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- (54) **Title:** HIGHLY ARTICULATED PROBES WITH ANTI-TWIST LINK ARRANGEMENT, METHODS OF FORMATION THEREOF, AND METHODS OF PERFORMING MEDICAL PROCEDURES

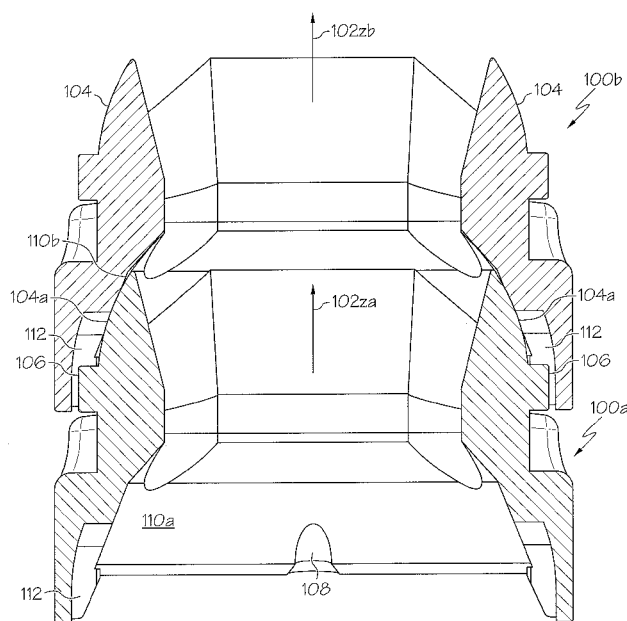


FIG. 1C

- (57) **Abstract:** An articulating probe, comprises a first mechanism including a first link comprising a first longitudinal axis, a first articulation surface and a first motion-limiting element; and a second link comprising a second longitudinal axis, a second articulation surface and a second motion-limiting element. An articulation joint comprises the first articulation surface and the second articulation surface and constructed and arranged to allow two degree-of-freedom articulation of the second link relative to the first link. A motion resisting assembly comprises the first motion limiting element and the second motion limiting element, wherein the motion resisting assembly is constructed and arranged to resist rotation of the second link about the second longitudinal axis relative to the first longitudinal axis of the first link.



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HIGHLY ARTICULATED PROBES WITH ANTI-TWIST LINK ARRANGEMENT,
METHODS OF FORMATION THEREOF, AND METHODS OF PERFORMING
MEDICAL PROCEDURES

5

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 61/534,032, filed September 13, 2011, the content of which is incorporated herein by reference in its entirety.

10

This application claims the benefit of U.S. Provisional Application No. 61/578,582, filed December 21, 2011, the content of which is incorporated herein by reference in its entirety.

This application claims the benefit of U.S. Provisional Application No. 61/656,600, filed June 7, 2012, the content of which is incorporated herein by reference in its entirety.

15

This application claims the benefit of U.S. Provisional Application No. 61/681,340, filed August 9, 2012, the content of which is incorporated herein by reference in its entirety.

This application is related to PCT Application No. PCT/US2012/040414, filed June 1, 2012, the content of which is incorporated herein by reference in its entirety.

This application is related to U.S. Provisional Application No. 61/492,578, filed June 2, 2011, the content of which is incorporated herein by reference in its entirety.

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This application is related to PCT Application No PCT/US2012/032279, filed April 5, 2012, the content of which is incorporated herein by reference in its entirety.

This application is related to United States Provisional Application No. 61/472,344, filed April 6, 2011, the content of which is incorporated herein by reference in its entirety.

25

This application is related to PCT Application No PCT/US2011/060214, filed November 10, 2011, the content of which is incorporated herein by reference in its entirety.

This application is related to U.S. Provisional Application No. 61/412,733, filed November 11, 2010, the content of which is incorporated herein by reference in its entirety.

This application is related to PCT Application No PCT/US2011/057282, filed October 21, 2011, the content of which is incorporated herein by reference in its entirety.

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This application is related to U.S. Provisional Application No. 61/406,032, filed October 22, 2010, the content of which is incorporated herein by reference in its entirety.

This application is related to PCT Application No PCT/US2011/044811, filed July 21, 2011, the content of which is incorporated herein by reference in its entirety.

This application is related to U.S. Provisional Application No. 61/368,257, filed July 28, 2010, the content of which is incorporated herein by reference in its entirety.

5 This application is related to U.S. Patent Application No. 11/630,279, filed December 20, 2006, published as U.S. Patent Application Publication No. 2009/0171151, the content of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

10 Embodiments of the present inventive concepts relate generally to the field of robotics and, more particularly, to three-dimensional, flexible, steerable robotic devices, and methods of forming and controlling the same.

BACKGROUND

15 As less invasive medical techniques and procedures become more widespread, medical professionals, such as surgeons, may employ snake-like robotic systems having highly articulated multi-link probes to access parts of the human anatomy that were otherwise difficult to reach. With the use of such robotic systems, medical professionals may be able to replace open-cavity surgical procedures with less invasive procedures.

20 Robotic systems of the type described above may have multiple device channels, referred to as working channels, for guiding a variety of surgical and/or interventional tools during surgical procedures. Conventional articulating probes, which generally comprise a series of steerable links, are subject to twisting, from link to link, which can adversely affect the performance of the articulating probe.

25

SUMMARY

Embodiments of the present inventive concepts may be directed to articulating robotic systems, robotic system user interfaces, human interface devices for controlling robotic systems and methods of controlling robotic systems.

30 In an aspect, an articulating probe, comprises: a first mechanism comprising: a first link comprising a first longitudinal axis, a first articulation surface and a first motion-limiting element; a second link comprising a second longitudinal axis, a second articulation surface and a second motion-limiting element; an articulation joint comprising the first articulation

surface and the second articulation surface and constructed and arranged to allow two degree-of-freedom articulation of the second link relative to the first link; and a motion resisting assembly comprising the first motion limiting element and the second motion limiting element, wherein the motion resisting assembly is constructed and arranged to resist rotation
5 of the second link about the second longitudinal axis relative to the first longitudinal axis of the first link.

In some embodiments, the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.

10 In some embodiments, the convex, first articulation surface comprises a semi-spherical surface.

In some embodiments, the concave, second articulation surface comprises a semi-spherical surface.

15 In some embodiments, the first motion-limiting element comprises a pin and wherein the second motion-limiting element comprises a slot and wherein the pin of the first link engages the slot of the second link.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface and wherein the pin is positioned to extend from an equatorial plane of the semi-spherical surface.

20 In some embodiments, the first motion-limiting element comprises first and second pins and wherein the second motion-limiting element comprises first and second corresponding slots and wherein over a range of articulation motion of the second link relative to the first link, at least one of the first and second pins is at least partially engaged with the corresponding at least one of the first and second slots.

25 In some embodiments, at an articulation angle of zero of the second link relative to the first link, both of the first and second pins are partially engaged with the first and second corresponding slots.

In some embodiments, the first and second pins are angularly spaced apart 180 degrees about the first longitudinal axis relative to the first articulation surface.

30 In some embodiments, the first and second slots are angularly spaced apart 180 degrees about the second longitudinal axis relative to the second articulation surface.

In some embodiments, the first motion-limiting element comprises a single pin and wherein the second motion-limiting element comprises a single slot and wherein over a range

of articulation motion of the second link relative to the first link, the pin is at least partially engaged with the slot.

In some embodiments, the pin is positioned on the first articulation surface and wherein the slot is positioned on the second articulation surface.

5 In some embodiments, the slot is positioned on the first articulation surface and wherein the pin is positioned on the second articulation surface.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface and wherein the pin is positioned on the first articulation surface between an equator and a pole of the first articulation surface and wherein the slot is positioned on the
10 second articulation surface.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface and wherein the slot is positioned on the semi-spherical first articulation surface between an equator and a pole of the first articulation surface and wherein the pin is positioned on the second articulation surface.

15 In some embodiments, the first motion-limiting element comprises a single slot and wherein the second motion-limiting element comprises a single pin and wherein over a range of articulation motion of the second link relative to the first link, the pin is at least partially engaged with the slot.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface and wherein the slot is positioned on the semi-spherical first articulation surface and extends from an equator of the first articulation surface in a direction toward a pole of the first articulation surface of the first link and wherein the pin is positioned below the second articulation surface of the second link.
20

In some embodiments, the pin is positioned on the second link at a position that aligns with an equator of the semi-spherical first articulation surface of the first link, when the second link is at an articulation angle of zero relative to the first link.
25

In some embodiments, the second link further comprises a third motion-limiting element comprising a single slot that is spaced apart 120 degrees in position relative to the pin, the third motion limiting element comprising a second motion limiting assembly that is constructed and arranged to resist rotation of a third link having a mating pin about a third longitudinal axis relative to the second link about the second longitudinal axis.
30

In some embodiments, the first motion-limiting element comprises at least one rib and wherein the second motion-limiting element comprises at least one recess and wherein over a

range of articulation motion of the second link relative to the first link, the at least one rib is at least partially engaged with the at least one recess.

In some embodiments, the first motion-limiting element comprises a plurality of ribs and wherein the second motion-limiting element comprises a plurality of corresponding
5 recesses and wherein over a range of articulation motion of the second link relative to the first link, at least one of the plurality of ribs is at least partially engaged with the corresponding at least one of the plurality of recesses.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface and wherein the plurality of ribs are spaced about an equator region of the
10 semi-spherical first articulation surface at regular angular intervals about the first longitudinal axis.

In some embodiments, the plurality of ribs comprises two ribs that are spaced at 180 degrees about the first longitudinal axis of the first link.

In some embodiments, the plurality of recesses comprises two recesses that are spaced
15 at 180 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises three ribs that are spaced at 120 degrees about the first longitudinal axis of the first link.

In some embodiments, the plurality of recesses comprises three recesses that are spaced at 120 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises four ribs that are spaced at 90
20 degrees about the first longitudinal axis of the first link.

In some embodiments, the plurality of recesses comprises four recesses that are spaced at 90 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises five ribs that are spaced at 72
25 degrees about the first longitudinal axis of the first link.

In some embodiments, the plurality of recesses comprises five recesses that are spaced at 72 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises six ribs that are spaced at 60 degrees about the first longitudinal axis of the first link.

In some embodiments, the plurality of recesses comprises six recesses that are spaced
30 at 60 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises seven ribs that are spaced at 360/7 degrees about the first longitudinal axis.

In some embodiments, the plurality of recesses comprises seven recesses that are spaced at 360/7 degrees about the second longitudinal axis.

In some embodiments, the plurality of ribs comprises eight ribs that are spaced at 45 degrees about the first longitudinal axis of the first link.

5 In some embodiments, the plurality of recesses comprises eight recesses that are spaced at 45 degrees about the second longitudinal axis.

In some embodiments, an outer surface of the first link at a portion between neighboring ones of the ribs is planar.

10 In some embodiments, an inner surface of the second link at a portion between neighboring ones of the recesses is planar.

In some embodiments, an inner surface of the second link at a portion between neighboring ones of the recesses is curved.

In some embodiments, the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.

15 In some embodiments, the convex, first articulation surface comprises a semi-ellipsoidal surface.

In some embodiments, the concave, second articulation surface comprises a semi-ellipsoidal surface.

20 In some embodiments: the semi-ellipsoidal, convex, first articulation surface of the first link comprises the first motion limiting element; and the semi-ellipsoidal, concave, second articulation surface of the second link comprises the second motion limiting element.

In some embodiments, an outermost surface of the first and second links is circular in cross section about the respective first and second longitudinal axes.

25 In some embodiments, the semi-ellipsoidal surface of the first articulation surface has a major axis and a minor axis and wherein the major axis is greater in length than the minor axis.

In some embodiments, the semi-ellipsoidal surface of the second articulation surface has a major axis and a minor axis and wherein the major axis is greater in length than the minor axis.

30 In some embodiments, the first articulation surface comprises convex and concave regions and wherein the second articulation surface comprises concave and convex regions that correspond to the convex and concave regions of the first articulation surface.

In some embodiments: the first articulation surface of the first link comprises the first motion limiting element; and the second articulation surface of the second link comprises the second motion limiting element.

5 In some embodiments, an outermost surface of the first and second links is circular in cross section about the respective first and second longitudinal axes.

In some embodiments, the first and second links comprise outer links of the articulating probe.

In some embodiments, the first and second links comprise inner links of the articulating probe.

10 In some embodiments, the first motion-limiting element comprises a first magnet and wherein the second motion-limiting element comprises a second magnet, and wherein the first and second magnets are positioned on the first and second links respectively so as to magnetically engage each other.

15 In some embodiments, the first and second links each comprises a base having a lower surface and an upper shoulder, wherein: the first magnet is positioned on the upper shoulder of the base; and the second magnet is positioned on the lower surface of the base, and wherein the first and second magnets are aligned relative to each other so as to magnetically engage each other.

In some embodiments, the first and second magnets have opposed polarity.

20 In some embodiments, the first magnet comprises multiple first magnets and wherein the second magnet comprises multiple second magnets and wherein the multiple first and second magnets are positioned about the longitudinal axes of the respective first and second links at regular angular intervals.

25 In some embodiments, the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.

In some embodiments, the convex, first articulation surface comprises a semi-spherical surface.

In some embodiments, the concave, second articulation surface comprises a semi-spherical surface.

30 In some embodiments: the first magnet is positioned on the first articulation surface; and the second magnet is positioned on the second articulation surface, wherein the first and second magnets are aligned relative to each other so as to magnetically engage each other.

In some embodiments, the first and second magnets have opposed polarity.

In some embodiments, a subset of the first magnets has a first polarity and a remaining subset of the first magnets has a second polarity opposite the first polarity.

In some embodiments, the first magnets all have a same, first polarity and the second magnets all have a same, second polarity.

5 In some embodiments, the first magnet comprises multiple first magnets and wherein the second magnet comprises multiple second magnets and wherein the multiple first and second magnets are positioned about the longitudinal axes of the respective first and second links at regular angular intervals.

10 In some embodiments, the multiple first and second magnets comprise discrete magnetic elements embedded in the respective first and second articulating surfaces.

In some embodiments, the multiple first and second magnets comprise magnetic strips embedded in the respective first and second articulating surfaces.

In some embodiments, the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.

15 In some embodiments, the first motion-limiting element comprises a pin and wherein the second motion-limiting element comprises a slot and wherein the pin of the first link engages the slot of the second link, and wherein the pin of the first link interfaces with sidewalls of the slot of the second link to resist the rotation of the first link relative to the second link.

20 In some embodiments, the first mechanism comprises an outer link mechanism of the articulating probe.

In some embodiments, the first mechanism comprises an inner link mechanism of the articulating probe.

25 In some embodiments, the motion limiting assembly limits rotation of the second link to about 1 degree of rotation about its longitudinal axis.

In some embodiments, the articulating probe further comprises at least one steering cable opening through the first link and the second link extending in a direction that is parallel to the respective first and second longitudinal axes.

30 In some embodiments, the articulating probe further comprises at least one steering cable corresponding to links in the first mechanism that is selectively tensioned to retain the first and second articulation surfaces of the first and second links in physical contact and selectively released to allow for selective motion of the second link relative to the first link.

In some embodiments, the at least one steering cable opening comprises multiple steering cable openings and wherein the at least one steering cable comprises multiple steering cables.

5 In some embodiments, the articulating probe comprises two steering cable openings and two steering cables.

In some embodiments, the articulating probe comprises three steering cable openings and three steering cables.

In some embodiments, the articulating probe comprises four steering cable openings and four steering cables.

10 In some embodiments, the first link further comprises a first articulation axis and a second articulation axis, the first and second articulation axes normal to each other and normal to the first longitudinal axis of the first link; the second link further comprises a first articulation axis and a second articulation axis, the first and second articulation axes normal to each other and normal to the second longitudinal axis of the second link; and two-degree-
15 of-freedom articulation of the second link relative to the first link comprises angular movement of the second link about the first and second articulation axes of the first link.

In another aspect, an articulating probe, comprises: a plurality of outer links, each outer link comprising a first longitudinal axis and an inner surface, the inner surface of each outer link having at least one first concave region that extends in a direction along the first
20 longitudinal axis; a plurality of inner links, each inner link comprising a second longitudinal axis and an outer surface, the outer surface of each inner link having at least one second concave region that extends in a direction along the second longitudinal axis; an anti-twist member positioned between the first concave regions and the second concave regions of the plurality of inner links and the plurality of outer links to allow two degree-of-freedom
25 articulation of the inner links with respect to each other and to allow two degree-of-freedom articulation of the outer links with respect to each other and to limit rotation of an inner link relative to a neighboring inner link and limit rotation of an outer link relative to a neighboring outer link.

In some embodiments, the first concave regions of the outer links and the second
30 concave regions of the inner links comprise working channels of the probe.

In some embodiments, the anti-twist member comprises a tube-shaped member.

In some embodiments, the anti-twist member is continuous from a proximal link to a distal link of the plurality of inner and outer links.

In some embodiments, the anti-twist member is segmented from a proximal link to a distal link of the plurality of inner and outer links.

In another aspect, a method of performing a surgical procedure comprises: selecting the articulating probe as described herein; and manipulating the articulating probe to position at least one tool using the probe.

In another aspect, a system for performing a surgical procedure includes an articulating probe as described herein.

In another aspect, a method of forming an articulating probe comprises: providing a first mechanism comprising: forming a first link comprising a first longitudinal axis, a first articulation surface and a first motion-limiting element; forming a second link comprising a second longitudinal axis, a second articulation surface and a second motion-limiting element; forming an articulation joint comprising the first articulation surface and the second articulation surface and constructed and arranged to allow two degree-of-freedom articulation of the second link relative to the first link; and forming a motion resisting assembly comprising the first motion limiting element and the second motion limiting element, wherein the motion resisting assembly is constructed and arranged to resist rotation of the second link about the second longitudinal axis relative to the first longitudinal axis of the first link.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of embodiments of the present inventive concepts will be apparent from the more particular description of embodiments, as illustrated in the accompanying drawings in which like reference characters refer to the same elements throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the embodiments.

FIG. 1A is a side view of first and second outer links of an articulating probe of a system for performing a medical procedure according to embodiments of the present inventive concepts. **FIG. 1B** is a lower perspective view of the first and second outer links of **FIG. 1A**. **FIG. 1C** is a cutaway side view of the first and second outer links of **FIG. 1A**. **FIG. 1D** is a cutaway side view of the first and second outer links of **FIG. 1A** illustrated with the second link articulated relative to the first link. **FIG. 1E** is a side perspective view of one of the first and second outer links of **FIG. 1A**.

FIG. 2 is a lower perspective view of an outer link of an articulating probe of a system for performing a medical procedure according to embodiments of the present inventive concepts.

FIG. 3A and 3B are perspective views of outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

FIG. 4 is a perspective view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

FIG. 5A is a side view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 5B** is a close-up side view of one of the first and second outer links of **FIG. 5A**. **FIG. 5C** is a lower perspective view of the link of **FIG. 5B**.

FIG. 6A is a lower perspective view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 6B** is a top perspective view of one of the first and second outer links of **FIG. 6A**. **FIG. 6C** is a lower perspective view of the link of **FIG. 6B**.

FIG. 7A is a lower perspective view of first and second inner links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 7B** is a top perspective view of one of the first and second inner links of **FIG. 7A**.

FIG. 8A-8C are top views of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

FIG. 9 is a cross-sectional view of an inner link and an outer link including an anti-twist member positioned therebetween, in accordance with embodiments of the present inventive concepts.

FIGs. 10A-10C are graphic demonstrations of a highly articulated probe device, according to embodiments of the present inventive concepts.

FIGs. 11A-11B illustrate various configurations assumed by a highly articulated probe, according to embodiments of the present inventive concepts.

FIGs. 12A-12D illustrate various views of a link of an outer sleeve, according to embodiments of the present inventive concepts.

FIGs. 13A and 13B illustrate end and cross-sectional views, respectively, of a link of an inner core, according to embodiments of the present inventive concepts.

FIGs. 14A and 14B illustrates one example of a feeder mechanism, according to embodiments of the present inventive concepts.

5 **FIG. 15** illustrates devices for controlling the tension on cables, according to embodiments of the present inventive concepts.

FIG. 16 illustrates devices for controlling the tension on the cables of the outer sleeve, according to embodiments of the present inventive concepts.

10 **FIG. 17** illustrates a device for controlling the tension on the cable of the inner sleeve, according to embodiments of the present inventive concepts.

FIG. 18 is a block diagram illustrating the components of a control system and the flow of information between those components, according to embodiments of the present inventive concepts.

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DETAILED DESCRIPTION OF EMBODIMENTS

The terminology used herein is for the purpose of describing particular embodiments and is not intended to be limiting of the inventive concepts. As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes” and/or “including,” when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

25 It will be understood that, although the terms first, second, third etc. may be used herein to describe various limitations, elements, components, regions, layers and/or sections, these limitations, elements, components, regions, layers and/or sections should not be limited by these terms. These terms are only used to distinguish one limitation, element, component, region, layer or section from another limitation, element, component, region, layer or section. Thus, a first limitation, element, component, region, layer or section discussed below could be termed a second limitation, element, component, region, layer or section without departing from the teachings of the present application.

It will be further understood that when an element is referred to as being “on” or “connected” or “coupled” to another element, it can be directly on or above, or connected or coupled to, the other element or intervening elements can be present. In contrast, when an element is referred to as being “directly on” or “directly connected” or “directly coupled” to another element, there are no intervening elements present. Other words used to describe the relationship between elements should be interpreted in a like fashion (e.g., “between” versus “directly between,” “adjacent” versus “directly adjacent,” etc.). When an element is referred to herein as being “over” another element, it can be over or under the other element, and either directly coupled to the other element, or intervening elements may be present, or the elements may be spaced apart by a void or gap. There are numerous types of steerable multi-linked, highly articulated probes. Robert Sturges’ U.S. Patent No. 5,759,151, which is hereby incorporated by reference in its entirety, discloses a flexible, steerable device for conducting exploratory procedures. The device includes at least one spine, each having stiffening means for selectively rendering the spine rigid and flexible along its length. A flexible sheath surrounds the spine and is axially slidably moveable relative to the spine so that the sheath will follow and conform to the shape of a spine in the rigid state and resist further flexure when the spine is in a relaxed state. A steerable distal tip is provided on the distal end of the device. Controls for the distal tip are mounted on the proximal end of the device. Mechanisms are provided on the distal end of the device for selectively activating and deactivating the stiffening means of the spine. An instrument conduit may be mounted on the sheath. Howard Choset’s U.S. Patent Application Serial No. 11/630,279, which is hereby incorporated by reference in its entirety, discloses a feeder mechanism for advancing and retracting both an inner core and an outer sleeve, as well as selectively applying tension to control cables used for steering and causing either the inner core or outer sleeve to transition between a rigid state and a limp state.

U.S. Patent No. 6,610,007 discloses a steerable endoscope having an elongated body with a selectively steerable distal portion and an automatically controlled proximal portion. The endoscope body is inserted into a patient and the selectively steerable distal portion is used to select a desired path within the patient’s body. When the endoscope body is advanced, an electronic motion controller operates the automatically controlled proximal portion to assume the selected curve of the selectively steerable distal portion. Another desired path is selected with the selectively steerable distal portion and the endoscope body is advanced again. As the endoscope body is further advanced, the selected curves propagate

proximally along the endoscope body, and when the endoscope body is withdrawn proximally, the selected curves propagate distally along the endoscope body. This creates a serpentine motion in the endoscope body allowing it to negotiate tortuous curves along a desired path through or around and between organs within the body.

5 **FIGs. 10A-10C** are graphic demonstrations of a highly articulated probe device, according to embodiments of the present inventive concepts. A highly articulated robotic probe 10, according to the embodiment shown in FIGs. 10A-10C, comprises essentially two concentric mechanisms, an outer mechanism and an inner mechanism, each of which can be viewed as a steerable mechanism. FIGs. 10A-10C show the concept of how different
10 embodiments of the probe 10 operate. Referring to FIG. 10A, the inner mechanism can be referred to as a first mechanism, an inner core or inner core mechanism 12. The outer mechanism can be referred to as a second mechanism, an outer sleeve or outer sleeve mechanism 14. Each mechanism can alternate between being rigid and limp. In the rigid mode or state, the mechanism is relatively inflexible such that it cannot be readily re-shaped.
15 In the limp mode or state, the mechanism is highly flexible and thus either assumes the shape of its surroundings or can be re-shaped. It should be noted that the term “limp” as used herein does not denote a structure that passively assumes a particular configuration dependent upon gravity and the shape of its environment; rather, the “limp” structures described in this application are capable of assuming positions and configurations that are desired by the
20 operator of the device, and therefore are articulated and controlled rather than flaccid and passive.

 In some embodiments, one mechanism starts limp and the other starts rigid. For the sake of explanation, assume the outer sleeve 14 is rigid and the inner core 12 is limp, as seen in step 1 in FIG. 10A. Now, the inner core 12 is both pushed forward by a feeding
25 mechanism 16, described below, and its “head” or distal end is steered, as seen in step 2 in FIG. 10A. Now, the inner core 12 is made rigid and the outer sleeve 14 is made limp. The outer sleeve 14 is then pushed forward until it catches up or is coextensive with the inner core 12, as seen in step 3 in FIG. 10A. Now, the outer sleeve 14 is made rigid, the inner core 12 limp, and the procedure then repeats. One variation of this approach is to have the outer
30 sleeve 14 be steerable as well. The operation of such a device is illustrated in FIG. 10B. In FIG. 10B it is seen that each mechanism is capable of catching up to the other and then advancing one link beyond. According to one embodiment, the outer sleeve 14 is steerable and the inner core 12 is not. The operation of such a device is shown in FIG. 10C.

In medical applications, once the probe 10 arrives at a desired location, the operator, typically a surgeon, can slide one or more tools through one or more channels of outer sleeve 14, inner core 12, or a channel formed between outer sleeve 14 and inner core 12, such as to perform various diagnostic and/or therapeutic procedures. In some embodiments, the channel is referred to as a working channel, that can, for example extend between first recesses formed in a system of outer links and second recesses formed in a system of inner links. In some embodiments, the inner and outer links are of a type depicted in FIGs. 1-9 described in detail herein.

In addition to clinical procedures such as surgery, probe 10 can be used in numerous applications including but not limited to: engine inspection, repair or retrofitting; tank inspection and repair; spying and surveillance applications; bomb disarming; inspection or repair in tightly confined spaces such as submarine compartments or nuclear weapons; structural inspections such as building inspections; hazardous waste remediation; biological sample recovery such as anthrax recovery; and combination of these. Clearly, the device of the present disclosure has a wide variety of applications and should not be taken as being limited to any particular application.

Inner core 12 and/or outer sleeve 14 are steerable and inner core 12 and outer sleeve 14 can each be made both rigid and limp, allowing probe 10 to drive anywhere in three-dimensions. Probe 10 can “remember” its previous configurations and for this reason, probe 10 can go anywhere in a three dimensional volume such as the intracavity spaces in the body of a patient such as a human patient. **FIGS. 11A-11B** illustrate examples of various configurations assumable by probe 10.

As can be seen in **FIGS. 12A-12D and 13A and 13B**, according to one embodiment, the outer sleeve 14 and inner core 12, respectively, can be made up of concentric cylinders, outer links 22 and inner links 24, respectively, although links of other shapes may be used, e.g. a dog bone configuration (not shown) as well as links of a type that are not concentric, e.g. backbone configuration, among others. In some embodiments, the ends of the links 22, 24 are not flat but instead one end 26 is an “outer” or convex outer mating surface and the other end 28 is an “inner” or concave inner mating surface. In some embodiments, the inner and outer surfaces can comprise semi-spherical surfaces with similar radii of curvature; however, as described herein, embodiments of the present inventive concepts are not limited thereto. The links 22 are “chained”, or nested back-to-back such that the concave end 28 of one mates with the convex end 26 of an adjacent link. Similarly, the links 24 are chained, or

nested back-to-back. The result is a spherical-like joint, from a kinematic point of view. In the current embodiment, each link is able to rotate, or articulate on the adjacent link's head, acting as a spherical joint with approximately 10 to 20 degrees range of motion in any direction, although other ranges of motion are possible and potentially advantageous.

5 According to one embodiment, the links 22 have a plurality of channels 30, or cable openings, extending therethrough to accommodate, in some embodiments, a plurality of control cables. Alternatively, in some embodiments, the cable openings 30 can be configured to accommodate elongate devices such as elongate tools.

10 In some embodiments, the heads (i.e. the distal links) of both the outer sleeve 14 and the inner core 12 are steerable using three cables which are positioned at, for example, 120° from each other. As can be seen in FIGS. 12A-12D, there are three small cylindrical channels 30 respectively, for cables to pass through. In the embodiment depicted in FIGS. 13A and 13B, the inner link 24 has only one cable, in which case there is only a single hole 34 through its center.

15 It will be appreciated that although the embodiment described above utilizes cables such as conductive or non-conductive wires or other flexible filamentous structure, alternative means of manipulating the limp elements, such as miniature pneumatic or hydraulic pistons or other mechanical linkages situated between individual links, can be employed without falling outside the scope of the present inventive concepts.

20 The links, and hence probe 10, can comprise virtually any material, including plastic or other magnetic resonance imaging compatible material. The outer sleeve 14 may assume a broad range of diameters, typically greater than 5mm. Similarly, inner core 12 may assume a broad range of diameters, less than the diameter of outer sleeve 14 and typically more than 3mm. The total number of outer links in an outer link assembly, or inner links in an inner link assembly links can vary over a large range but is typically greater than 10 outer or inner links.

25 As noted, the inner core 12 and outer sleeve 14 can be made rigid or limp using cables or other flexible filament structures. In some embodiments, outer sleeve 14 comprises a set of links 22 strung on three cables. The three cables can be positioned 120 degrees apart, making it possible to steer the sleeve in any direction. Radius of curvature of probe 10 is dependent on a number of factors including length of links 22 as well as mating dimensions between the ends of mating links 22. When the cables are pulled towards the back of the outer sleeve 14, the links 22 are pulled towards each other. When the pulling force increases,

the friction force between adjacent links 22 increases until the whole outer sleeve 14 stiffens (i.e. enters the rigid mode). When the pulling force is released, the outer sleeve 14 becomes limp. Thus, the cables together with their respective tensioning assemblies (e.g. motor driven pulleys) form a locking device. The tensioning assemblies, along with the electronics for
5 controlling the tensioning assemblies, form a means for controlling the tension on the cable. When the outer sleeve 14 is positioned one link position in front of the inner core 12, and the inner core 12 is rigid, the distal link of the outer sleeve 14 can be oriented by pulling one or more of the three cables. In addition to advancing or retracting cable, the magnitude of the pulling force which is exerted on each cable can be monitored or controlled. By pulling the
10 three cables with the same magnitude, the outer sleeve 14 becomes rigid without changing its shape.

The inner core 12, like the outer sleeve 14, consists of a set of links. According to one embodiment, in contrast to the outer sleeve 14, the inner core 12 does not require a steering ability. In some embodiments, a steering feature is optional, and can be employed,
15 in connection with the inner core 12. In some embodiments, the inner core 12 can change between a rigid mode and a limp mode. Therefore, in embodiments where the inner core 12 need not be steerable, the links of the inner core 12 may be strung on a single cable, which enables a reduced diameter for probe 10.

As mentioned above, a feeding mechanism 16 can be used to control the probe 10.
20 One type of feeding mechanism 16, shown in **FIGS. 14A and 14B**, inserts and retracts the probe 10 into and out of, respectively, a region of interest such as the esophagus, the peritoneal space, the pericardial cavity, or another internal space of a patient. The feeder 16 has two movable carts. A first cart 42, carried in a first fixed tray 43, advances and retracts the outer sleeve 14 while a second cart 44 carried in a second fixed tray 45 advances and
25 retracts the inner core 12. Each cart 42, 44, and hence, each of the inner core 12 and outer sleeve 14, is driven independently by separate linear actuators 46, 48 respectively. The linear actuators 46, 48 may carry shaft encoders (not shown) used for position control as is known to those of skill in the art. Alternatively or additionally, motor current may be monitored to determine a value for tension in a cable used to control position. Cable tension may be
30 monitored with one or more sensors such as a load cell. Numerous positioning and other sensors may be included to provide information relative to cable tension; cart position; probe orientation and configuration; and other system parameters. Typical sensors include but are not limited to: optical sensors; magnetic sensors such as Hall effect sensors; force and

pressure sensors such as accelerometers, strain gauges and mechanical switches; and combinations of these. One or more sensors may be positioned in multiple locations including but not limited to: feeding mechanism 16, inner core 12 and outer sleeve 14.

Each of the carts 42, 44 carries one or more motors necessary for controlling the
5 cables of the inner core 12 and outer sleeve 14. For example, as seen in **FIG. 15** and **FIG. 16**, the cart 42 carries motors 50, 51, 52 which control the tension on cables 54, 55, 56 of outer sleeve 14. As shown in **FIG. 17**, second cart 44 has a motor 58 for controlling the tension on cable 59 of the inner core 12. Each of the motors 50, 51, 52 and 58 may be provided with shaft encoders (not shown) used for position control as is known. In an embodiment where
10 the inner core 12 is steerable, the inner core 12 requires two or more motors (e.g. to tension two or more cables) or another cable tensioning mechanism.

FIG. 18 is a block diagram illustrating the components of one embodiment of a control system and the flow of information between those components. The feeding mechanism 16 interfaces with a control computer 62 through a bus conversion module 64.
15 Outgoing data from the feeding mechanism 16 is input to the module 64 for conversion to a communication protocol, such as USB protocol, and is then input to a USB port 66 on the computer 62. Incoming data to control software 68 may include motor current data, motor encoder data and/or cable tension data associated with each of the cables in the feeding mechanism 16. Alternatively or additionally, incoming data to control software 68 may
20 include data from one or more sensors located in feeding mechanism 16, an inner core or an outer sleeve such as inner core 12 or outer sleeve 14 described herein. Joystick data (position data) may also be received from a joystick 70. A monitor 72 may be responsive to video data from a camera mounted on the distal end of the outer sleeve 14 and/or inner core 12 to provide visual feedback to a user regarding the position of the distal end of the probe 10. The
25 control software 68 may output motor current limit commands and motor position commands which are input to the feeding mechanism 16.

During operation of articulating probes, the outer sleeve link systems and inner core link systems are subject to twisting, from link to link. For example, during operation of the probe, an inherent amount of twisting can occur between neighboring links. Twisting of links
30 can be cumulative over the system of links. Accordingly, while the angle of misalignment can be minor from individual neighboring link to link, the total amount of twisting of the distal link of the system relative to the proximal link can be large. As the number of links in

a system increases, so too can the amount of cumulative twist. Such twisting can adversely affect the performance of the articulating probe.

Twisting can occur due to a number of factors, including a difference between the outer radii of the steering cables and the inner radii of the steering cable openings. Also, the neighboring links may become misaligned prior to, or during, a procedure. The twisting of links relative to each other can cause an inconsistent relation of steering input to steering output. Loss of alignment between user and robot coordinate systems can occur. As a result, for an operator to initiate a turn in a particular direction, the robot must be moved in a different direction to compensate for twist. In addition, links that are twisted relative to each other may be subject to a limited range of steering. Twisting can also cause neighboring links to become inadvertently locked together, and the steering cables can become pinched in the gaps between over-twisted links. This can, in turn, lead to binding of the cables, resulting in higher steering forces, or incomplete release of tension when in a limp mode of operation. Further problems due to twisting can include the binding of instruments inserted through internal channels of the link systems, possible occlusion of internal tool channels, as well as increased wear on electrical conduits present in the system. Twisting can also result in increased wear and friction between inner and outer links, causing neighboring links to bind, or preventing their ability to advance during a procedure. Also, twisting can result in the misalignment between the end of the probe and the target anatomy.

Twisting between neighboring links can be as severe as 5 degrees of offset. Cumulative twisting of a distal link relative to a proximal link in a link system can be as large as 45 degrees. Embodiments described herein are directed to systems and methods for resisting or preventing the amount of twist of a second neighboring link relative to a first link, while still allowing for articulation of the links for steering purposes.

FIG. 1A is a side view of first and second outer links of an articulating probe of a system for performing a medical procedure according to embodiments of the present inventive concepts. **FIG. 1B** is a lower perspective view of the first and second outer links of **FIG. 1A**. **FIG. 1C** is a cutaway side view of the first and second outer links of **FIG. 1A**. **FIG. 1D** is a cutaway side view of the first and second outer links of **FIG. 1A** illustrated with the second link articulated relative to the first link. **FIG. 1E** is a side perspective view of one of the first and second outer links of **FIG. 1A**.

Referring to **FIG. 1A**, first and second outer links 100a, 100b (generally 100) of the articulating probe are each constructed and arranged to have a longitudinal axis 102Za, 102Zb, an articulation joint (joint formed from articulating surfaces 104 and 110 shown specifically in **FIG. 1C**) and motion-limiting element 106. Multiple outer links 100 are stacked and nested relative to each other. The links are configured to articulate relative to each other and are prevented from separating relative to each other by steering cables 109 (see **FIG. 1B**) that pass through one or more steering cable openings 108 of the multiple links 100. In the present example, three steering cable openings 108 and three cables 109 are shown (see **FIG. 1B**); however fewer or more steering cable openings and steering cables can be employed, depending on the application of the articulating probe.

Illustrated in **FIG. 1C**, the articulation joint comprises a convex articulation surface 104a of the first outer link 100a and a concave articulation surface 110b of the second outer link 100b. The convex and concave surfaces engage each other throughout a range of articulation of the second outer link 100b relative to the first outer link 100a, under control of the steering cables 109. Tension that is present in at least one of the steering cables 109, at any given time, between the proximal and distal ends of the articulating probe retain the articulating joints of the various links of the assembly in place.

Referring to the illustrations of **FIGs. 1A-1C**, the respective longitudinal axes 102Za, 102Zb of the first and second outer links 100a, 100b are substantially in alignment with each other, or at an angle of zero degrees with respect to each other. In this position, the second outer links 100b can be considered to be in a non-articulated position relative to the first outer link 100a. However, in the illustration of **FIG. 1D**, the second longitudinal axis 102Zb of the second link 100b is at a non-zero angle relative to the first longitudinal axis 102Za of the first link 100a. In this position, the second outer link 100b can be considered to be in an articulated position relative to the first outer link 100a.

FIG. 2 is a lower perspective view of an outer link of an articulating probe of a system for performing a medical procedure according to embodiments of the present inventive concepts. In this view, first and second articulation axes 102X, 102Y of the outer link are illustrated. The first and second articulation axes 102X, 102Y are normal to each other and normal to the longitudinal axis 102Z of the outer link. Over a permitted range of articulation, a second outer link 100b neighboring a first outer link 100a will be permitted to articulate over a range of angles about the first articulation axis 102X as illustrated by arrow 103X and will be permitted to articulate over a range of angles about the second articulation

axis 102Y as illustrated by arrow 103Y, relative to the first and second articulation axes of the first outer link 100a. In this manner, articulation is permitted or allowed in two degrees of freedom. Twisting or rotation of the second outer link 100b relative to a neighboring first outer link 100a in the direction illustrated by arrow 103Z is undesirable, for various reasons described herein. Embodiments of the present inventive concepts described herein include a motion-resisting assembly of any of a number of various types for limiting, mitigating or otherwise resisting rotation or twisting of a second outer link relative to a neighboring first outer link of the articulating probe assembly, or of a second inner link relative to a neighboring first inner link of the articulating probe assembly.

Returning to **FIG. 1A**, the first and second outer links 100a, 100b each include a motion limiting element, pin 106 (also visible in the perspective view of FIG. 1E), that operates in conjunction with a corresponding slot 112 of a neighboring link to provide a motion resisting assembly 106, 112 suitable for limiting rotation of the second link 100b relative to the first link 100a. In particular, motion resisting assembly 106, 112 is suitable for limiting rotation of the second link 100b about its longitudinal axis 102Zb relative to the longitudinal axis 102Za of the first link 100a.

At the same time, the motion resisting assembly 106, 112 operates to limit rotation of the first link 100a relative to the second link 100b. In this manner, the motion resisting assembly 106, 112 can be said to limit rotation of the first link 100a and the second link 100b relative to each other.

In some embodiments, the pin 106 extends in an outward direction from a lower portion of the convex articulation surface 104 of the outer link 100. In an embodiment where the convex articulation surface 104 is semi-spherical, the pin 106 can be positioned at, or along, an equator of the semi-spherical surface. In some embodiments, the pin 106 may be circular in cross-section to allow for pivoting of a slot 112 of a neighboring link during articulation. In other embodiments, the pin 106 can have a cross-sectional shape that is other than circular.

In some embodiments, the slot 112 can be formed in a pin extension or tab 114 that extends from a lower portion of the link 100. The slot 112 can have a width W (see FIG. 1B) that is sized to accommodate the pin 106 width. In some embodiments, the pin 106 can be permitted to slide freely along the slot 112 in a direction of extension of the slot, while limiting gaps or play of the pin 106 between the sidewalls of the slot 112. The slot 112 can have a length L that is sufficient to allow the pin 106 to slide between a range of desired

articulation of neighboring links 100a, 100b. A top portion of the slot 112 can be rounded to interface with the rounded, corresponding pin 106.

In some embodiments, as illustrated in **FIG. 1C**, each link 100 includes two pins 106 and two pin slots 112 for mating with pins of neighboring links. Each link, however, can include a single pin 106, or more than two pins, or a single slot 112, or more than one slot 112, depending on the application. In the embodiment illustrated in **FIG. 1C**, the first link 100a is in alignment with the second link 100b so that their respective longitudinal axes 102Za, 102Zb are in alignment. In this non-articulated state, the first and second pins 106 are at least partially engaged with the respective first and second slots 112 of the neighboring second link 100b. In this position, the second link 100b is prevented, or otherwise limited, from rotating or twisting, about its longitudinal axis 102Zb, relative to the longitudinal axis 102Za of the first link 100a, as the first and second pins 106 are engaged with their respective mating slots 112. In particular, with any such twisting moment imparted on the second link 100b, the sidewalls of the slots 112 of the second link abut the pins 106 of the first link 100a and thus prevent the first link 100b from rotating about its longitudinal axis 102Zb. At the same time, the interaction of the pins 106 and slots 112 do not obstruct or limit articulation of the second link 100b relative to the first link 100a, for example articulation of the second link 100b about the first and second articulation axes 102x, 102y of the first link 100a (see **FIG. 2**). Free articulation of the second link 100b relative to the first link 100a is maintained, while mitigating or preventing undesired twisting of the second link relative to the first link.

Referring to **FIG. 1D**, upon further articulation of the second link 100b relative to the first link 100a, in the present embodiment, one of the pins 106-1 becomes disengaged from its corresponding slot 112-1, while the other of the pins 106-2 becomes engaged more deeply into its corresponding slot 112-2. Similarly, in this articulated position, the sidewalls of the slot 112-2 of the second link 100b interacting with the corresponding pin 106-2 of the first link 100a prevents twisting of the second link 100b about its longitudinal axis 102Zb relative to the first link 100a. At the same time, free articulation of the second link 100b relative to the first link 100a is maintained.

Referring to **FIGs. 1A-1E**, the links 100a, 100b each include a lower portion 126 and an upper portion 128. In some embodiments, the lower portion 126 includes the concave articulation surface 110 and the upper portion 128 includes the convex articulation surface 104 which combine to form the articulation joint. At an interface of the outer surfaces of the lower portion 126 and the upper portion 128, a shoulder 120 can be provided. The shoulder

120 of a first link 100a and a lower surface 121 of the second link 100b operate to limit the amount of articulation of the second link 100b relative to the first link 100a. For example, articulation can be limited to an angle that corresponds to the position at which the lower surface 121 of the second link 100b physically abuts the shoulder 120 of the first link 100a.

5 Continuing to refer to **FIGs. 1A-1E**, in some embodiments, a recess 122 can be formed in the shoulder 120 of the lower portion. The recess 122 can be formed to have a shape that accommodates the pin extension or tab 114. In this manner, the slot 112 of the tab 114 can engage its corresponding pin 106, while maintaining the outer profile of the links 100a, 100b so that their outer perimeters are not increased. In some embodiments, the tab
10 114 and corresponding recess 122 can be constructed and arranged so that they do not limit articulation of the second link 100b relative to the first link 100a. In other words, at the greatest degree of articulation, the shoulder 120 of the first link 100a makes contact with the lower surface 121 of the neighboring link 100b while a clearance is maintained between the tab 114 and the surface of the corresponding recess 122. In other embodiments, the tab 114
15 and corresponding recess 122 can be configured so that the interface of the tab 114 and recess 122 provides an articulation-limiting function, while a clearance is maintained between the shoulder 120 and corresponding lower surface 121 of the neighboring links 100a, 100b.

Continuing to refer to **FIGs. 1A-1E**, in some embodiments, the links 100a, 100b comprise outer links of an articulating probe having a plurality of articulating inner links and
20 a plurality of articulating outer links. In some embodiments, recesses 124 are provided at an interface between inner regions of the outer links and corresponding outer regions of the inner links. The recesses 124 correspond to working channels of the articulating probe to allow for delivery of functional elements from the proximal end to the distal end of the articulating probe, as described herein.

25 In some embodiments, for example in the embodiment depicted in **FIGs. 1A-1E**, the convex articulation surface 104a of the first outer link 100a comprises a semi-spherical convex surface and the concave articulation surface 110 of the second outer link 100b comprises a semi-spherical concave surface. In some embodiments, the radius of the convex articulation surface 104a of the first outer link 100a can be the same as the radius of the
30 concave articulation surface 110b of the second outer link 100b. In some embodiments, the radius of the convex articulation surface 104a of the first outer link 100a can be greater than the radius of the concave articulation surface 110b of the second outer link 100b. In some embodiments, the radius of the convex articulation surface 104a of the first outer link 100a

can be less than the radius of the concave articulation surface 110b of the second outer link 100b.

In some embodiments, for example in the embodiment depicted in FIGs. 1A-1E, the convex articulation surface 104a of the first outer link 100a comprises a semi-spherical convex surface and the concave articulation surface 110b of the second outer link 100b comprises a semi-conical concave surface. An advantage of this configuration is that the contact region of the resulting articulation joint corresponds to a circular region. As a result, the resulting interface is less likely to bind, since the region of contact is reduced. Also, the mating properties of the convex and concave articulation surfaces can be more readily controlled, since the interface is less susceptible to variation in manufacturing process parameters such as variation in texture, material, friction, and the like. The resulting interface also allows for greater tolerance variation in the links, reducing manufacturing costs.

In one example, assuming a semi-spherical convex articulation surface, variation in the spherical diameter can affect the amount of surface contact between the convex and concave surfaces. This can result in variation of the steering forces, variation in the amount of compression between neighboring links and binding of the articulation surfaces. Assuming a semi-conical concave articulation surface, any variation in the convex surface as a result of manufacturing or use have little effect on the contact angle and location of contact between the convex and concave articulation surfaces. Variations in the size of the convex surface may have an effect on how far into the semi-conical surface the convex surface engages, but, owing to the geometry, the contact angle will be the same, despite the variations.

The angle of the semi-conical surface can be varied to accommodate tradeoffs between steerability and payload of the resulting articulating probe. The angle of the semi-conical surface controls the contact point between the convex, semi-spherical and the concave, semi-conical articulation surfaces. In general, as the contact point is lowered to a wider region of the cone, the strength of the interface, and therefore the strength of the articulating probe, is improved. As the contact point is raised to a narrower region of the cone, steerability of the articulating probe is improved.

In some embodiments, the angle of the semi-conical surface can be approximately 23°, or 46° included. This angle can be suitable when considering the combined factors of outer link geometry, material strength, and material friction properties. A range of angles were subject to testing, and compression testing indicated that the 23 degree conical provided optimal compression, in other words, the least amount of compression, as a result of where

the concave conical surface comes in contact with the convex spherical mating surface, while still providing optimal friction for locking ability in a rigid state, as recorded in friction/steering test results. Steeper angles, for example a 14 degree angle, resulted in the outer links sticking or binding to each other under compression, while more gradual angles, for example, angles greater than about 23 degrees resulted in reduced locking while in a rigid state. However, with a different combination of geometry, friction and material strength, conical angles less than 23 degrees or greater than 23 degrees may be desirable.

In the embodiments depicted herein, the system of outer links 100 employ three steering cables spaced apart from each other at 120 degree intervals. The steering cables are selectively tensioned to retain the articulation surfaces of the links in a rigid position and are selectively released to allow for selective motion of the links in a limp position. Other numbers of steering cables can be employed, for example two, four, or more, and they can be spaced apart at regular angular intervals or at different angles.

FIG. 3A is a perspective view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

Referring to **FIG. 3A**, in this embodiment, the motion resisting assembly comprises one or more slots 312 positioned on an external portion of the convex articulation surface 304 of the link 100c, 100d. The motion resisting assembly further comprises one or more corresponding pins 306, in this example two opposed pins, that are positioned on tabs 314 configured to engage the corresponding slots 312 of a neighboring link 100c, 100d.

In some embodiments, the convex articulation surface 304 of the links 100c, 100d is semi-spherical. In such an arrangement, the pins 306 of a neighboring second link 100d can be positioned such that when the neighboring links are at an articulation angle of zero, and therefore, their respective longitudinal axes are aligned, the pins 306 of the neighboring second link 100d are aligned with the equator of the semi-spherical convex articulation surface 304 of the first link 100c. The slots 312 can be oriented to extend along the outer surface of the semi-spherical convex articulation surface 304 in a direction that is along a meridian curve, or longitude curve, from the equator of the surface 304 to a pole of the surface 304. In some embodiments, the length L of the slots 312 can be extended beyond the equator of the surface 304, to accommodate articulation of the neighboring second link 100d relative to the first link 100c. In some embodiments, at a maximum articulation angle, the lower surface 321 of the second link 100d abuts a shoulder 320 of the first link 100c to limit

articulation. A recess 322 formed in the shoulder 320 accommodates the tab 314 in this position, without interfering with free articulation of the second link 100d relative to the first link 100c. Alternatively, the tab 314 and corresponding recess 322 can be configured to provide an articulation-limiting function.

5 In the present embodiment, with any such twisting moment imparted on the second link 100d, the sidewalls of the slots 312 of the first link 100c abut the pins 306 of the second link 100d and thus prevent the second link 100d from rotating about its longitudinal axis relative to the first link 100c. At the same time, the interaction of the pins 306 and slots 312 do not obstruct or limit articulation of the second link 100d relative to the first link 100c, for
10 example articulation of the second link 100d about the first and second articulation axes 102x, 102y of the first link 100c (see **FIG. 2**). Free articulation of the second link 100d relative to the first link 100c is maintained, while mitigating or preventing undesired twisting of the second link 100d relative to the first link 100c

In some embodiments, two pins 306 and slots 312 can be positioned on each link 100c,
15 100d at opposed 180 degree positions, as shown in **FIG. 3A**.

Referring to **FIG. 3B**, in other embodiments, a single pin 306 and a single slot 312 can be positioned on each link 100d', 100d'', 100d'''. In an example embodiment, the pin 306 and slot 312 of each link 100d', 100d'', 100d''' can be positioned at an angular distance of 120 degrees apart from each other about the perimeter of the link 100d', 100d'', 100d'''.
20 During assembly, each respective link 100d', 100d'', 100d''' can be seated into its respective position by rotating each link by 120 degrees relative to the neighboring link as the links progress from the proximal end to the distal end of the articulating probe. Engagement of the single pin 306 and slot 312 is sufficient for mitigating or preventing undesired twisting of the link 100d'' relative to an adjacent link, e.g. 100' and 100''', since the pin 306 and
25 corresponding slot 112 remain engaged throughout the range of articulation.

FIG. 4 is a perspective view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

Referring to **FIG. 4**, in this embodiment, the motion resisting assembly comprises one
30 or more pins 406 positioned on an external portion of the convex articulation surface 404 of the link 400a, 400b. The motion resisting assembly further comprises one or more corresponding slots 406 that are positioned within the concave articulation surface 410a and configured to engage the corresponding pins 406 of a neighboring link 400a, 400b. In the

embodiment illustrated in FIG. 4, a single pin 406 and a single corresponding slot 412 are used.

In some embodiments, the convex articulation surface 404 of the links 400a, 400b is semi-spherical. In such an arrangement, the pin 406 of each link can be positioned to lie on the convex articulation surface 404 at a position above the equator of the semi-spherical convex articulation surface 404, and between the equator and the pole of the surface 404.

The slots 412 can be oriented to extend along the inner surface of the semi-spherical concave articulation surface 410a in a direction that is oriented along a meridian curve, or longitudinal curve, from the equator of the surface 410a toward a pole of the surface 410a. In some embodiments, the length L of the slots 412 can accommodate articulation of the neighboring second link 400b relative to the first link 400a. In some embodiments, at a maximum articulation angle, the lower surface 421 of the second link 400b abuts a shoulder 420 of the first link 400a to limit articulation.

In the present embodiment, with any such twisting moment imparted on the second link 400b, the sidewalls of the slot 412 of the second link 400b abut the pin 406 of the first link 400a and thus prevent the second link 400b from rotating about its longitudinal axis relative to the first link 400a. At the same time, the interaction of the pin 406 and slot 412 do not obstruct or limit articulation of the second link 400b relative to the first link 400a, for example articulation of the second link 400b about the first and second articulation axes 102x, 102y of the first link 400a (see FIG. 2). Free articulation of the second link 400b relative to the first link 400a is maintained, while mitigating or preventing undesired twisting of the second link 400b relative to the first link 400a.

FIG. 5A is a side view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 5B** is a close-up side view of one of the first and second outer links of FIG. 5A. **FIG. 5C** is a lower perspective view of the link of FIG. 5B.

Referring to **FIGs. 5A-5C**, in some embodiments, the motion resisting assembly comprises a plurality of lobes, or ribs, 150, spaced apart from each other about an outer perimeter of the convex articulation surface 104 of the link 100e, 100f. In some embodiments, the convex articulation surface 104 is semi-spherical and the plurality of lobes 150 are spaced apart about an equator region of the convex articulation surface 104. In other embodiments, the lobes 150 can be placed between the equator region and the polar region of the convex articulation surface. The lobes 150 can be linked to each other by planar outer

linking surfaces 152; however, the linking surfaces can alternatively be curved or angular, depending on the application. The motion resisting assembly further comprises a plurality of recesses 154 spaced apart from each other about an inner surface of the lower portion of the concave articulation surface 110. The recesses 154 are similarly linked to each other by planar inner linking surfaces 156, which otherwise can also be curved or angular, depending on the application. The lobes 150 and outer linking surfaces 152 of a first neighboring link 100e are positioned to correspond with the recesses 154 and inner linking surfaces 156 of a second neighboring link 100f. In this manner, throughout the range of articulation of the second link 100f relative to the first link 100e, at least one of the plurality of recesses 154 and/or planar inner linking surfaces 156 remains engaged with the corresponding lobes 150 and/or outer linking surfaces 152 of the neighboring link. In some embodiments, in a position where the second link 100f is in position at a zero-degree articulation angle relative to the first link 100e, at least top portions of all lobes 150 and outer linking surfaces 152 can be in position to engage at least bottom portions of all recesses 154 and inner linking surfaces 156. On the other hand, at a position of full articulation limited by contact of the lower surface 121 of the second link 100f and the shoulder 120 of the first link 100e, such as in the example depicted in **FIG. 5A**, the leftmost lobes 150 and corresponding recesses 154 are fully engaged, the central lobes 150 and recesses 154 are partially engaged and the rightmost lobes 150 and recesses 154 are not engaged.

In the present embodiment, with any such twisting moment imparted on the second link 100f, the inner walls of the recesses 154 and inner linking surfaces 156 of the second link 100f abut the lobes 150 and outer linking surfaces 152 of first link 100e and thus prevent the second link 100f from rotating about its longitudinal axis. At the same time, the interaction of the recesses and lobes 154, 150 and inner and outer linking surfaces 156, 152 do not obstruct or limit articulation of the second link 100f relative to the first link 100e, for example articulation of the second link 100f about the first and second articulation axes 102x, 102y of the first link 100e (see **FIG. 2**). Free articulation of the second link 100f relative to the first link 100e is maintained, while mitigating or preventing undesired twisting.

In the embodiment of **FIGs. 5A-5C**, six lobes 150 and corresponding recesses 154 are depicted so as to be evenly distributed about the links in mating hexagonal shapes. In various embodiments, any of a number of lobes 150 and recesses 154 can be employed. For example, any of two through eight, or more, lobes 150 can be employed and two through eight, or more, recesses 154 can be employed. The number of lobes 150 can be the same as, or different than

the number of recesses 154. The lobes and/or recesses can be evenly distributed at angular intervals about the links or can be unevenly distributed. The outer linking surfaces 152 can be planar, or otherwise curved or angular, depending on the application. Similarly, the inner linking surfaces 156 can be planar, or otherwise curved or angular, depending on the application

FIG. 6A is a lower perspective view of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 6B** is a top perspective view of one of the first and second outer links of FIG. 6A. **FIG. 6C** is a lower perspective view of the link of FIG. 6B.

Referring to **FIGs. 6A-6C**, in some embodiments, the motion resisting assembly comprises a convex first articulation surface 604 on an upper portion 128 of a first link 100g and a concave second articulation surface 610 in a lower portion of a second link 100h neighboring the first link 100g.

In some embodiments, the convex first articulation surface 604 is semi-ellipsoidal. In some embodiments, the concave second articulation surface 610 is semi-ellipsoidal. In some embodiments, the semi-ellipsoidal surface has a major axis *A_{major}* and a minor axis *A_{minor}* in the plane of the first and second articulation axes 102x, 102y (see **FIG. 2**). Referring to **FIGs. 6B and 6C**, the major axis *A_{major}* can have a greater length than the minor axis *A_{minor}* for both the convex first articulation surface 604 and the concave second articulation surface 610.

Interaction of the corresponding convex and concave semi-ellipsoidal articulation surfaces 604, 610 of the neighboring links permit free articulation of the second link 100h relative to the first link 100g. The articulation can be limited for example, by positioning of the lower surface 121 of the second link 100h relative to the shoulder 120 of the first link 100g, as described herein in connection with various other embodiments.

In the present embodiment, with any such twisting moment imparted on the second link 100h, the elongated shapes of the mating semi-ellipsoidal surfaces 604, 610 of the neighboring links prevent the second link 100h from rotating about its longitudinal axis 602Zh relative to the longitudinal axis 602Zg of the first link 100g. At the same time, the interaction of the semi-ellipsoidal surfaces 604, 610 does not obstruct or limit articulation of the second link 100h relative to the first link 100g, for example articulation of the second link 100h about the first and second articulation axes 102x, 102y of the first link 100g (see **FIG.**

2). Free articulation of the second link 100h relative to the first link 100g is maintained, while mitigating or preventing undesired twisting of the second link relative to the first link.

FIG. 7A is a lower perspective view of first and second inner links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts. **FIG. 7B** is a top perspective view of one of the first and second inner links of **FIG. 7A**.

Referring to **FIGs. 7A-7B**, in some embodiments, the motion resisting assembly comprises a first articulation surface 704 on an upper surface of a first link 700i and a second articulation surface 710 on a lower surface of a second link 700j neighboring the first link 700i.

In the present example of **FIGs. 7A and 7B**, the first and second links 700i, 700j comprise inner links of the articulating probe. The first and second inner links 700i, 700j are configured to be positioned within the longitudinal openings present in the arrangement of outer links.

In some embodiments, the first and second links 700i, 700j (generally 700) include a central cable opening 732 that passes through the links 700 in a longitudinal direction of the links 700 along their respective longitudinal axes 702Zi, 702Zj. The cable opening 732 is configured to receive an operating cable for the inner mechanism of the articulating probe. In some embodiments, the outermost surface portions 734 of the first and second links lie on a circle. In some embodiments recesses 724 can be provided to accommodate working channels of the articulating probe that are formed between the inner regions of the outer links and outer regions of the inner links, as described herein. In a case where three working channel recesses 724 are present, then the links are generally shaped to have three lobe regions 736a-c surrounding the cable opening 732.

In some embodiments, the first articulation surface 704 comprises convex features and concave features. For example, referring to **FIG. 7B**, the first articulation surface 704 is convex in profile between points G and H on the surface 704 between the first and second lobes 736a, 736b. At the same time, the first articulation surface 704 is concave in profile between points E and F on the surface 704 between the third lobe 736c and the saddle region 738 between the first and second lobes 736a, 736b.

Similarly, the second articulation surface 710, as shown in **FIG. 7A** comprises concave features and convex features that correspond with those of the first articulation surface 704 of a neighboring link. In particular, the second articulation surface 710 is

concave in profile between points C and D on the surface 710 between the first and second lobes 736a, 736b. At the same time, the second articulation surface 710 is convex in profile between points A and B on the surface 710 between the third lobe 736c and the saddle region 738 between the first and second lobes 736a, 736b.

5 Accordingly, the convex features of the first articulation surface 704 mate with, or otherwise interface with, the concave features of the second articulation surface 710 of a neighboring link. Similarly, the concave features of the first articulation surface 704 mate with, or otherwise interface with, the convex features of the second articulation surface 710 of a neighboring link.

10 Interaction of the corresponding convex and concave features of the first and second articulation surfaces 704, 710 of the neighboring links permit free articulation of the second link 700j relative to the first link 700i. For example, the concave feature between points C and D of the second articulation surface interacting with the corresponding feature on the neighboring first articulation surface permits free articulation in a first plane; while the
15 convex feature between points A and C of the second articulation surface interacting with the corresponding feature on the neighboring first articulation surface permits free articulation in a second plane.

In the present embodiment, with any twisting moment imparted on the second link 700j, the opposed convex and concave features of the first and second articulation surfaces
20 704, 710 prevent the second link 700j from rotating about its longitudinal axis 702Zj relative to the longitudinal axis 702Zi of the first link 700i, or otherwise limit or mitigate such rotation. At the same time, the interaction of the opposed convex and concave features does not obstruct or limit articulation of the second link 700j relative to the first link 700i, for example articulation of the second link 700j about the first and second articulation axes 702x,
25 702y of the first link 700i. Free articulation of the second link 700j relative to the first link 700i is maintained, while mitigating or preventing undesired twisting of the second link relative to the first.

The inventive concepts of the present embodiment including opposed and mating convex and concave features is not only applicable to inner links 700, but also can be applied
30 to the outer links 100 of the articulating probe.

FIG. 8A-8C are top views of first and second outer links of an articulating probe of a system for performing a medical procedure according to other embodiments of the present inventive concepts.

Referring to the embodiment of **FIG. 8A**, first magnets 802k are positioned about the shoulder 120 of a first link 800k. The first magnets 802k can be positioned at regular angular intervals about the shoulder 120. In the present example embodiment, a 90 degree interval is illustrated. Similarly, second magnets 802l are positioned about the lower surface 121 of a second link 800l to correspond with those of the first link. In some examples, the ends of the first magnets 802k positioned on the shoulder 120 of the first link 800k have a first polarity, for example South (S), and ends of the second magnets 802l positioned on the lower surface 121 of the second link 800l have a second polarity, for example, North (N). In other embodiments, mating pairs of the first and second magnets 802k, 802l can be selected so as to have opposite polarities, and the polarities of all magnets of a given link do not need to have the same orientation.

Referring to the embodiment of **FIG. 8B**, first magnets 802m are positioned about the convex first articulating surface 804 of a first link 800m. The first magnets 802m can be positioned at regular angular intervals about first articulating surface 804. In the present example embodiment, a 90 degree interval is illustrated. Similarly, second magnets 802n are positioned about the concave second articulating surface 810 of a second link 800n to correspond with those of the first link 800m. In some examples, the first magnets 802m positioned on the first link 800m have a first polarity, for example South (S), and the second magnets 802n positioned on the second link 800n have a second polarity, for example, North (N). In other embodiments, mating pairs of the first and second magnets 802m, 802n can be selected so as to have opposite polarities, and the polarities of all magnets of a given link do not need to have the same orientation.

Referring to the embodiment of **FIG. 8C**, first magnetic strips 802p are positioned circumferentially about the convex first articulating surface 804 of a first link 800p. The first magnetic strips 802p can be positioned at regular angular intervals about first articulating surface 804. In the present example embodiment, two strips at a 180 degree interval are illustrated. Similarly, second magnetic strips 802q are positioned about the concave second articulating surface 810 of a second link 800q and are oriented to correspond with those of the first link 800p. In some examples, the first magnetic strips 802p positioned on the first link 800p have a first polarity, for example South (S), and the second magnetic strips 802q positioned on the second link 800q have a second polarity, for example, North (N). In other embodiments, mating pairs of the first and second magnets 802p, 802q can be selected so as

to have opposite polarities, and the polarities of all magnets of a given link do not need to have the same orientation.

In some embodiments, the first and second magnets are positioned so as to magnetically engage each other over a range of articulation angles of the second link relative to the first link. The magnetic engagement between the magnets of the neighboring links permits articulation of the second link relative to the first link. The articulation can be limited for example, by positioning of the lower surface 121 of the first link relative to the shoulder 120 of the second link, as described herein in connection with various other embodiments.

In the present embodiments of **FIGs. 8A-8C**, with any such twisting moment imparted on the second link, the magnetic interaction of the neighboring links prevent the second link from rotating about its longitudinal axis relative to the longitudinal axis of the first link, or otherwise limit or mitigate such rotation. At the same time, the magnetic interaction does not obstruct or limit articulation of the second link relative to the first link. Free articulation of the second link relative to the first link is maintained, while mitigating or preventing undesired twisting of the second link relative to the first. The embodiments illustrated in **FIGs. 8A-8C** can be employed in connection with any of the other embodiments described herein to further restrict or limit twisting of the links.

In the present example embodiment, the magnets are illustrated as being applied to outer links of the articulating probe, however, the principles of this concept of the invention are equally applicable to inner links, as well.

FIG. 9 is a cross-sectional view of an inner link and an outer link including an anti-twist member positioned therebetween, in accordance with embodiments of the present inventive concepts.

Referring to **FIG. 9**, an articulating probe includes an assembly of outer links 100r having a central opening. An assembly of inner links 700s is positioned through the central opening of the inner links. As described herein the plurality of outer links 100r have recesses 124 on their inner sidewalls and the plurality of inner links 700s have recesses 724 on their outer sidewalls. Together, the opposed recesses 124, 724 form working channels for the articulating probe for the purposes described herein, and for other purposes.

An anti-twist member 942 is positioned in at least one of the working channels 125. In some embodiments, the anti-twist member comprises a tube-shaped member that is hollow or solid in cross-section. In other embodiments, the anti-twist member 942 comprises a

flexible material that permits articulation of neighboring inner links and articulation of neighboring outer links. At the same time, the tube can exhibit strength or rigidity when subjected to a twisting motion between neighboring links. In some embodiments, the anti-twist member 942 can be configured to extend along an entire length, or nearly the entire length, of the working channel 125 of the articulating probe, from its proximal to distal end. In some embodiments, the anti-twist member 942 can be segmented so that it extends through portions of the working channel 125. In some embodiments, the anti-twist member 942 can be affixed to a recess 724 of the inner link 700s or a recess 124 of the outer link 100r. In some embodiments, the anti-twist member 942 can be affixed to both a recess 724 of the inner link 700s and a recess 124 of the outer link 100r.

In some embodiments, the tube-shaped anti-twist member 942 can be fixed at its proximal and distal ends. The torsional rigidity of the anti-twist member 942 will determine the degree to which it prevents twisting.

In the present embodiments of FIG. 9, with any such twisting moment imparted on a second link neighboring a first link, the presence of the anti-twist member prevents the second link from rotating about its longitudinal axis relative to the longitudinal axis of the first link. At the same time, the anti-twist member does not obstruct or limit, or minimally obstructs or limits, articulation of the second link relative to the first link. Free articulation of the second link relative to the first link is maintained, while mitigating or preventing undesired twisting. The embodiments illustrated in FIG. 9 can be employed in connection with any of the other embodiments described herein to further restrict or limit twisting of the links.

As described herein, the systems and methods of the present inventive concepts prevent, mitigate, or otherwise restrict, torsional rotation, or twisting, of links in a system of links in a highly articulated robotic system. The systems and methods can be applied to both an inner link mechanism and an outer link mechanism of the robotic system. In some embodiments, rotation of a second link relative to a first link can be limited to about 1 degree of rotation. Other rotational limit amounts are equally applicable, depending on the configuration, and the inventive concepts are not limited thereto.

While the present inventive concepts have been particularly shown and described above with reference to exemplary embodiments thereof, it will be understood by those of ordinary skill in the art, that various changes in form and detail can be made without

departing from the spirit and scope of the present inventive concepts described and defined by the following claims.

CLAIMS:

What is claimed is:

1. An articulating probe, comprising:
 - a first mechanism comprising:
 - a first link comprising a first longitudinal axis, a first articulation surface and a first motion-limiting element;
 - a second link comprising a second longitudinal axis, a second articulation surface and a second motion-limiting element;
 - an articulation joint comprising the first articulation surface and the second articulation surface and constructed and arranged to allow two degree-of-freedom articulation of the second link relative to the first link; and
 - a motion resisting assembly comprising the first motion limiting element and the second motion limiting element, wherein the motion resisting assembly is constructed and arranged to resist rotation of the second link about the second longitudinal axis relative to the first longitudinal axis of the first link, and a second mechanism comprising:
 - a third link comprising a third longitudinal axis and a third articulation surface;
 - a fourth link comprising a fourth longitudinal axis and a fourth articulation surface;
 - an articulation joint comprising the third articulation surface and the fourth articulation surface and constructed and arranged to allow at least two degrees of freedom articulation of the fourth link relative to the third link, wherein the first mechanism and the second mechanism extend in a longitudinal direction, wherein a link of one of the first and second mechanisms has an opening having an inner width greater than a greatest outer width of a link of the other of the first and second mechanisms, and wherein the link of the other of the first and second mechanisms extends through the opening of the link of the one of the first and second mechanisms and an entire length of the link of the other of the first and second mechanisms is movable in a longitudinal direction through the opening of the link of the one of the first and second mechanisms.

2. The articulating probe of claim 1 wherein the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.
3. The articulating probe of claim 2 wherein the convex, first articulation surface comprises a semi-spherical surface.
4. The articulating probe of claim 2 or claim 3 wherein the concave, second articulation surface comprises a semi-spherical surface.
5. The articulating probe of any one of claims 1 to 4 wherein the first motion-limiting element comprises a pin and wherein the second motion-limiting element comprises a slot and wherein the pin of the first link engages the slot of the second link.
6. The articulating probe of claim 5 wherein the convex, first articulation surface comprises a semi-spherical surface and wherein the pin is positioned to extend from an equatorial plane of the semi-spherical surface.
7. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises first and second pins and wherein the second motion-limiting element comprises first and second corresponding slots and wherein over a range of articulation motion of the second link relative to the first link, at least one of the first and second pins is at least partially engaged with the corresponding at least one of the first and second slots.
8. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises a single pin and wherein the second motion-limiting element comprises a single slot and wherein over a range of articulation motion of the second link relative to the first link, the pin is at least partially engaged with the slot.
9. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises a single slot and wherein the second motion-limiting element comprises a single pin and wherein over a range of articulation

motion of the second link relative to the first link, the pin is at least partially engaged with the slot.

10. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises at least one rib and wherein the second motion-limiting element comprises at least one recess and wherein over a range of articulation motion of the second link relative to the first link, the at least one rib is at least partially engaged with the at least one recess.

11. The articulating probe of claim 10 wherein the first motion-limiting element comprises a plurality of ribs and wherein the second motion-limiting element comprises a plurality of corresponding recesses and wherein over a range of articulation motion of the second link relative to the first link, at least one of the plurality of ribs is at least partially engaged with the corresponding at least one of the plurality of recesses.

12. The articulating probe of any one of the preceding claims wherein the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.

13. The articulating probe of claim 12 wherein an outermost surface of the first and second links is circular in cross section about the respective first and second longitudinal axes.

14. The articulating probe of any one of the preceding claims wherein the first articulation surface comprises convex and concave regions and wherein the second articulation surface comprises concave and convex regions that correspond to the convex and concave regions of the first articulation surface.

15. The articulating probe of claim 14 wherein:
the first articulation surface of the first link comprises the first motion limiting element; and
the second articulation surface of the second link comprises the second motion limiting element.

16. The articulating probe of claim 14 wherein an outermost surface of the first and second links is circular in cross section about the respective first and second longitudinal axes.
17. The articulating probe of claim 14 wherein the first and second links comprise outer links of the articulating probe.
18. The articulating probe of claim 14 wherein the first and second links comprise inner links of the articulating probe.
19. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises a first magnet and wherein the second motion-limiting element comprises a second magnet, and wherein the first and second magnets are positioned on the first and second links respectively so as to magnetically engage each other.
20. The articulating probe of any one of the preceding claims wherein the first articulation surface comprises a convex surface and wherein the second articulation surface comprises a concave surface.
21. The articulating probe of any one of the preceding claims wherein the first motion-limiting element comprises a pin and wherein the second motion-limiting element comprises a slot and wherein the pin of the first link engages the slot of the second link, and wherein the pin of the first link interfaces with sidewalls of the slot of the second link to resist the rotation of the first link relative to the second link.
22. The articulating probe of any one of the preceding claims wherein the first mechanism comprises an outer link mechanism of the articulating probe.
23. The articulating probe of any one of the preceding claims wherein the first mechanism comprises an inner link mechanism of the articulating probe.
24. The articulating probe of any one of the preceding claims wherein the motion limiting assembly limits rotation of the second link to about 1 degree of rotation about its longitudinal axis

25. The articulating probe of any one of the preceding claims further comprising at least one steering cable opening through the first link and the second link extending in a direction that is parallel to the respective first and second longitudinal axes.

26. The articulating probe of claim 25 further comprising at least one steering cable corresponding to links in the first mechanism that is selectively tensioned to retain the first and second articulation surfaces of the first and second links in physical contact and selectively released to allow for selective motion of the second link relative to the first link.

27. The articulating probe of claim 26 wherein the at least one steering cable opening comprises multiple steering cable openings and wherein the at least one steering cable comprises multiple steering cables.

28. The articulating probe of any one of the preceding claims wherein:
the first link further comprises a first articulation axis and a second articulation axis, the first and second articulation axes normal to each other and normal to the first longitudinal axis of the first link;

the second link further comprises a first articulation axis and a second articulation axis, the first and second articulation axes normal to each other and normal to the second longitudinal axis of the second link; and

two-degree-of-freedom articulation of the second link relative to the first link comprises angular movement of the second link about the first and second articulation axes of the first link.

29. A method of performing a surgical procedure comprising:
selecting the articulating probe of any one of claims 1 through 28; and
manipulating the articulating probe to position at least one tool using the probe.

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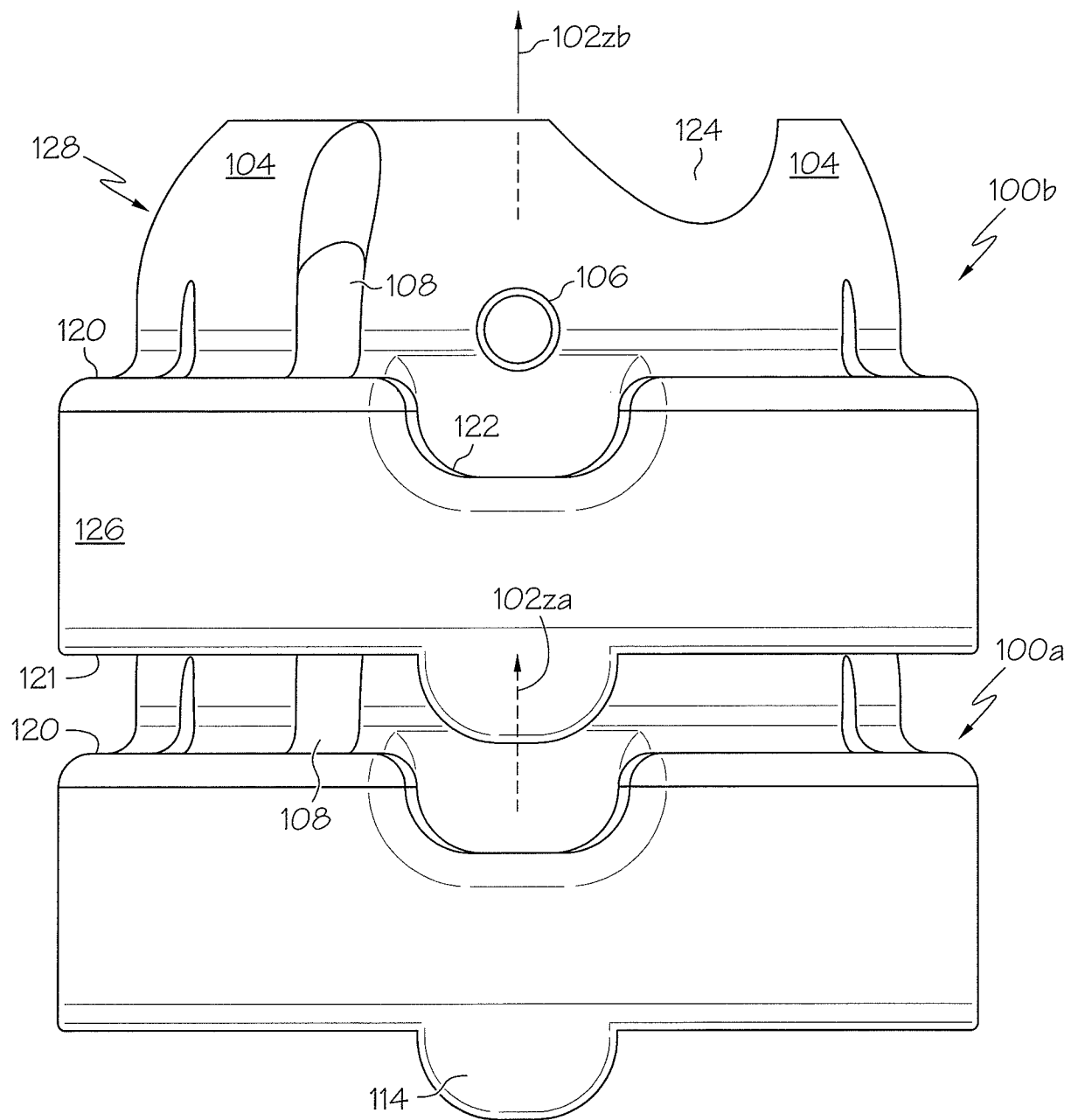


FIG. 1A

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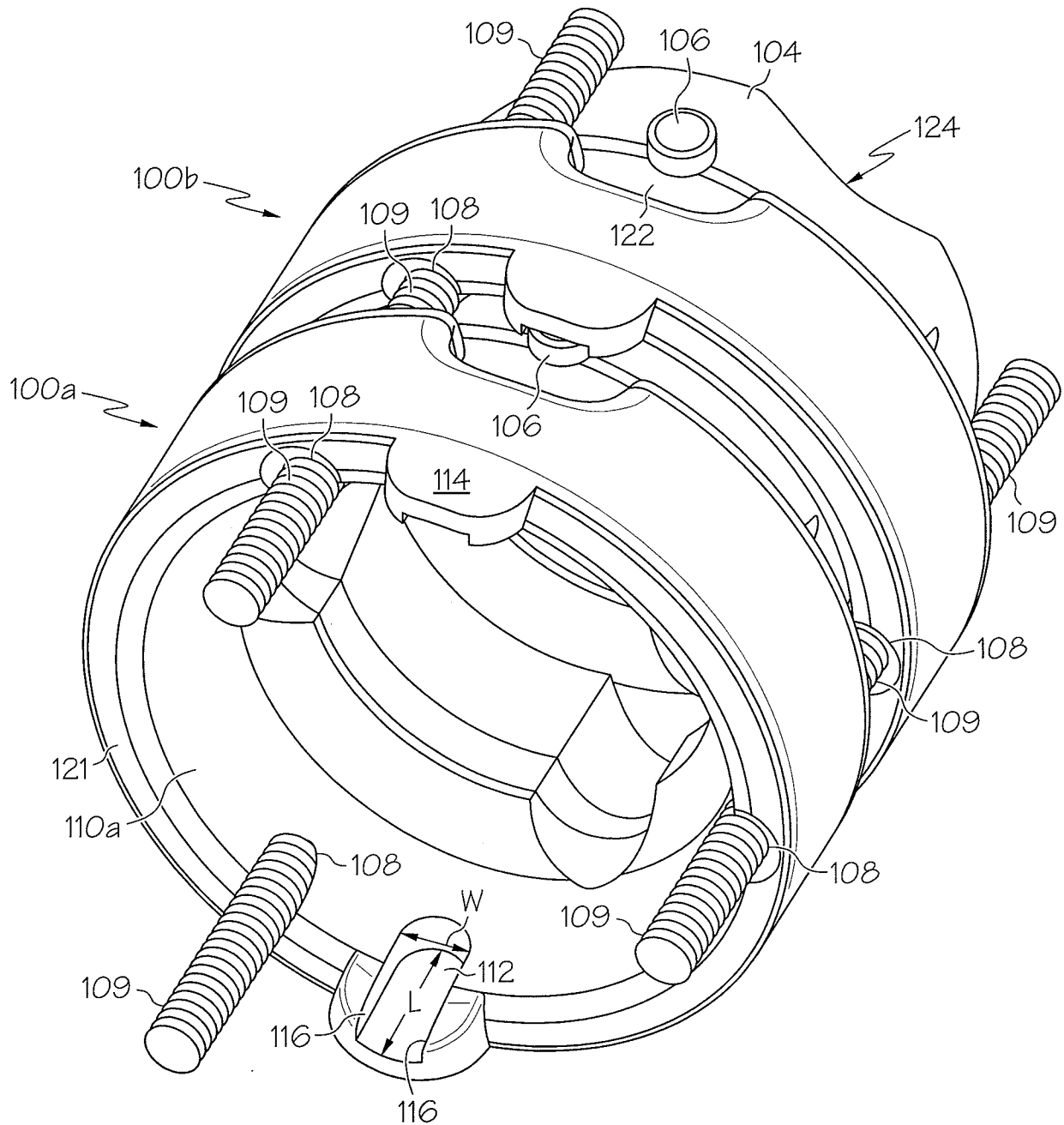


FIG. 1B

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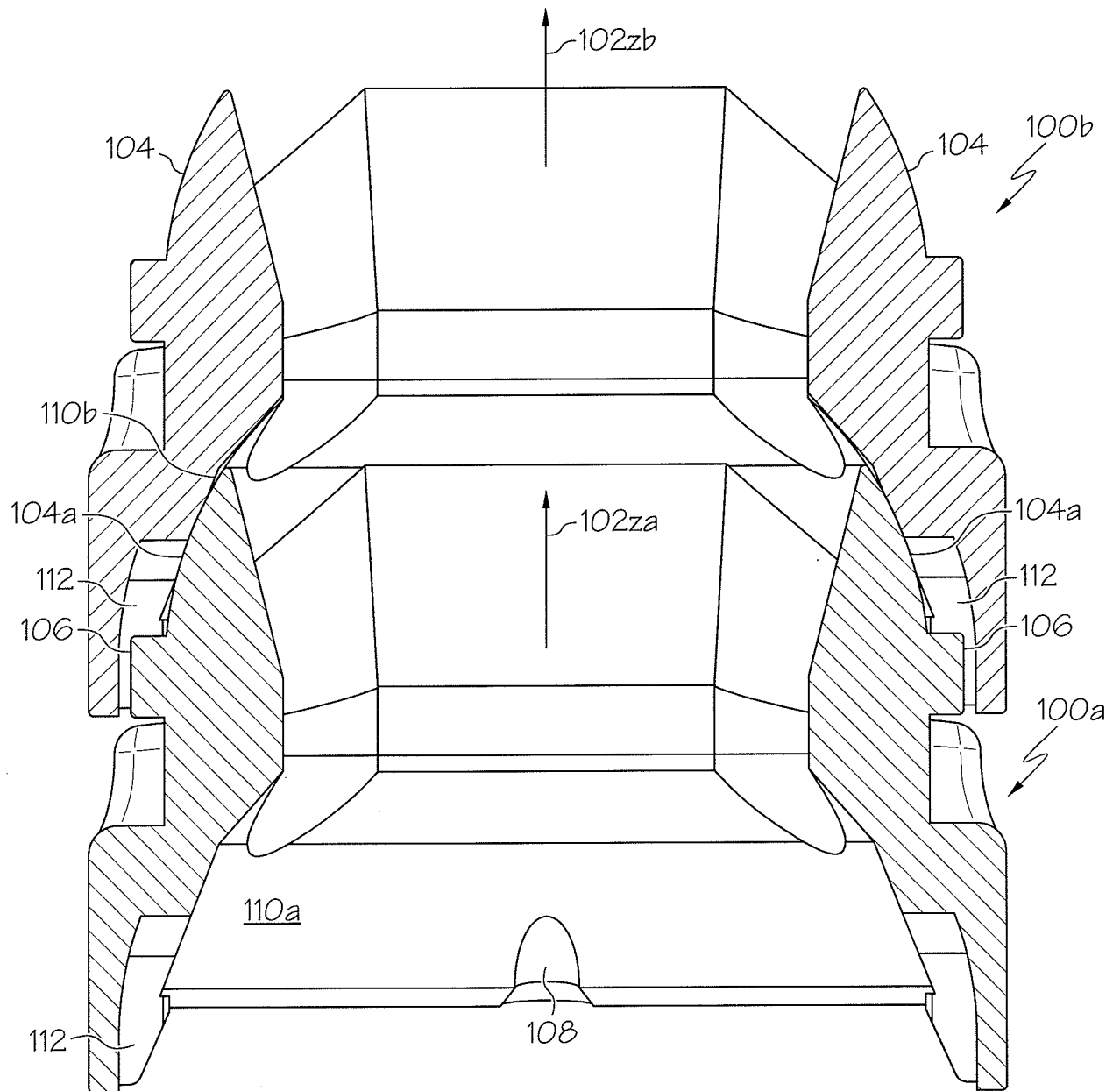


FIG. 1C

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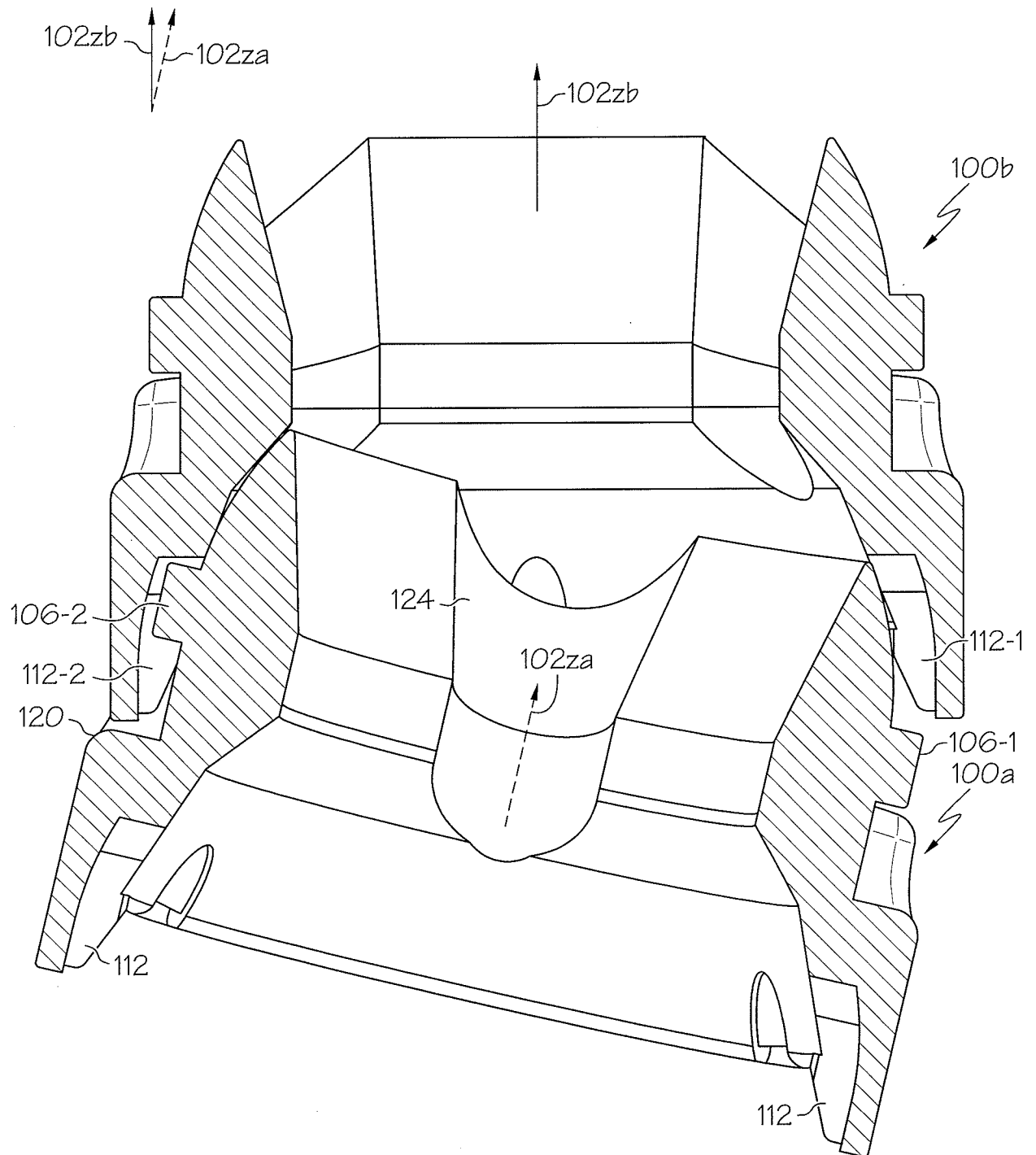


FIG. 1D

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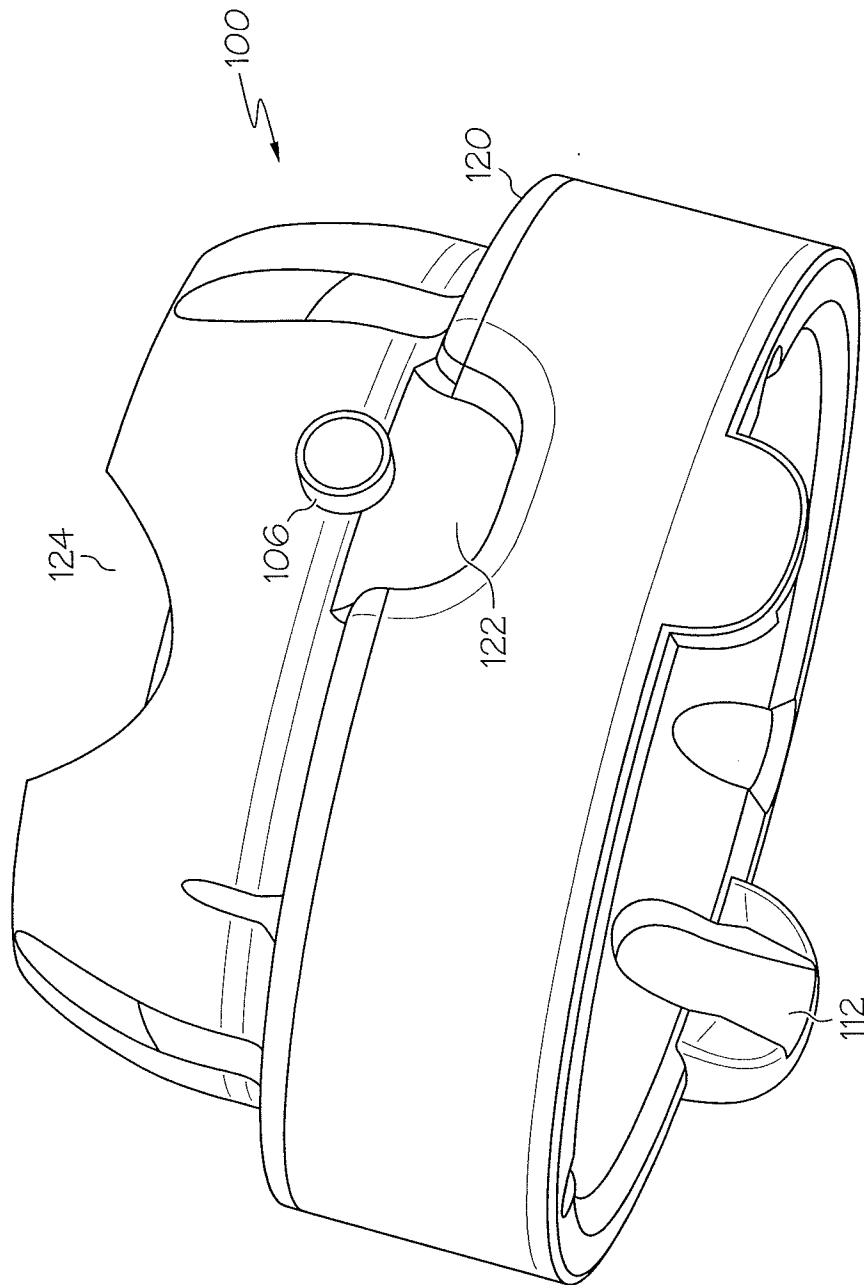


FIG. 1E

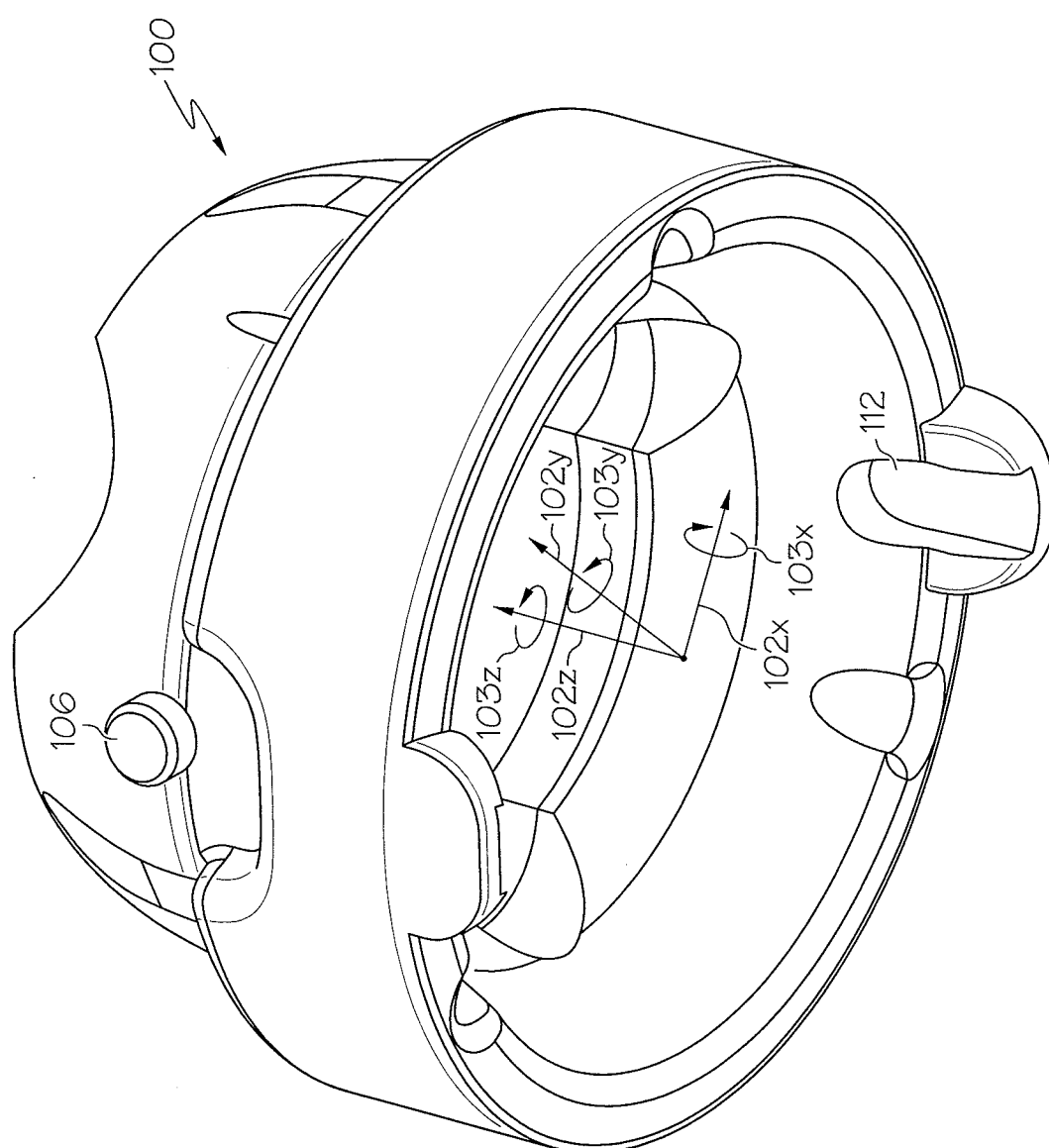


FIG. 2

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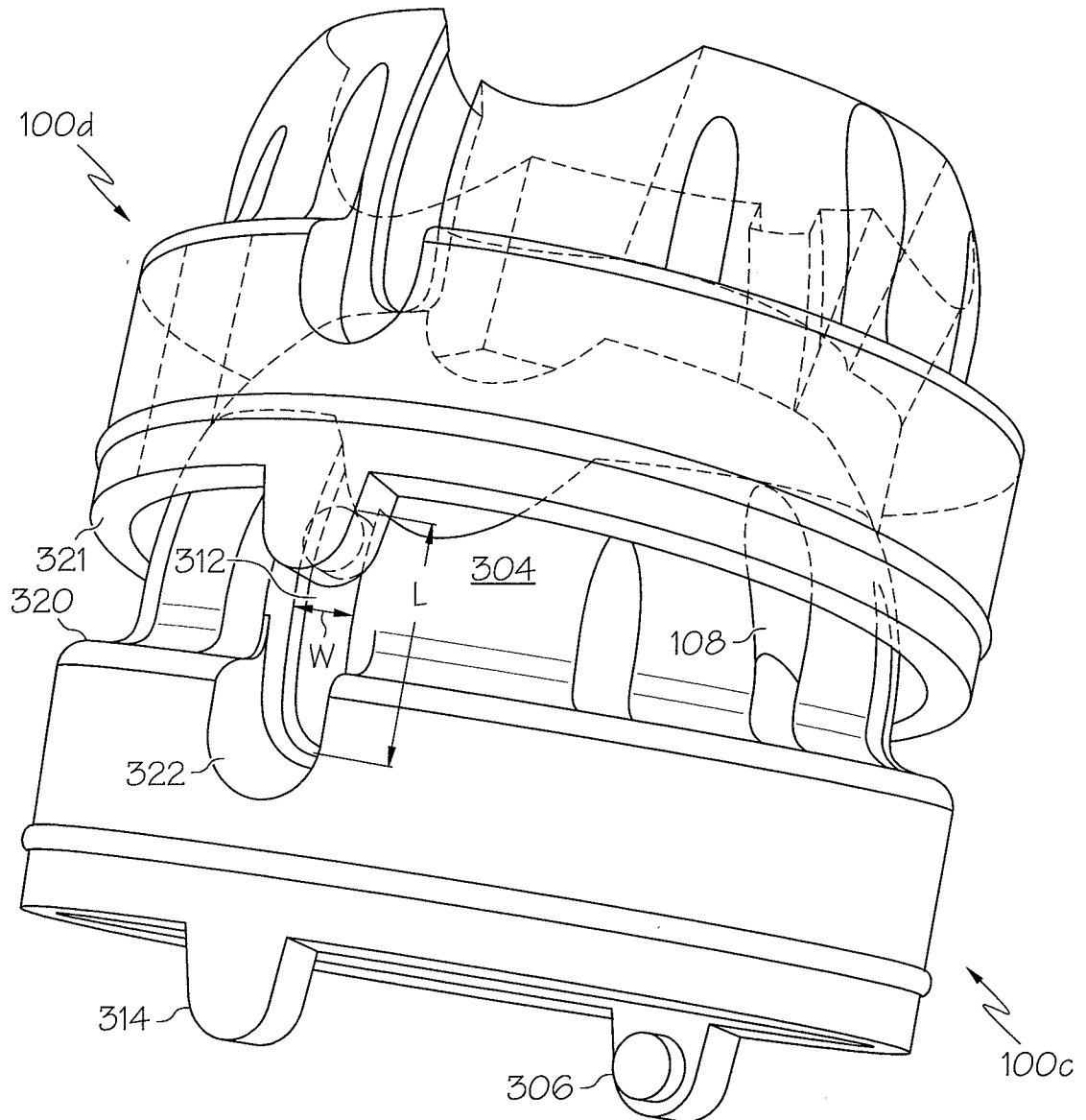


FIG. 3A

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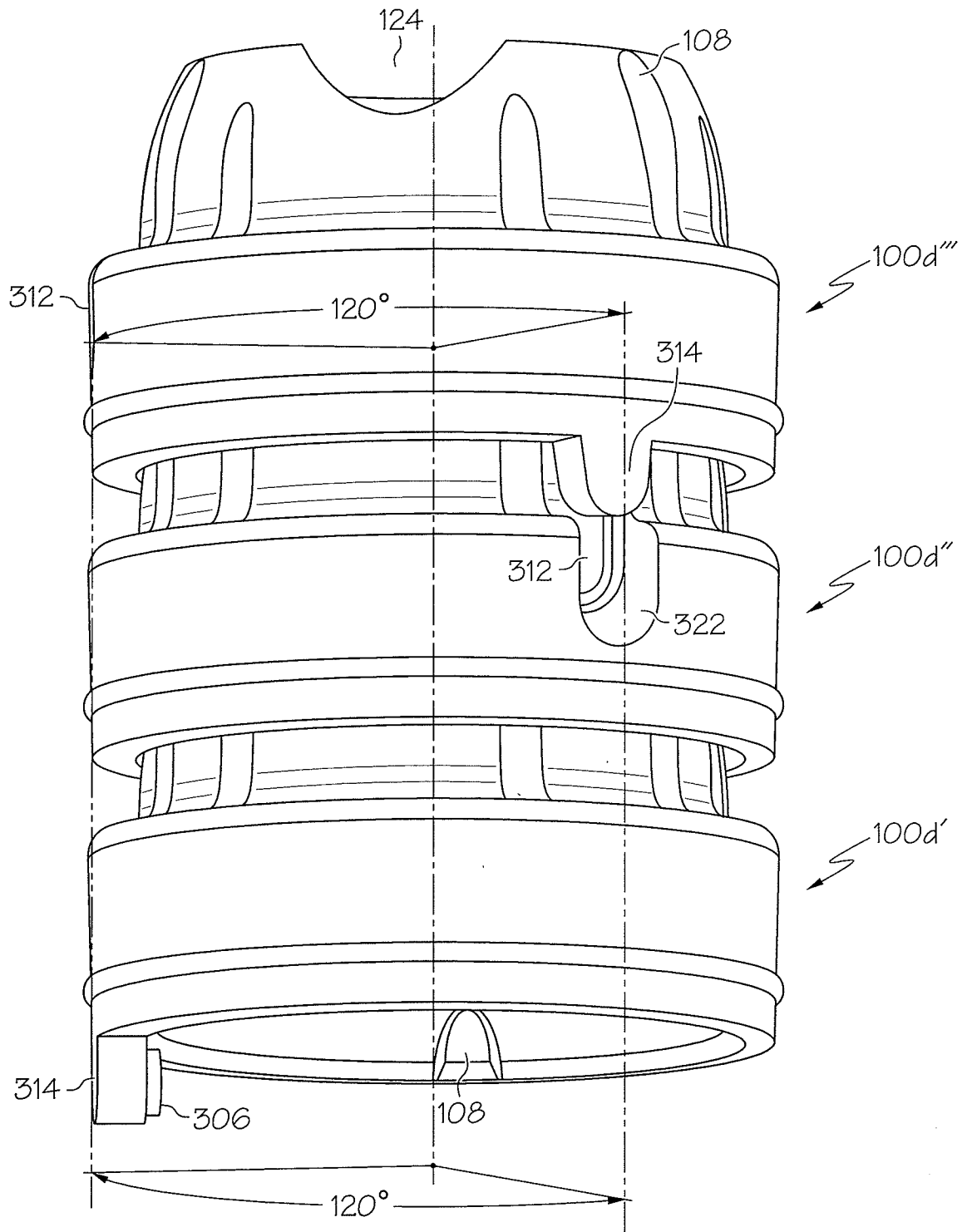


FIG. 3B

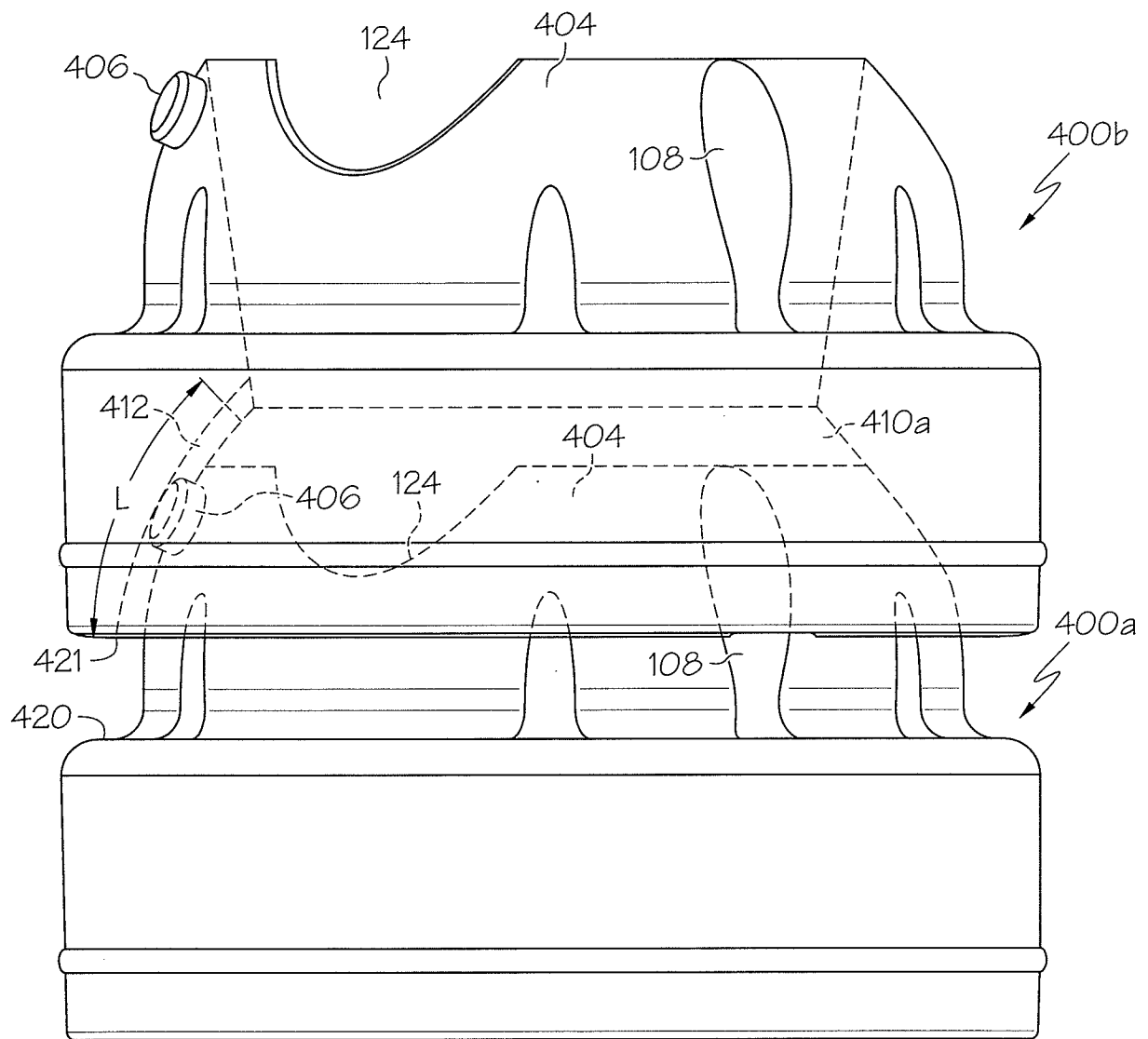
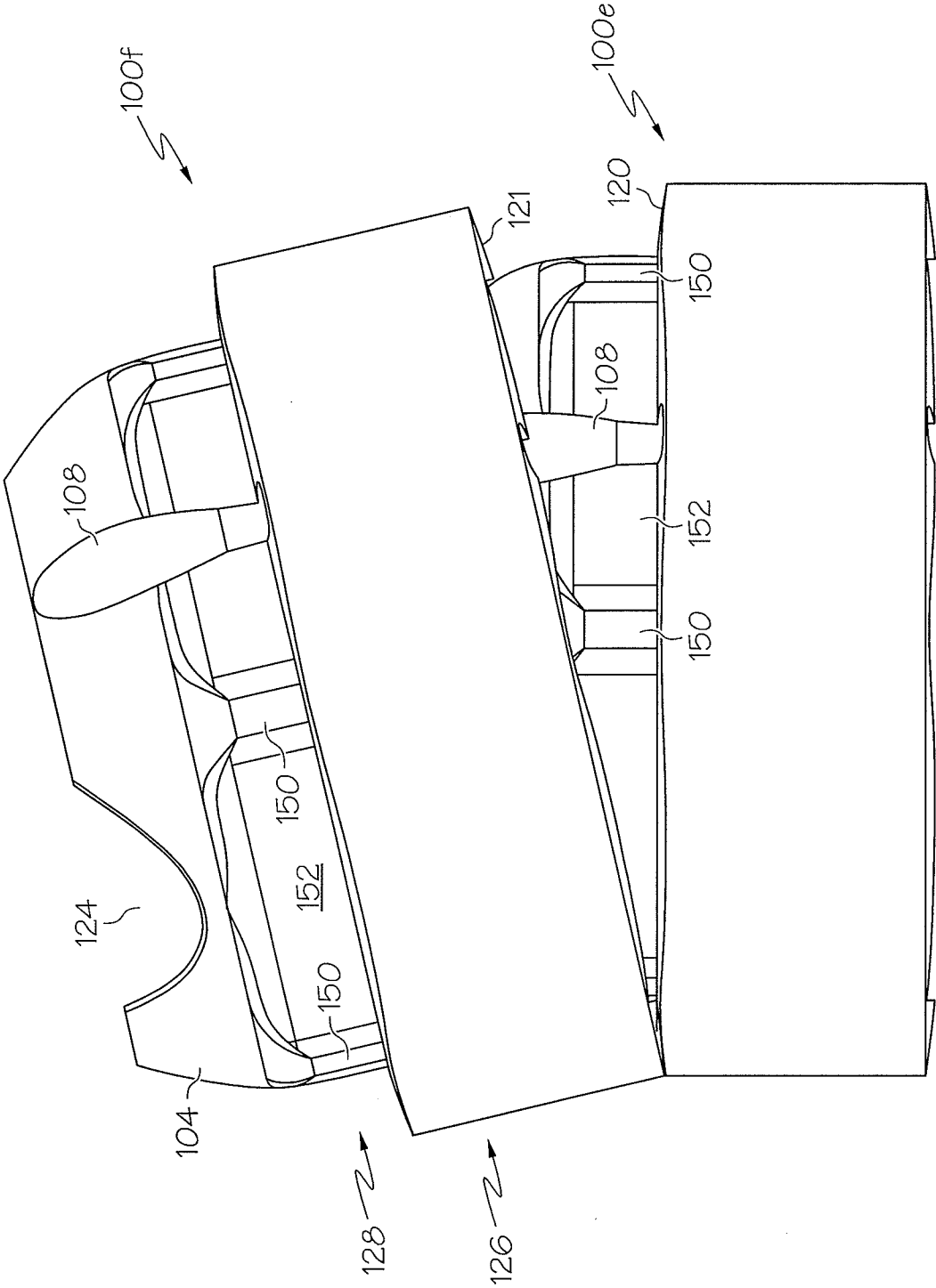


FIG. 4



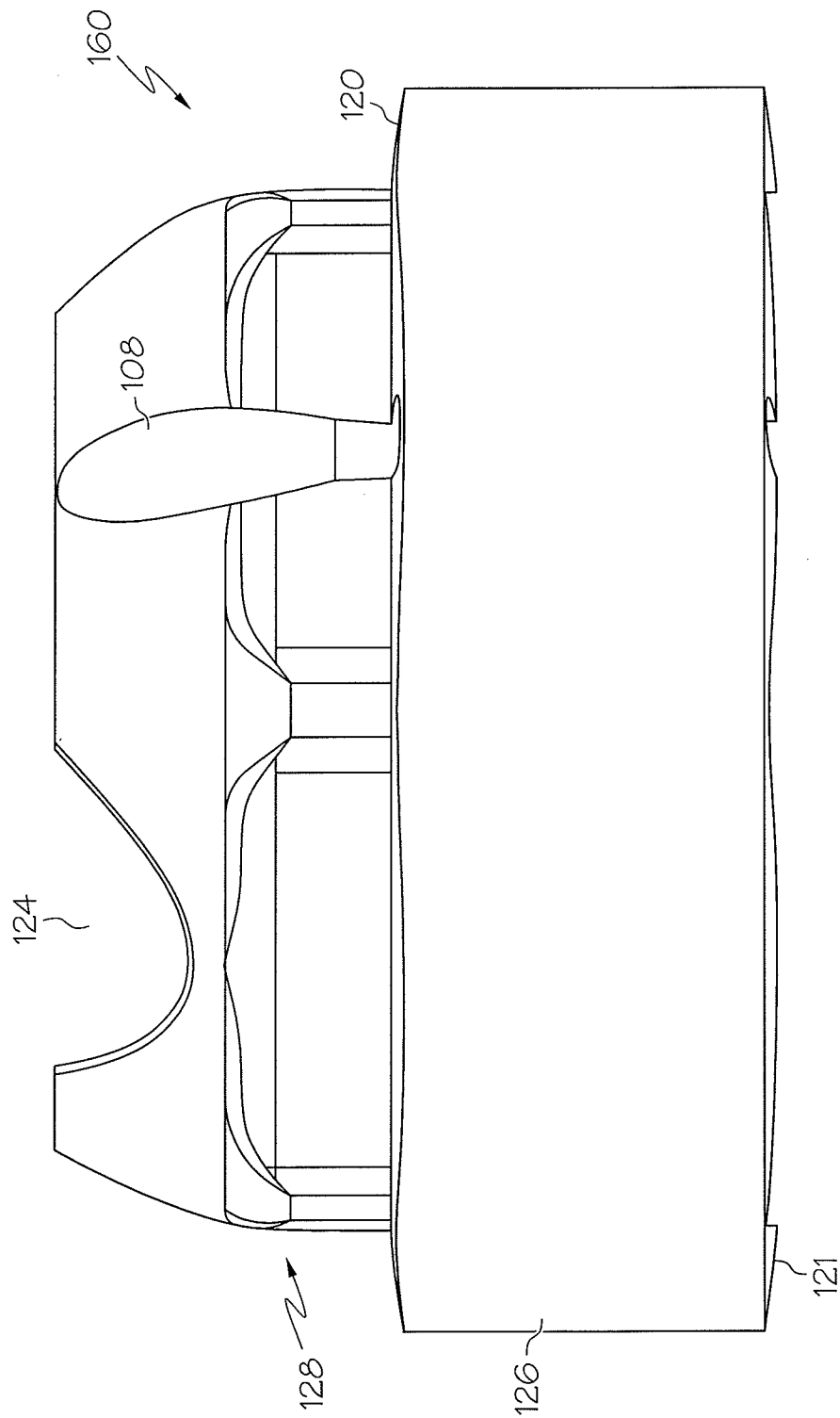


FIG. 5B

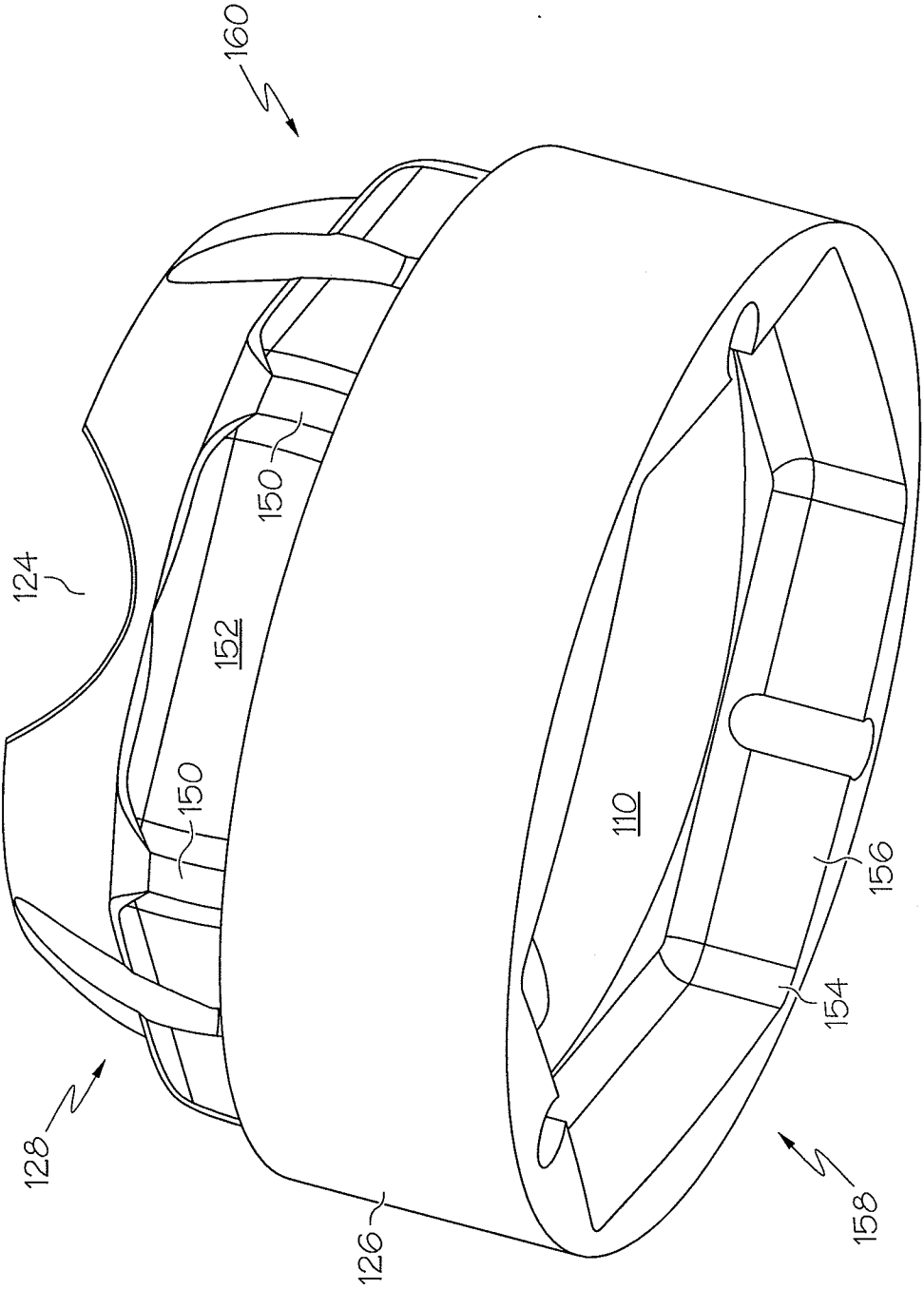


FIG. 5C

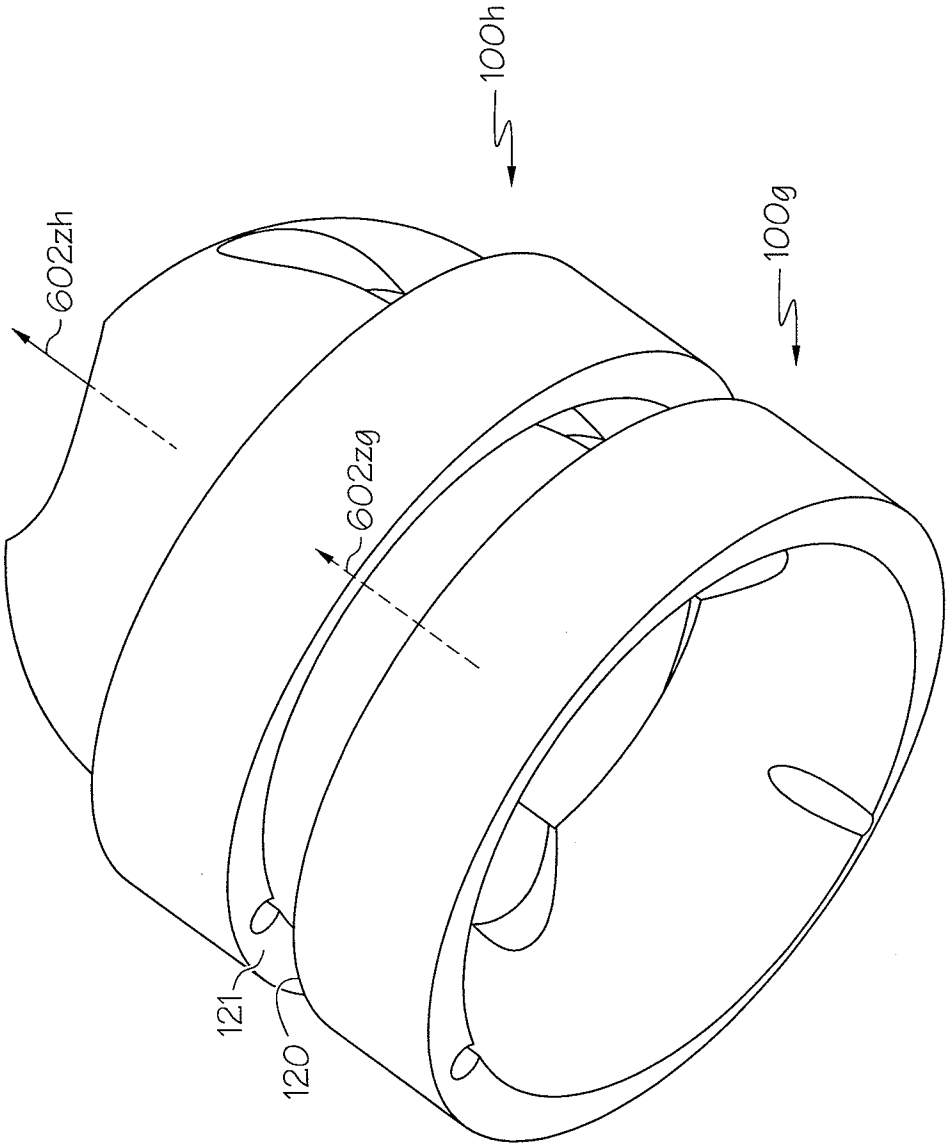


FIG. 6A

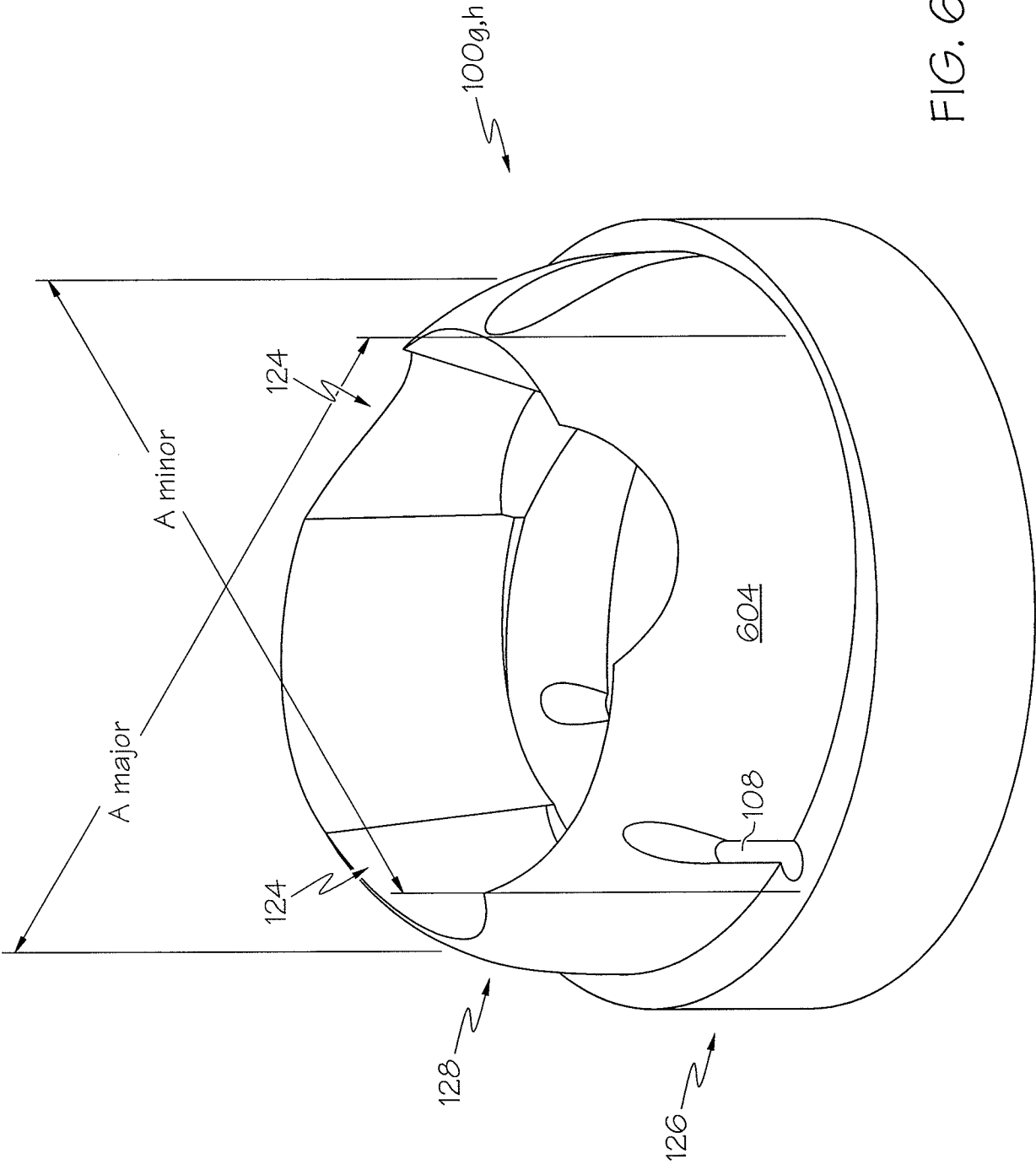
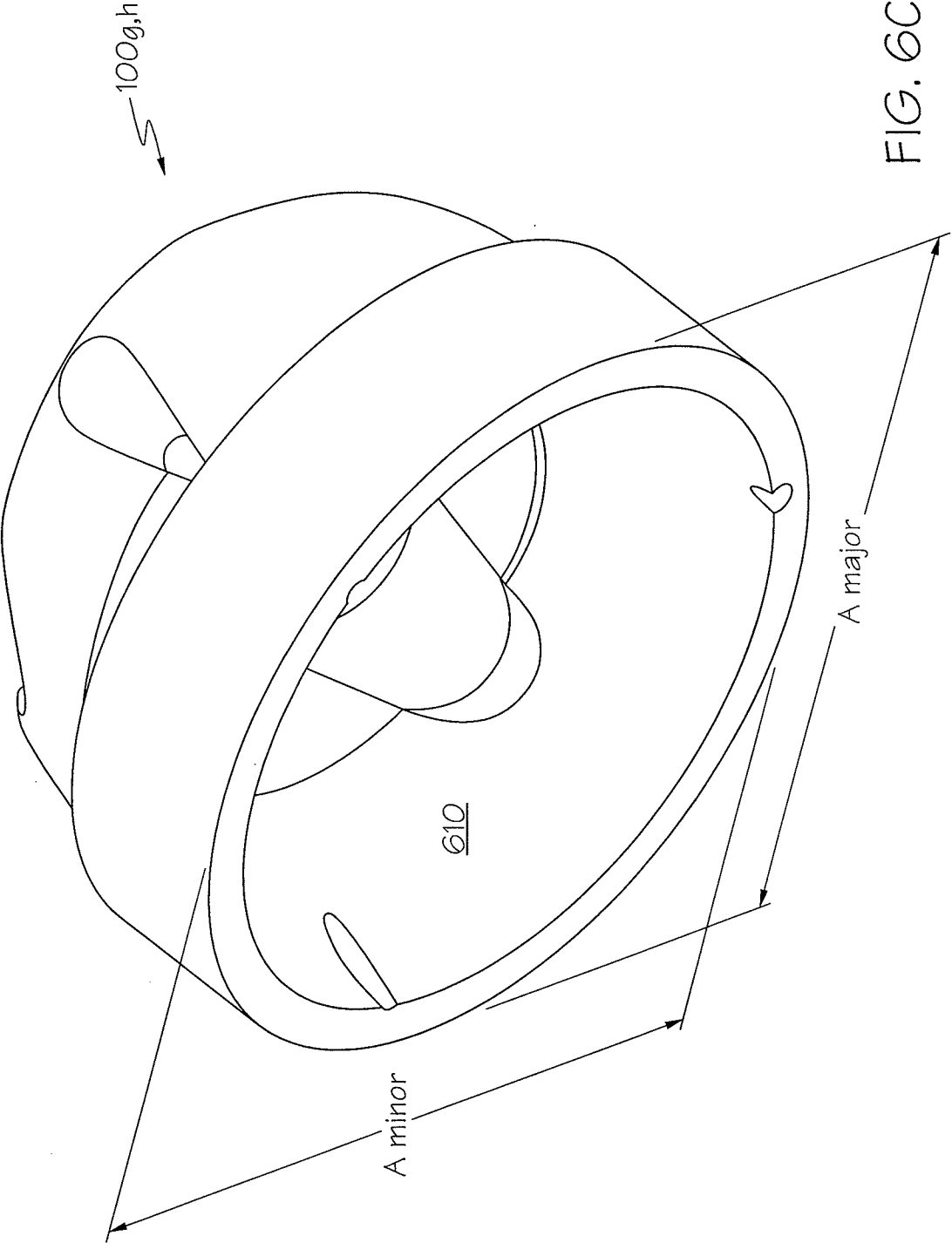


FIG. 6B



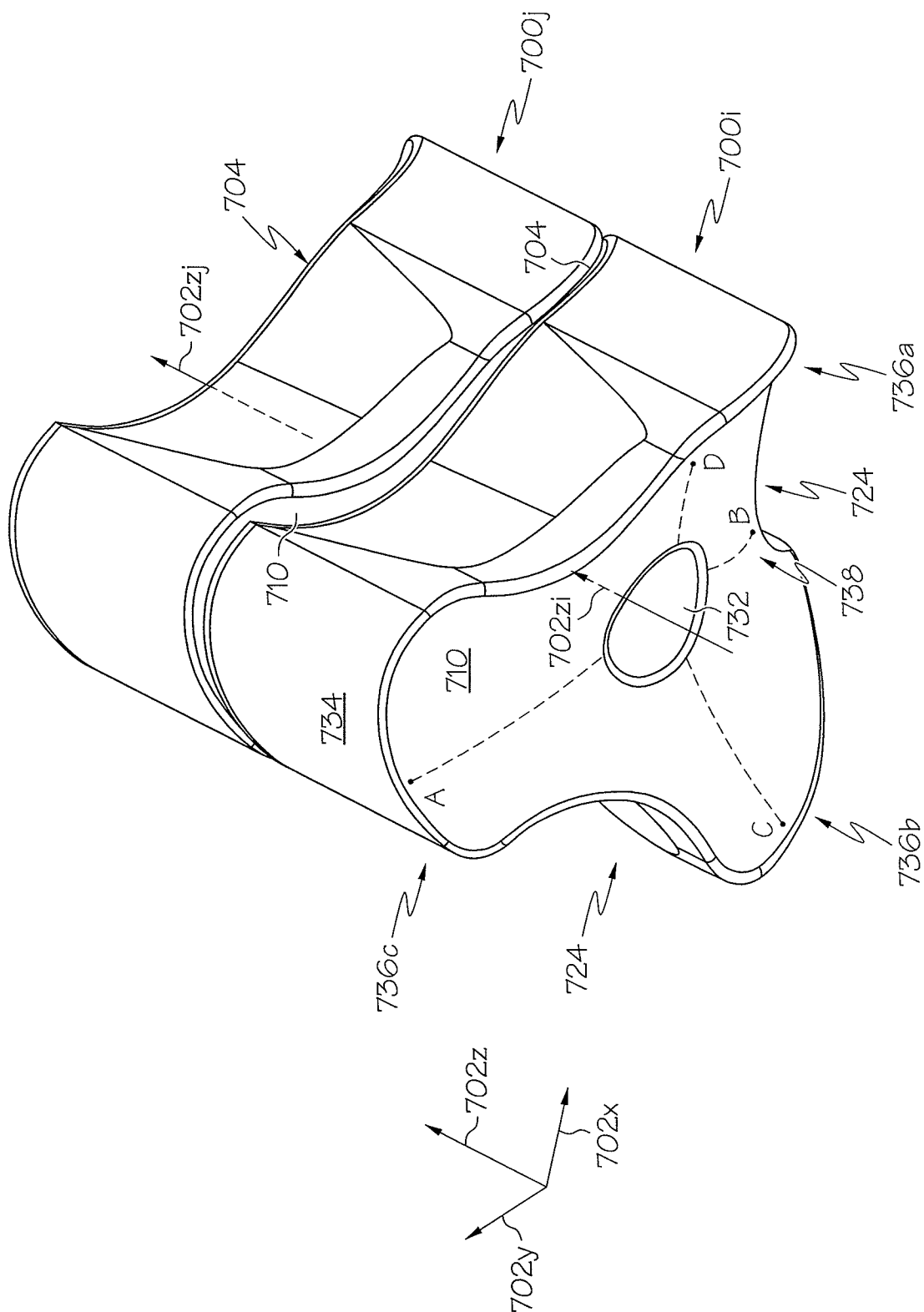


FIG. 7A

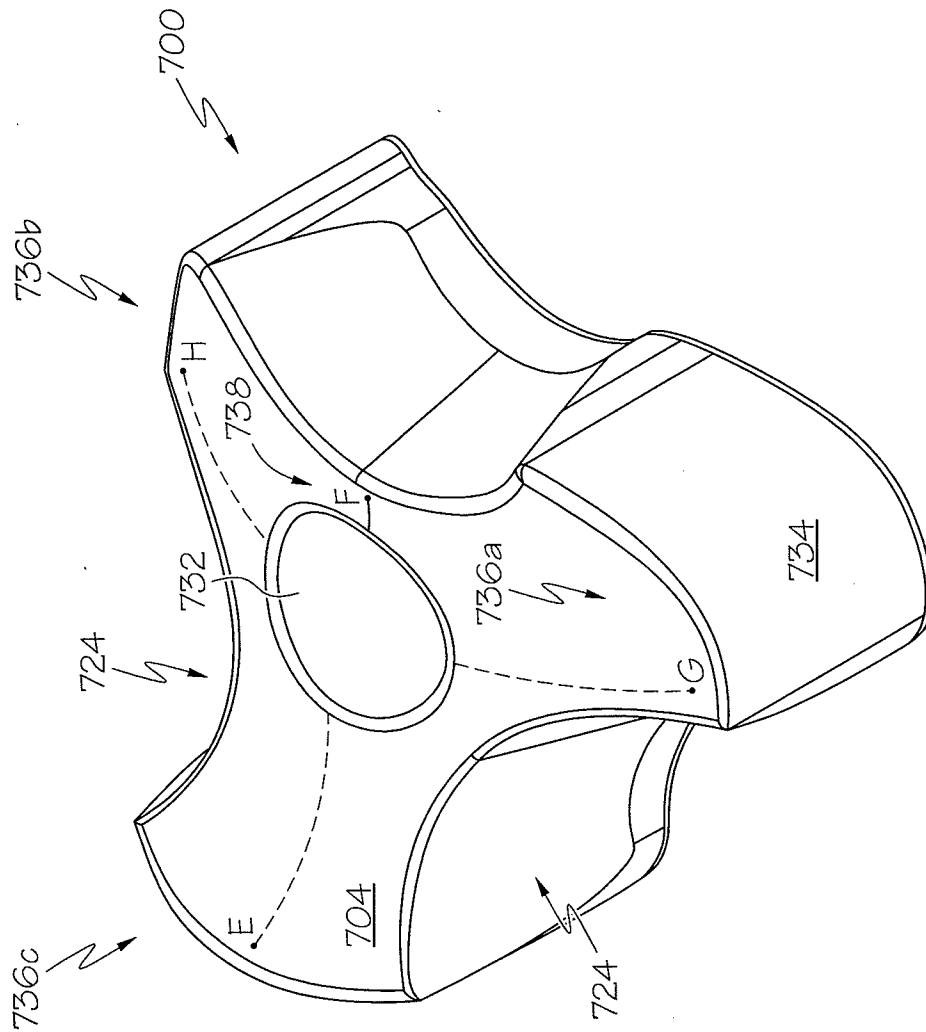


FIG. 7B

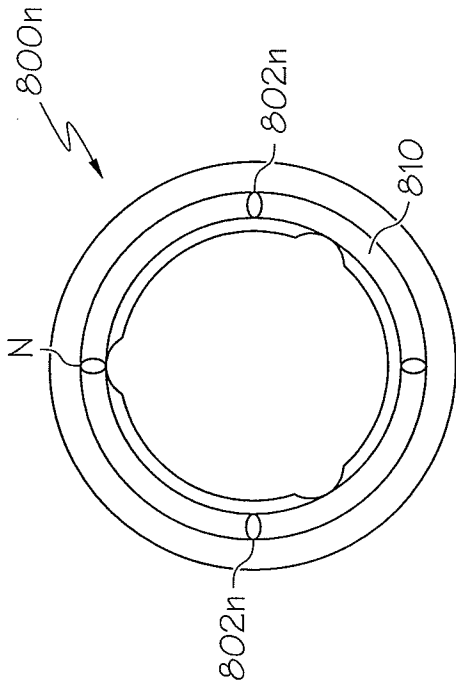


FIG. 8A(1)

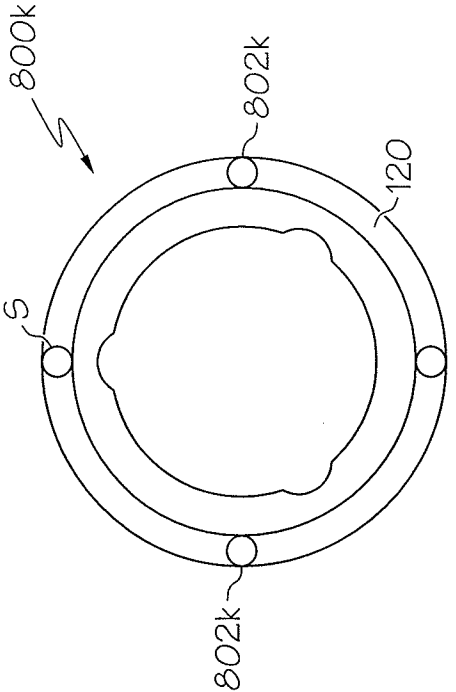


FIG. 8A(2)

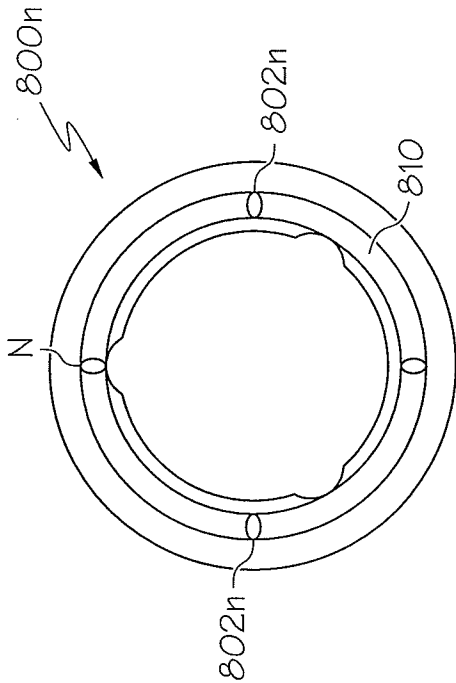


FIG. 8B(1)

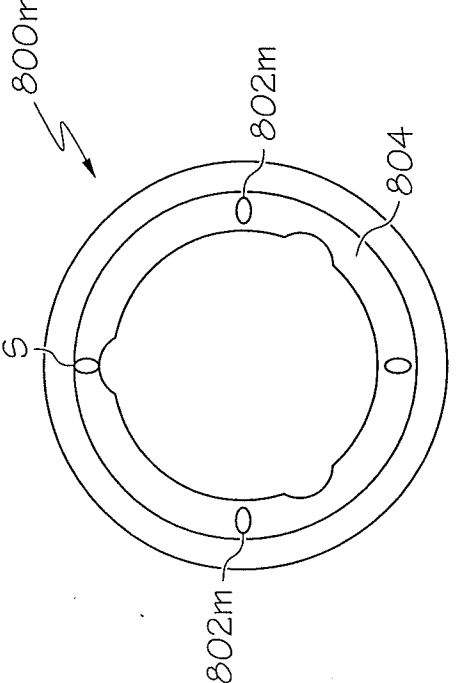
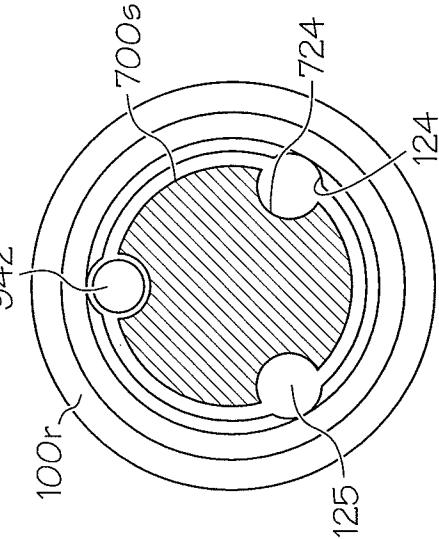
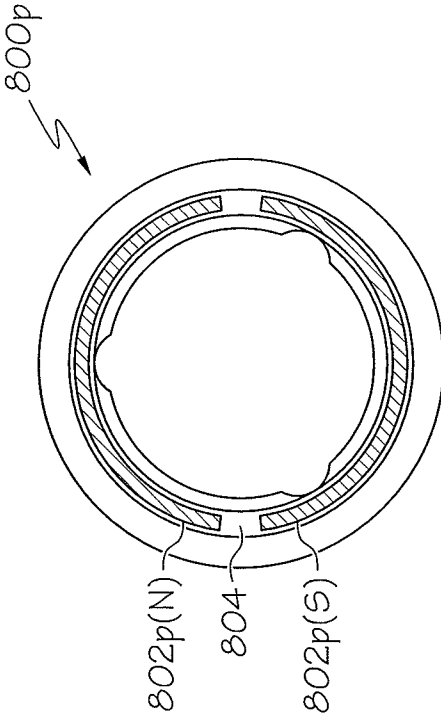
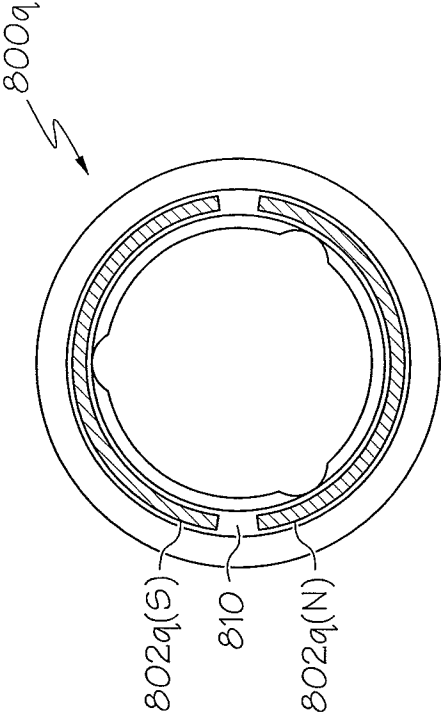


FIG. 8B(2)



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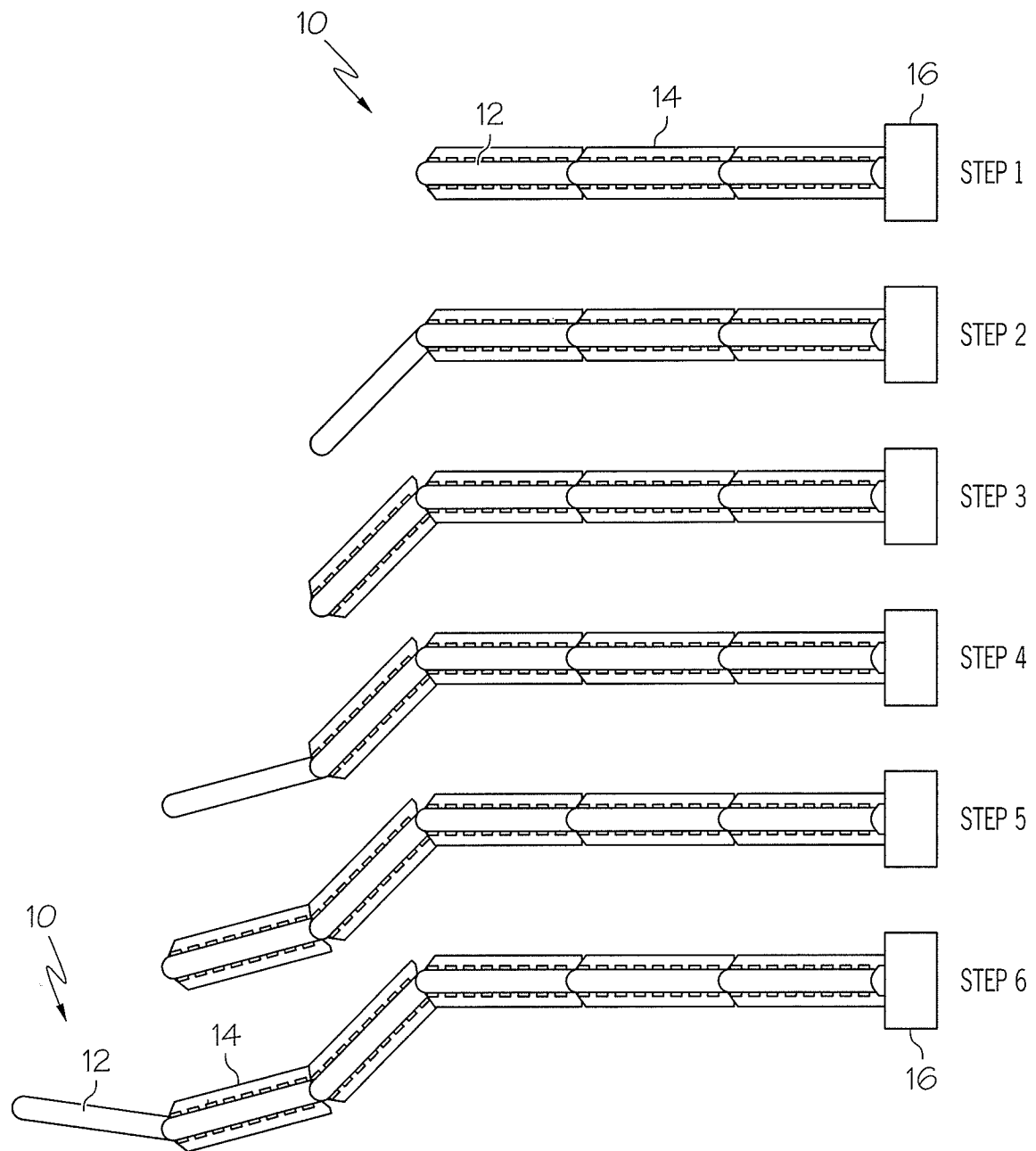


FIG. 10A

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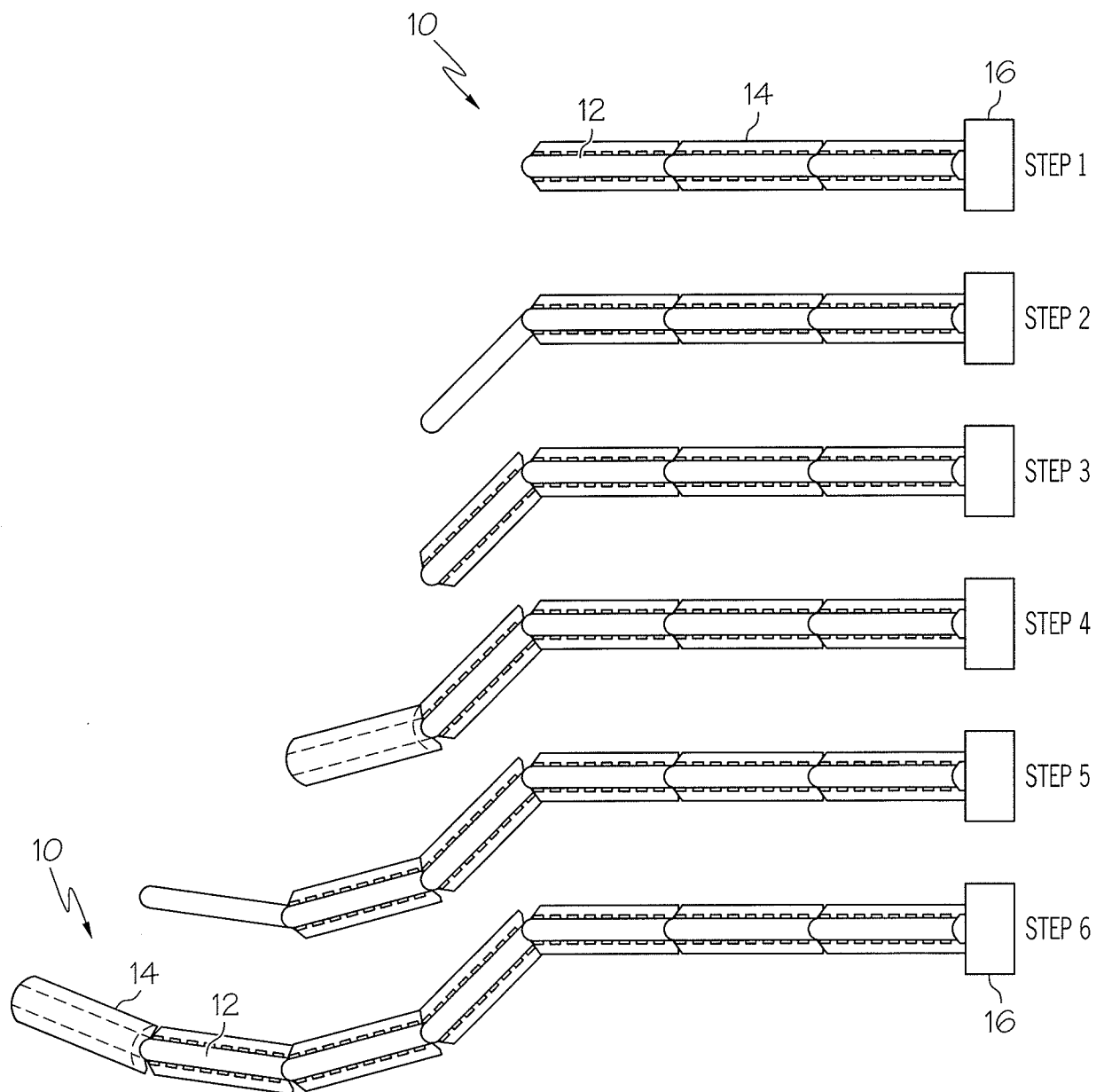


FIG. 10B

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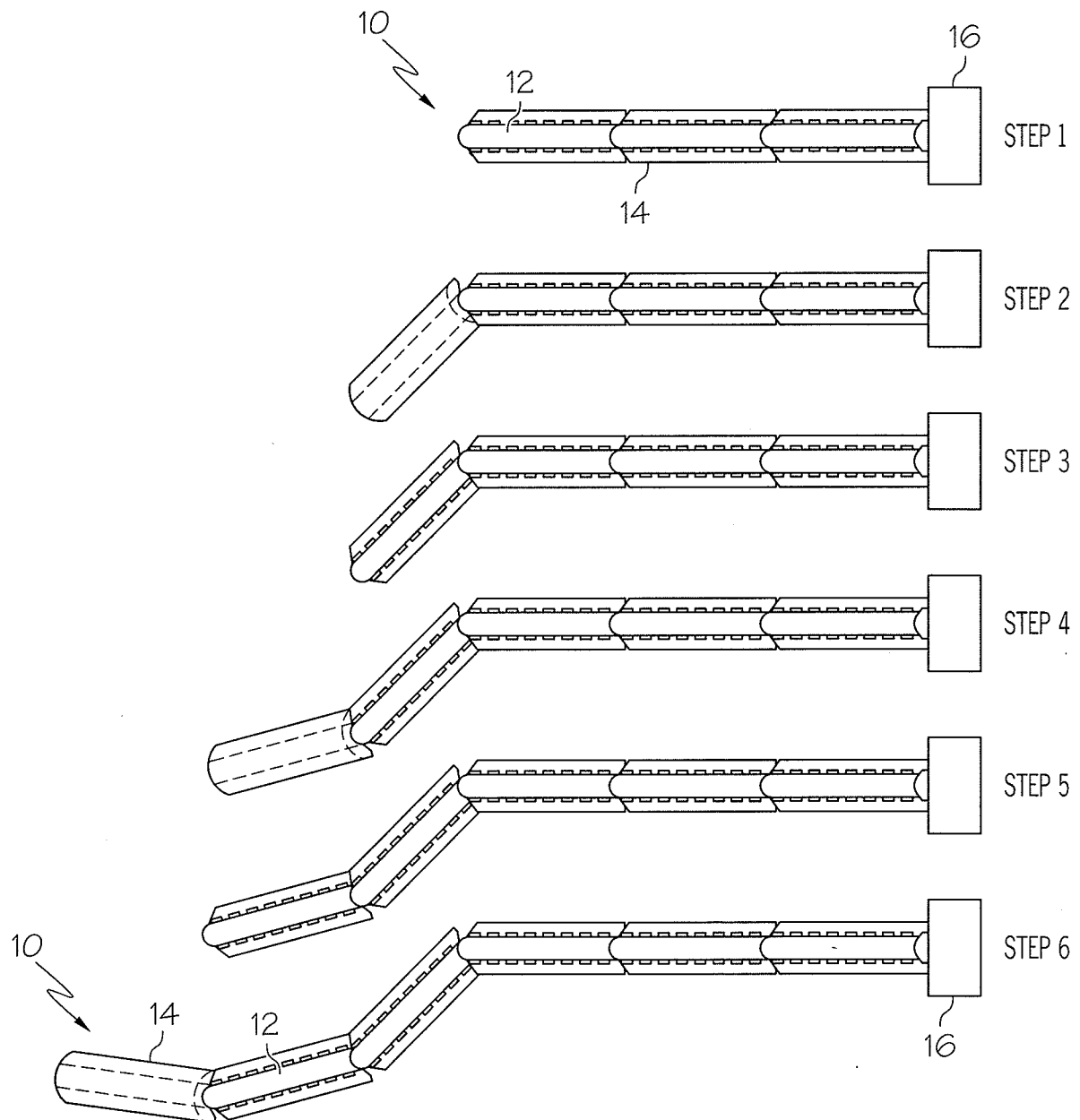


FIG. 10C

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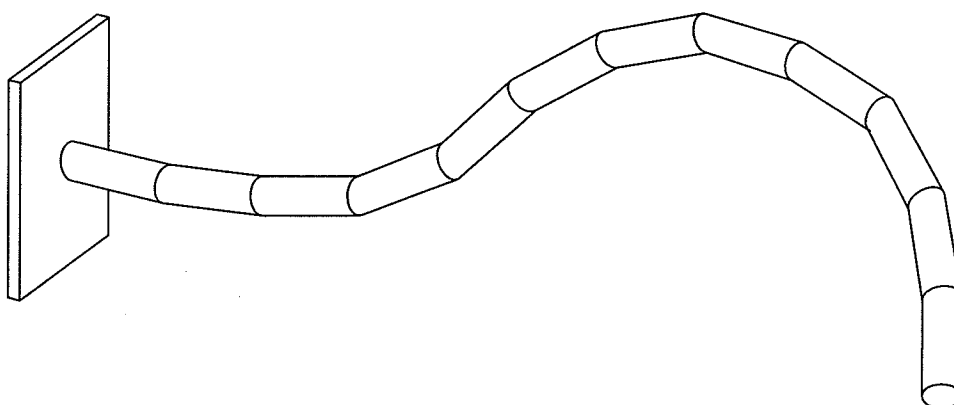


FIG. 11A

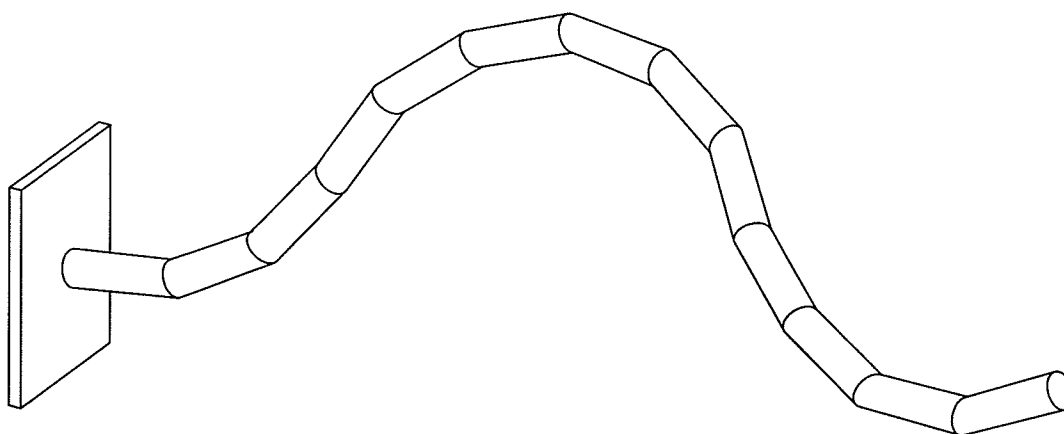


FIG. 11B

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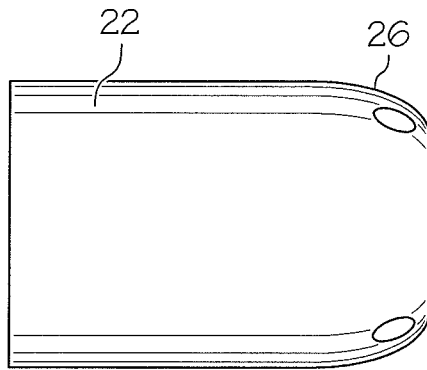


FIG. 12A

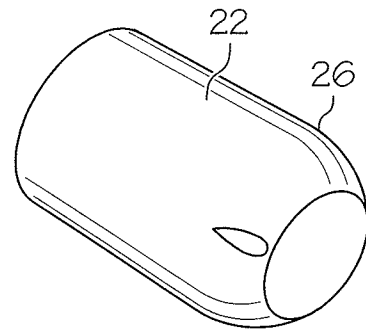


FIG. 12B

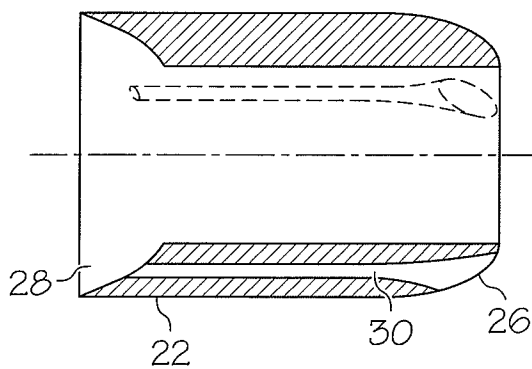


FIG. 12C

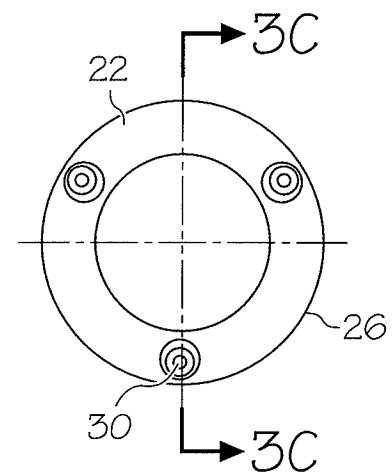


FIG. 12D

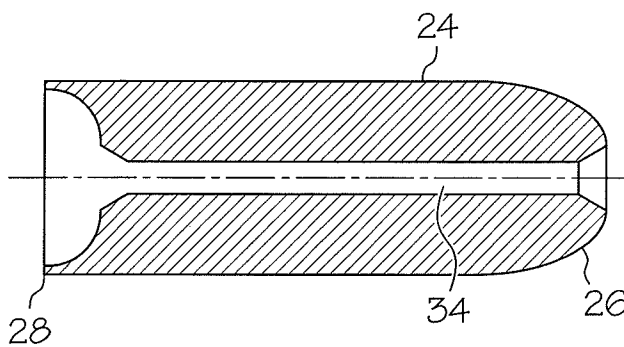


FIG. 13A

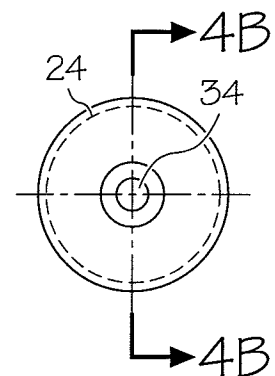
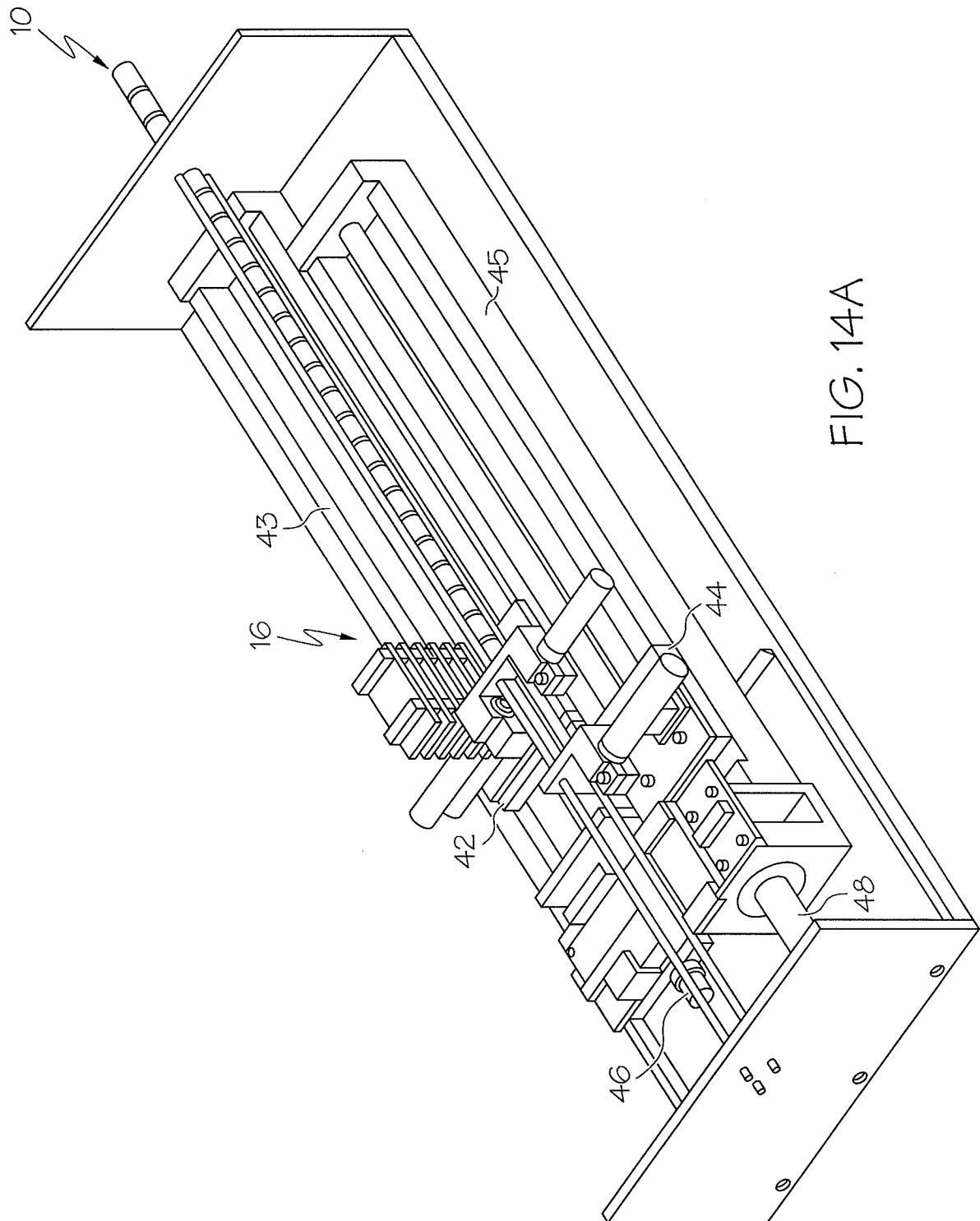


FIG. 13B

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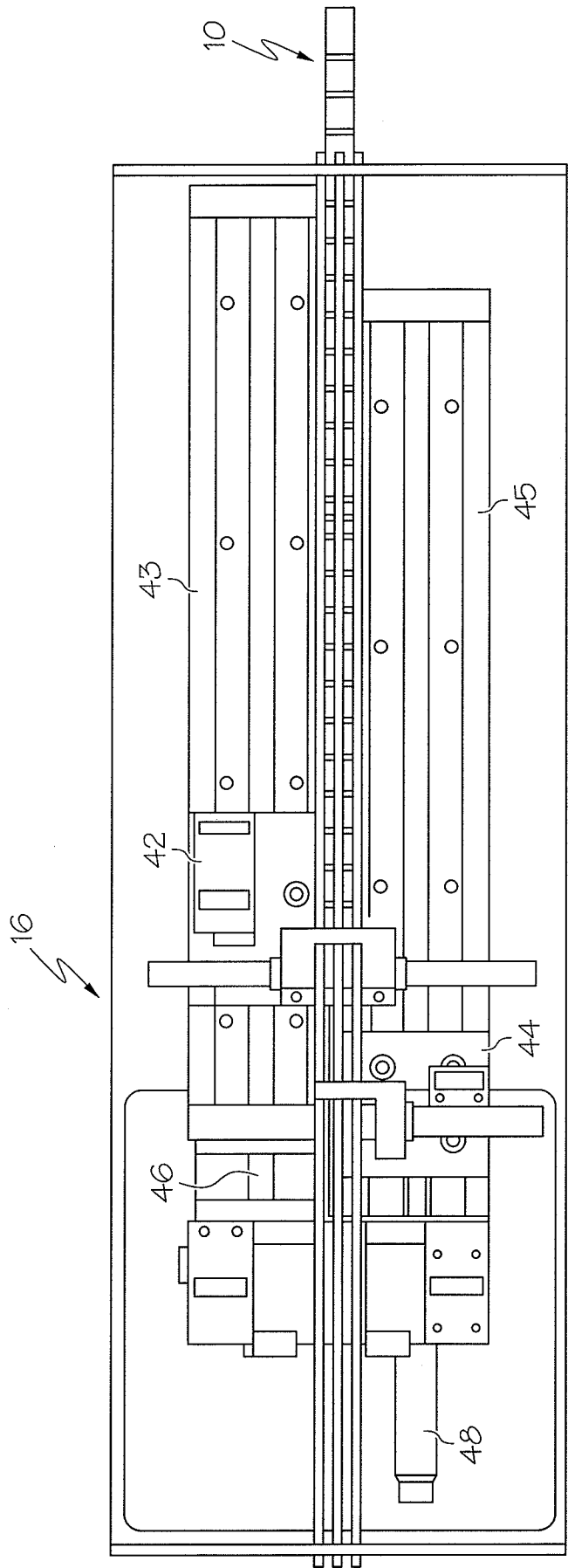


FIG. 14B

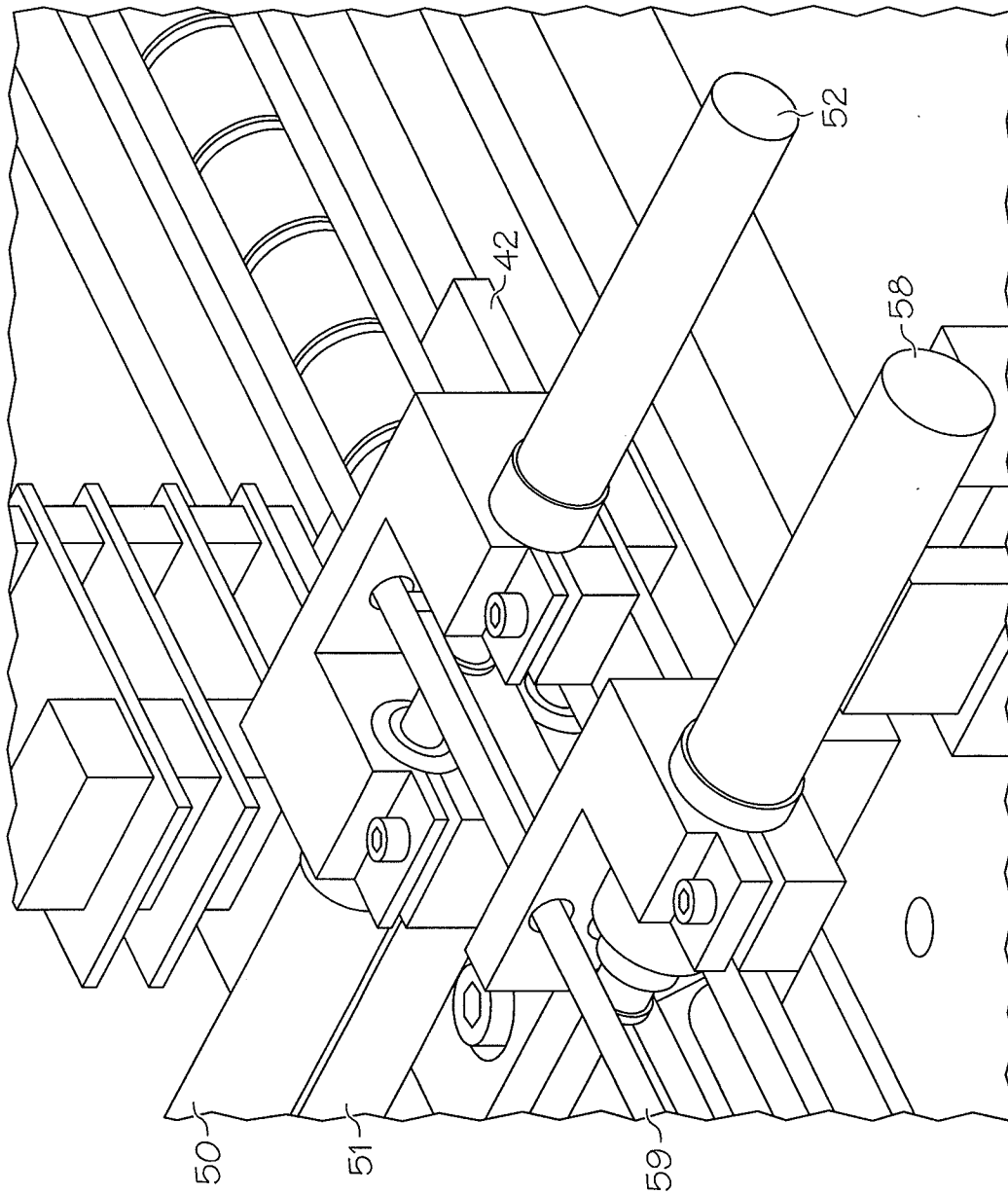


FIG. 15

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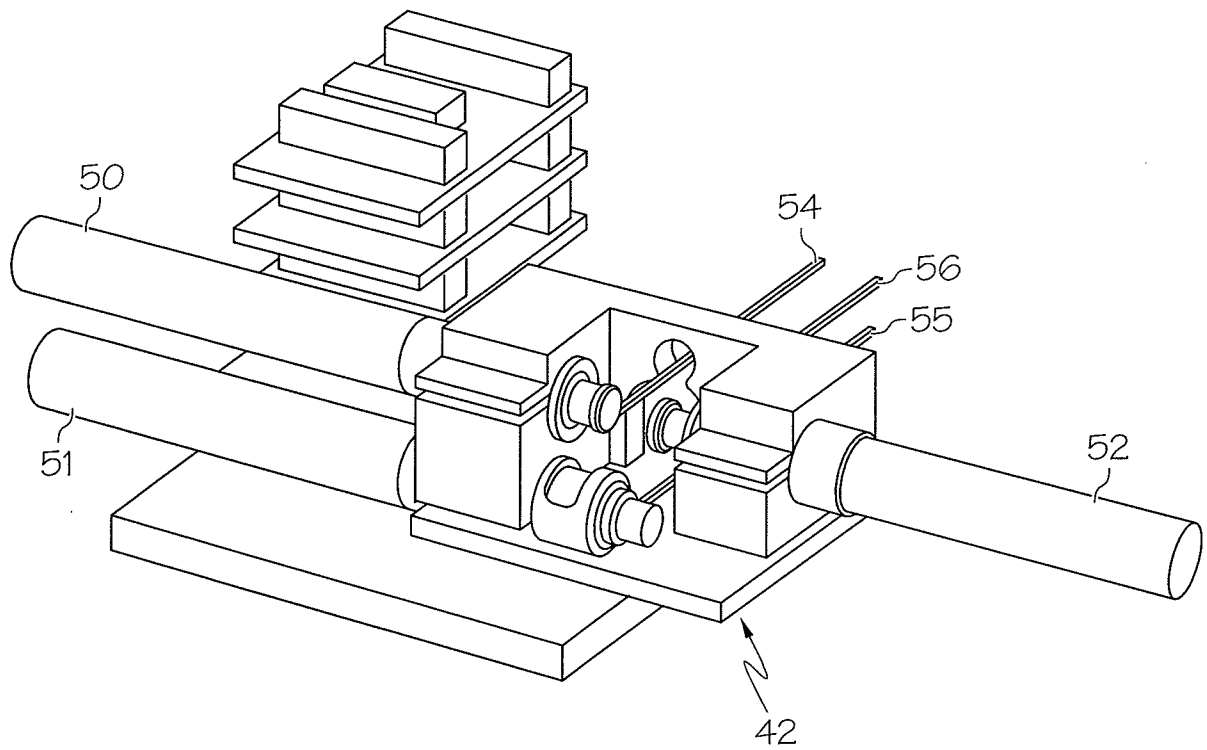


FIG. 16

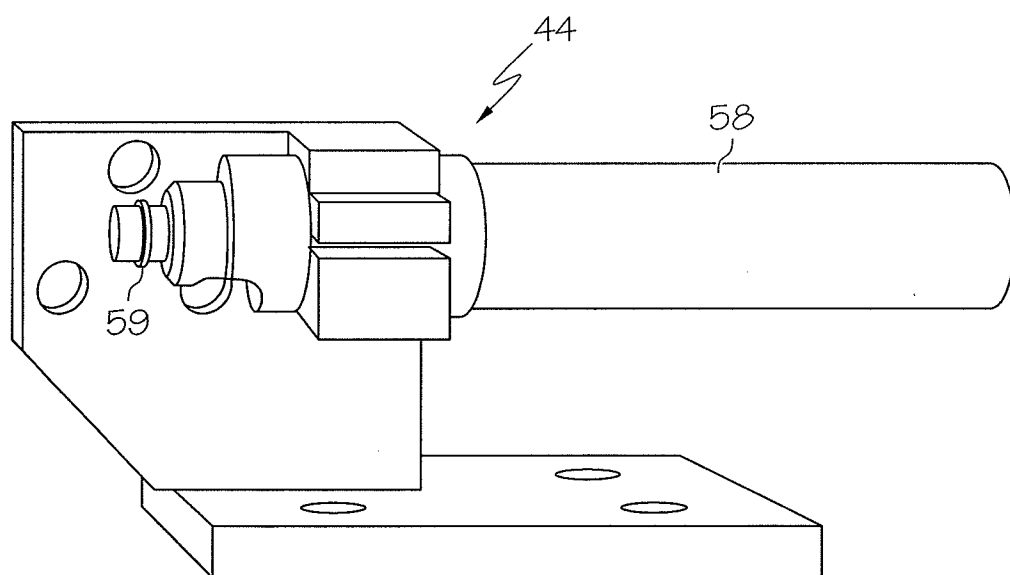


FIG. 17

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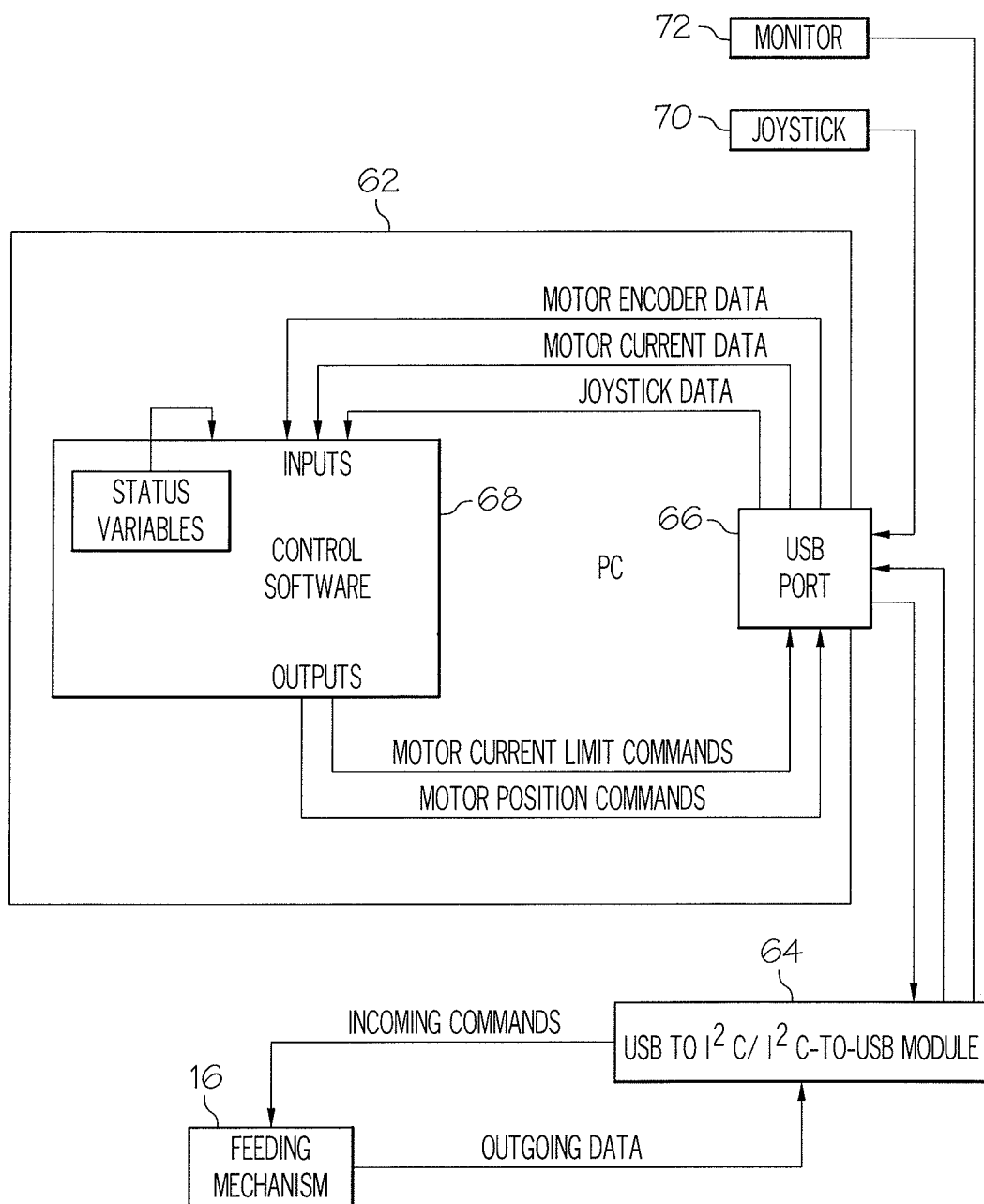


FIG. 18