cam **304**. Then, the algorithm finds the coordinates of points A and D. The algorithm increments the angle to ϕ', and get new points A' and B', and finds the intersection **320-1** of line AD and EF. The process repeats for each increment of the angle (e.g., the dotted and dashed iterations in FIG. **41** are each an increment of the angle), finding a new intersection point between the new tangential line and the previous tangential line. The curve formed by the intersection points **320-1**, **320-2** corresponds to the shape of the cam **304**. The equations for determining the shape are as follows:

$$\theta(\phi):=\mathrm{asin}((r_2(\phi*\mathrm{Ratio})+r_4)/S);[\text{e.g.}\ \theta(\phi)=22.242\ \text{deg}]$$

$$C(\phi):=(S\cdot\cos(\phi)S\cdot\sin(\phi))(C\ \text{is the center of the idler pulley308, e.g.,}\ C(\phi)=(-20)\ \text{in}).$$

The vector from the center C of the idler pulley to the point of tangency A is:

$$CA(\theta,\phi):=(r_4*\cos(\theta+\phi+\pi/2)r_4*\sin(\theta+\phi+\pi/2));[\text{e.g.,}\ CA(\theta(\phi),\phi=(0.231-0.566)\ \text{in.}]$$

$$A(\phi):=C(\phi)+CA(\theta(\phi),\phi;[\text{e.g.,}\ A(\phi)=(-1.769-0.566)\ \text{in.}]$$

$$D(\phi):=(r_2(\phi*\mathrm{Ratio})*\cos(\theta(\phi)+\phi-\pi/2)r2(\phi\cdot\mathrm{Ratio})\sin(\theta(\phi)+\phi-\pi/2));[\text{e.g., where}\ r_2(\phi\cdot\mathrm{Ratio})=0.146\text{in},D(\phi)=(-0.055\ 0.135)\ \text{in.}]$$

The center C of the idler pulley is incremented by the angle ϵ (e.g., ϵ:=0.1 deg.) to determine the next tangential line of the cord **302** and its point of intersection with the previous line.

$$E(\phi):=C(\phi+\epsilon)+CA(\theta(\phi+\epsilon),\phi+\epsilon);[\text{e.g.,}\ E(\phi)=(-1.768-0.569)\ \text{in.}]$$

$$F(\phi):=[r2[(\phi+\epsilon)\cdot\mathrm{Ratio}]\cos(\theta(\phi+\epsilon)+\phi+\epsilon-\pi/2),\ r2[(\phi+\epsilon)\cdot\mathrm{Ratio}]\sin(\theta(\phi+\epsilon)+\phi+\epsilon-\pi/2)];\ [\text{e.g.,}\ F(\phi)=(-0.055,0.135)\ \text{in.}]$$

The algorithm finds the points of intersection:

$$x1(\phi):=|A(\phi)^{(0)}/m|;x1=f(\text{Unitless})\rightarrow\text{Unitless}$$

$$y1(\phi):=|A(\phi)^{(1)}/m|$$

$$x2(\phi):=|D(\phi)^{(0)}/m|$$

$$y2(\phi):=|D(\phi)^{(1)}/m|$$

$$x3(\phi):=|E(\phi)^{(0)}/m|$$

$$y3(\phi):=|E(\phi)^{(1)}/m|$$

$$x4(\phi):=|F(\phi)^{(1)}/m|$$

$$y4(\phi):=|F(\phi)^{(1)}/m|$$

FIG. **42** shows the equations for computing the output of the X(ϕ) and Y(ϕ), which provides the shape of the cam corresponding by the points of intersection.

The following describes an example of determining a range in the number of twists needed in each twisted string section **314** (FIG. **37**) to complete a desired range of rotation of a finger joint (each string will have the same number of twists). For example, consider the desired range of rotation for the joint to be between −90° and +90° (i.e., total range of 180°, or π radians) with reference to a neutral position (i.e., the midpoint). For the cam output, ϕ, to go through this angle of π radians, the motor must go through Ratio*π radians, which is equal to 188.496 total rotations of motor in radians. If the midpoint is given as a number of twists (e.g., mid:=50) in each string, then mid·2·π=314.159 is the number of radians the motor has spun to get this many twists. For a range centered at mid radians, rotating plus Ratio*π/2 radians and minus Ratio*π/2 radians produces a minimum number of twists (min) and a maximum number of twists (max) to achieve the full desired range of rotation (min:=mid*2*π−Ratio*π/2, and max:=mid*2*π+Ratio*π/2). In the present example, min=219.911 rad and max=408.407 rad, and the corresponding radians of rotation for the motor are min/2−π=35 twists and max/2−π=65 twists.

The orientation of the output cam at extremes of cable twists: min/Ratio=210 deg; and max/Ratio=390 deg.

A check of the total travel:

$$(\max-\min)/\mathrm{Ratio}=180\ \text{deg}.$$

A check of that angle at mid-range of the travel:

$$(\text{mid}\cdot 2\cdot\pi)/\text{Ratio}=300\ \text{deg.}$$

$$\Phi:=\text{min/Ratio},\text{min/Ratio}+\epsilon\ \ldots\ \text{max/Ratio.}$$

$$i:=0,1\ \ldots\ \pi/\epsilon$$

$$\text{Output}_{i,0}:=X(\text{min/Ratio}+\epsilon^{*}\text{i})$$

$$\text{Output}_{i,1}:=Y(\text{min/Ratio}+\epsilon^{*}i)$$

A check of the slope of a line between first and last point:

$$\text{atan}((\text{Output}_{1800,1}-\text{Output}_{0,1})/(\text{Output}_{1800,0}-\text{Output}_{0,0}))=-12.693\cdot\text{deg.}$$

Table 1 shows the cam Output (in.)=

TABLE 1

	0	1
0	−0.173	0.06
1	−0.173	0.06
2	−0.173	0.06
3	−0.174	0.059
4	−0.174	0.059
5	−0.174	0.059
6	−0.174	0.059
7	−0.174	0.058
8	−0.175	0.058
9	−0.175	0.058
10	−0.175	0.058
11	−0.175	0.057
12	−0.175	0.057
13	−0.175	0.057
14	−0.176	0.056
15	−0.176	. . .

FIG. **43** shows the output, which corresponds to the shape of the cam **304**. The common axis **306** of the cam **304** is at the origin (0,0) of the graph.

Reference in the 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 of the teaching. References to a particular embodiment within the specification do not all: necessarily refer to the same embodiment. The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention.

As will be appreciated by one skilled in the art, aspects of the present invention may be embodied as a system, method, and computer program product. Thus, aspects of the present invention may be embodied entirely in hardware, entirely in software (including, but not limited to, firmware, program code, resident software, microcode), or in a combination of hardware and software. All such embodiments may generally be referred to herein as a circuit, a module, or a system. In addition, aspects of the present invention may be in the form of a computer program product embodied in one or more computer readable media having computer readable program code embodied thereon.

Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable storage medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

A computer readable signal medium may include a propagated data signal with computer readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A computer readable signal medium may be any computer readable medium that is not a computer readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

Program code embodied on a computer readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wired, optical fiber cable, radio frequency (RF), etc. or any suitable combination thereof.

Computer program code for carrying out operations for aspects of the present invention may be written in any combination of one or more programming languages, including an object oriented programming language such as JAVA, Smalltalk, C++, and Visual C++ or the like and conventional procedural programming languages, such as the C and Pascal programming languages or similar programming languages.

Aspects of the present invention may be described with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

These computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The computer program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

Aspects of the described invention may be implemented in one or more integrated circuit (IC) chips manufactured with semiconductor-fabrication processes. The maker of the IC chips can distribute them in raw wafer form (on a single wafer with multiple unpackaged chips), as bare die, or in packaged form. When in packaged form, the IC chip is mounted in a single chip package, for example, a plastic carrier with leads affixed to a motherboard or other higher level carrier, or in a multichip package, for example, a ceramic carrier having surface and/or buried interconnections. The IC chip is then integrated with other chips, discrete circuit elements, and/or other signal processing devices as part of either an intermediate product, such as a motherboard, or of an end product. The end product can be any product that includes IC chips, ranging from electronic gaming systems and other low-end applications to advanced computer products having a display, an input device, and a central processor.

While the invention has been shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the following claims.

What is claimed is:

1. A robotic finger assembly comprising:

a finger skeleton with one or more joints;

a motor generating rotary motion of a rotor;

a twisted string comprised of a pair of cords, one end of the twisted string being attached to the rotor and an opposite end of the twisted string being coupled to the finger skeleton, the cords being twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string; and

a cord guide fixedly disposed between the cords, wherein the first section of the twisted string is on a first side of the cord guide, the second section of the twisted string is on a second side of the cord guide, and rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide while pulling a portion of the pair of cords from the second side of the cord guide into the first side of the cord guide.

2. The robotic finger assembly of claim **1**, wherein the cord guide comprises a pulley.

3. The robotic finger assembly of claim **1**, further comprising a tendon passing through each of the one or more joints of the finger skeleton, the tendon having a first end attached to the finger skeleton and a second end coupled to the opposite end of the twisted string.

4. The robotic finger assembly of claim **1**, further comprising a tendon having one end coupled to the opposite end of the twisted string and a second end attached to a non-circular pulley.

5. The robotic finger assembly of claim **1**, wherein a distance between the cord guide and the rotor of the motor remains constant throughout the operation of the motor.

6. The robotic finger assembly of claim **1**, wherein the pair of cords can be foreshortened by approximately 86 percent of an original length of the pair of cords before knotting in the first section of the twisted string occurs.

7. The robotic finger assembly of claim **1**, wherein the cord guide comprises a fixed pin.

8. A robotic finger assembly comprising:

a finger skeleton with a pair of pulleys having a common axis of rotation, each pulley having a non-circular shape;

a motor for generating rotary motion of a rotor;

first and second twisted string actuators each including a twisted string coupled at one end to the rotor and attached at an opposite end to one of the non-circular pulleys, the twisted string actuators being configured to operate in an antagonistic manner such that one twisted string actuator lengthens the twisted string of that twisted string actuator while the other twisted string actuator shortens the twisted string of that twisted string actuator in response to rotary motion produced by the motor, wherein the non-circular shape of the pulleys is adapted to keep both twisted strings in tension throughout a range of the rotary motion produced by the motor.

9. The robotic finger assembly of claim **8**, further comprising a pair of tendons each having a first end coupled to one of the non-circular pulleys and an opposite end attached to the finger skeleton.

10. The robotic finger assembly of claim **8**, wherein the finger skeleton includes a joint, wherein the joint comprises the pair of non-circular pulleys.

11. The robotic finger assembly of claim **8**, further comprising a pair of idler pulleys disposed between the motor and the pair of non-circular pulleys, wherein the twisted strings pass on opposite sides of the idler pulleys and cross each other before attaching to the non-circular pulleys.

12. The robotic finger assembly of claim **11**, wherein each twisted string comprises a pair of cords twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string, and wherein each twisted string actuator further comprises a cord guide fixedly disposed between the rotor and the idler pulleys, wherein the first section of the twisted string of each twisted string actuator is on a first side of the cord guide of that twisted string actuator, the second section of the twisted string of each twisted string actuator is on a second side of the cord guide of that twisted string actuator, and rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide of a given one of the twisted string actuators while pulling a portion of the pair of cords of that given one twisted string actuator from the second side of the cord guide of that given one twisted string actuator into the first side of the cord guide of that one twisted string actuator.

13. The robotic finger assembly of claim **12**, wherein the cord guide comprises a fixed pin.

14. The robotic finger assembly of claim **12**, wherein the cord guide comprises a pulley.

15. The robotic finger assembly of claim **12**, wherein a distance between the cord guide and rotor of each twisted string actuator remains constant throughout the operation of that twisted string actuator.

16. A twisted string actuator system comprising:

a motor generating rotary motion of a rotor;

a twisted string comprised of a pair of cords, one end of the twisted string being attached to the rotor and an opposite end of the twisted string being coupled to a load, the cords being twisted about each other for a first section of the twisted string and untwisted for a second section of the twisted string; and

a cord guide fixedly disposed between the cords,

wherein the first section of the twisted string is on a first side of the cord guide, the second section of the twisted string is on a second side of the cord guide, and rotary motion of the rotor in one direction operates to twist the pair of cords on the first side of the cord guide while pulling a portion of the pair of cords from the second side of the cord guide into the first side of the cord guide.

17. The twisted string actuator system of claim **16**, wherein the cord guide comprises a fixed pin.

18. The twisted string actuator system of claim **16**, wherein the cord guide comprises a pulley.

19. A twisted string actuator system comprising:

a motor for generating rotary motion of a rotor;

a pair of cams having a common axis of rotation, each cam having a non-circular shape;

first and second twisted string actuators each including a twisted string coupled at one end to the rotor and attached at an opposite end to one of the non-circular cams, the twisted string actuators being configured to operate in an antagonistic manner such that one twisted string actuator lengthens the twisted string of that twisted string actuator while the other twisted string actuator shortens the twisted string of that twisted string actuator in response to rotary motion produced by the motor, wherein the non-circular shape of the cams is adapted to keep both twisted strings in tension throughout a range of the rotary motion produced by the motor.

20. The twisted string actuator system of claim **19**, further comprising a pair of idler pulleys disposed between the motor and the pair of cams having the non-circular shape, wherein the twisted strings pass on opposite sides of the idler pulleys and cross each other before attaching to the cams.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,272,425 B2
APPLICATION NO. : 14/745668
DATED : March 1, 2016
INVENTOR(S) : Garcia et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 14, Line 8:
• Add close ")" between "φ" and "="

Column 14, Line 10:
• Replace ";" with ");" between the fourth occurrence of "φ" and ";"

Column 14, Line 36:
• Replace the number "1" after the second occurrence of "(φ)" with "0"

Signed and Sealed this
Twenty-first Day of June, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office