



(51) International Patent Classification:

A61B 19/00 (2006.01) A61B 17/29 (2006.01)
A61B 1/05 (2006.01)

(21) International Application Number:

PCT/CA2013/001076

(22) International Filing Date:

20 December 2013 (20.12.2013)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/837,112 19 June 2013 (19.06.2013) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on nextpage]

(54) Title: ARTICULATED TOOL POSITIONER AND SYSTEM EMPLOYING SAME

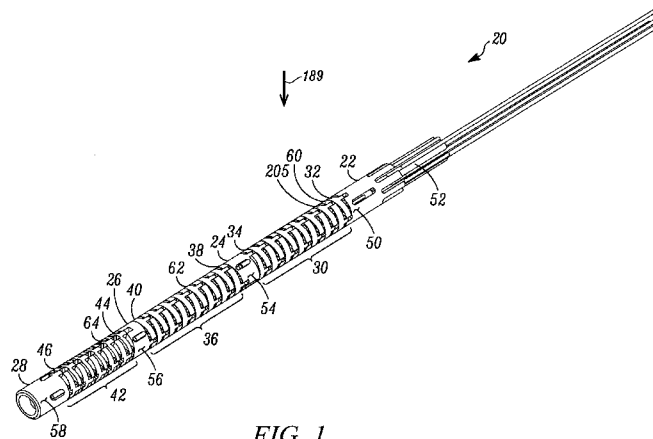


FIG. 1

(57) Abstract: An articulated tool positioning apparatus comprising a base member, an intermediate member, an end member and a first tool holder arranged in succession, each of the base member, intermediate member, end member and tool holder having a respective central opening. A first plurality of coupled guides is positioned between the base member and the intermediate member and a second plurality of coupled guides is positioned between the intermediate member and the end member. A third plurality of coupled guides is disposed between the end member and the tool holder. The base member, intermediate member, end member, first tool holder and first second and third pluralities of coupled guides all have a central opening and guide openings or securing points for securing pluralities of flexible control links to the base member or to an object separated from the base member. Pushing or pulling control links of a first plurality of control links causes the base member, the first plurality of coupled guides, the intermediate member, the second plurality of coupled guides and the end member to selectively define a continuous curve. A second plurality of control links causes the end member to maintain an orientation generally the same as the base member, when any of the other flexible control links is pushed or pulled. Pushing or pulling control links of a third plurality of control links causes the tool holder to be selectively moved into any of a plurality of orientations, such that the third plurality of coupled guides between

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Declarations under Rule 4.17:

- as to the identity of the inventor (Rule 4.17(i))
- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(H))

— of inventorship (Rule 4.17(iv))

Published:

- with international search report (Art. 21(3))

ARTICULATED TOOL POSITIONER AND SYSTEM EMPLOYING SAME

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention relates to robotic manipulators and more particularly to an articulated tool positioner with an example of a use of the articulated tool positioner for laparoscopic surgery.

2. Related Art

Articulating surgical systems for laparoscopic surgery are gaining acceptance. Various systems exist including a system described in US Publication No. 2012/0253131 A1 published October 4, 2012 to Malkowski et al.

Malkowski et al. describe a surgical system that includes one or more arms defining a passageway therethrough. The arm includes a proximal portion configured for positioning externally of a patient's body and a distal portion configured for positioning within an internal body cavity. The distal portion includes first and second articulatable segments spaced apart from one another and capable of independent articulation between a substantially straight configuration and an articulated configuration. A first articulation assembly is coupled to the proximal portion of the one arm and is transitionable between a first state and a second state for articulating the first articulatable segment between the substantially straight configuration and the articulated configuration. A second articulation assembly is coupled to the proximal portion of the arm and is configured to move between a plurality of positions for articulating the second articulatable segment between the substantially straight configuration and the articulated configuration. Links forming articulatable segments of the articulation assemblies are biased by springs into a substantially straight position and cables are tensioned and untensioned to selectively pull on parts of the first and second

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articulation assemblies such that neutrality of tension between opposed internal cables is lost and this moves the arm between the plurality of positions.

The arrangement described by Malkowski et al. could be complicated to assemble due to the springs in the links and is likely to require careful manipulation by an operator who must be mindful to counteract the bias exerted by the springs to avoid undesired straightening of the articulable segments.

SUMMARY

The present invention provides an alternative articulated tool positioning apparatus that avoids the need for springs biasing articulated segments into a straight position through the use of cables capable of tension and compression connecting terminating members between articulating links, thereby supporting both pushing and pulling on the cables and providing for simpler assembly.

In accordance with one aspect of the invention, there is provided an articulated tool positioning apparatus. The apparatus includes a base member, an intermediate member, an end member and a first tool holder arranged in succession, each of the base member, intermediate member, end member and tool holder having a respective central opening. The apparatus further includes a first plurality of coupled guides between the base member and the intermediate member at least one of the first plurality of coupled guides is coupled to the base member and at least one of the first plurality of coupled guides is coupled to the intermediate member. Each coupled guide of the first plurality of coupled guides has a respective central opening. The apparatus further includes a second plurality of coupled guides between the intermediate member and the end member. At least one of the second plurality of coupled guides is coupled to the intermediate member and at least one of the second plurality of coupled guides is coupled to the end member. Each coupled guide of the second plurality of coupled guides also has a respective central opening. The apparatus further

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includes a third plurality of coupled guides between the end member and the tool holder. At least one of the third plurality of coupled guides is coupled to the end member and at least one of the third plurality of coupled guides is coupled to the tool holder. Each coupled guide of the third plurality of coupled guides also has a respective central opening. The apparatus further includes first guide openings in the base member and corresponding first guide openings in each coupled guide of the first plurality of coupled guides. A first plurality of flexible control links disposed in parallel spaced apart relation extend through respective openings of the first guide openings in the base member and through respective openings of the corresponding first guide openings in the first plurality of coupled guides. Each of the first plurality of flexible control links has respective first end portions connected to the intermediate member and respective second end portions extending away from the base member.

The apparatus further includes second guide openings in the intermediate member and corresponding second guide openings in each coupled guide of the first and second pluralities of coupled guides. The apparatus further includes a second plurality of flexible control links disposed in parallel spaced apart relation, each having a first end connected to the end member, a second end connected to at least one of the base member and an object spaced apart from the base member. Each of the second flexible control links includes an intermediate portion between the first and second ends. Each intermediate portion extends through a respective second guide opening in the intermediate member and through respective second guide openings in each guide of the first and second pluralities of coupled guides.

The apparatus further includes third guide opening in the base member and in each coupled guide of the first plurality of coupled guides and in the intermediate member and in each coupled guide of the second plurality of coupled guides and

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in the end member and in each coupled guide of the third plurality of coupled guides.

The apparatus further includes a third plurality of flexible control links disposed in parallel spaced apart relation and extending through respective third guide openings in the base member, in each coupled guide of the first plurality of coupled guides through respective third guide openings, in the intermediate member through respective third guide openings, in each coupled guide of the second plurality of coupled guides through respective third guide openings, in the end member and through respective third guide openings in each coupled guide of the third plurality of coupled guides. Each flexible control link of the third plurality of flexible control links has a first end connected to the tool holder and a second end extending away from the base member.

Pushing or pulling control links of the first plurality of control links causes the base member, the first plurality of coupled guides, the intermediate member, the second plurality of coupled guides and the end member to selectively define a continuous curve. The second plurality of control links causes the end member to maintain an orientation generally the same as the base member, when any of the first or third flexible control links is pushed or pulled. Pushing or pulling control links of the third plurality of control links causes the tool holder to be selectively moved into any of a plurality of orientations, such that the third plurality of coupled guides between the end member and the tool holder defines a continuous curve from the end member to the tool holder.

The first, second and third pluralities of flexible control links may include wires capable of experiencing about 200N of tension and compression without yielding and up to about 2% to 4% strain.

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The wires may be comprised of a metal alloy of nickel and titanium having shape memory and superelasticity.

The second plurality of control links may include wires having a common stiffness.

The base member, the intermediate member, the end member, the first tool holder and the coupled guides of the first, second and third pluralities of coupled guides may each have a generally circular cylindrical outer surface portion, and each the generally circular cylindrical outer surface portion may have a common diameter.

The base member, the intermediate member, the end member, the first tool holder and the coupled guides of the first, second and third pluralities of coupled guides may each have generally annular segments. At least one annular segment of the base member and at least one annular segment of each coupled guide of the first plurality of coupled guides may have the first guide openings. At least one annular segment of each coupled guide of the first and second pluralities of coupled guides and at least one annular segment of the intermediate member may have the second guide openings, and at least one annular segment of each of the base member, the intermediate member, the end member, and each coupled guide of the first, second and third pluralities of coupled guides may have the third guide openings.

Each of the annular segments of the coupled guides of the first plurality of coupled guides may have opposite faces disposed at acute angles to an axis of the central opening in the coupled guide.

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Each of the annular segments of the second plurality of coupled guides may have opposite faces disposed at acute angles to an axis of the central opening in the coupled guide.

Each of the annular segments of the third plurality of coupled guides may have opposite faces disposed at acute angles to an axis of the central opening in the coupled guide.

The opposite faces of annular segments of the coupled guides of the first and second pluralities of coupled guides may be disposed at a first acute angle to the axis and the opposite faces of annular segments of the coupled guides of the third plurality of the coupled guides may be disposed at a second acute angle to the axis, the second acute angle may be different from the first acute angle.

The second acute angle may be greater than the first acute angle.

Adjacent pairs of coupled guides of the first, second and third pluralities of coupled guides may be coupled by at least one projection on one guide of the pair and a receptacle for receiving the projection on the other guide of the pair.

Each of the coupled guides of the first, second and third pluralities of coupled guides may have an axially extending projection having a truncated spherical portion and an axially aligned socket for receiving an axially extending projection of an adjacent coupled guide to permit adjacent coupled guides to spherically pivot relative to each other. The central opening of the coupled guide may have a first terminus on the projection and a second terminus in the socket so that central openings of adjacent coupled guides are in communication with each other so as to define a central channel operable to receive a portion of a tool held by the tool holder.

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The apparatus may further include a first support conduit having first and second open ends, and the base may be connected to the first open end of the support conduit to support the base and the second end portions of the first and third control links may extend through the first support conduit to extend out of the second open end of the first support conduit.

In accordance with another aspect of the invention, there is provided a tool assembly comprising the apparatus described above and further including a first tool. The first tool may include a first end effector, a first coupler for coupling the first end effector to the first tool holder, the tool may further include a first flexible shaft portion having a length approximately the same as a length defined between the base member and the tool holder, and a first rigid shaft portion having a length approximately equal to a length of the first support conduit. The tool may further include a first tool control link having a first end connected to the first end effector and a second end extending from the first rigid shaft portion. The first rigid shaft portion may be received in the central opening of the first tool holder and may extend through the central openings in the third plurality of coupled guides through the central opening in the end member, through the central openings in the second plurality of coupled guides, through the central opening in the intermediate member, the central openings in the first plurality of coupled guides, and through the central openings in the base member and the first support conduit such that the first flexible shaft portion is coaxial with the tool positioning apparatus and such that the first rigid shaft portion is generally coaxial with the first support conduit and such that the second end of the first tool control link extends from the second end portion of the first support conduit.

In accordance with another aspect of the invention, there is provided a tool controller assembly including the tool assembly described above and further including a first control mount. The first support conduit of the tool positioning apparatus may be connected to the first control mount such that the first control

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mount may be on a first side of a first longitudinal axis of the first support conduit. The first control mount may have a first plurality of actuators connected to respective flexible control links of the first and third pluralities of flexible control links of the first tool positioning apparatus, for selectively pushing and pulling on the second end portions of the respective flexible control links to cause the base member, the first plurality of coupled guides, the intermediate member, the second plurality of coupled guides and the end member to selectively define a continuous curve and to cause the tool holder to be selectively moved into any of a plurality of orientations, such that the third plurality of coupled guides between the end member and the first tool holder apparatus may define a continuous curve from the end member to the first tool holder. The first control mount may include a first tool actuator connected to the first tool control link of the first tool, for selectively pushing and pulling on the second end portion of the first tool control link to effect operation of the end effector.

Each actuator of the first plurality of actuators and the first tool actuator may include a respective rotatable spool portion to which a respective control link is connected to permit a portion of the respective control link to be taken up or payed out from the spool portion in response to corresponding rotation of the spool portion, and a respective driver for selectively rotating the spool portion in first and second opposite directions. The respective control link may be pulled when the spool portion is rotated in the first direction to take up the portion of the respective control link and the respective control link may be pushed when the spool portion is rotated in the second direction to pay out the portion of the respective control link.

Each driver may include a gear segment.

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The first control mount may have a first mounting surface and each gear segment may have a portion that projects beyond the first mounting surface to engage a corresponding drive gear on a first tool controller mount.

In accordance with another aspect of the invention, there is provided a tool controller mount including a first tool controller assembly as described above mounting interface for holding a first tool controller and may further include a first plurality of drive gears for engaging respective gear segments on the first tool controller assembly.

The drive gears of the first plurality of drive gears may include respective linear gear racks operably configured to slide linearly in parallel spaced apart relation.

The apparatus may include a first plurality of linear actuators connected to respective linear gear racks for sliding the linear gear racks linearly to impart movement to corresponding gears of the second plurality of drive gears.

The apparatus may include a second tool controller mounting interface comprising a second plurality of drive gears for engaging respective gear segments on a second tool controller similar to the first tool controller described above.

The drive gears of the second plurality of drive gears may include respective linear gear racks operably configured to slide linearly in parallel spaced apart relation.

The apparatus may include a second plurality of actuators connected to respective linear gear racks for sliding the linear gear racks linearly to impart movement to corresponding drive gears of the second plurality of drive gears.

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In accordance with another aspect of the invention, there is provided a tool supervisory apparatus including a positioning tube positioned to receive at least one support conduit of a tool controller assembly as described above. The positioning tube may have a length approximately the same as or less than a length of the support conduit so that a tool holder supported by the support conduit extends from a distal end of the positioning tube. The tool supervisory apparatus further includes a camera holder in a position off an axis of the positioning tube such that the camera may be directed toward an end effector of a tool held by the tool holder to facilitate visual monitoring of movement of the end effector.

The camera holder may include the tool holder. The support conduit of the camera holder may extend inside the positioning tube and a tool positioner of the camera holder may extend from the distal end of the positioning tube and may be operably configured to hold and position the camera in a position off the second axis. The second axis may be generally perpendicular to the longitudinal axis of the support conduit.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the invention,

- Figure 1 is a perspective view of an articulated tool positioning apparatus according to a first embodiment of the invention;
- Figure 2 is a perspective view of a distal end of a base member of the apparatus shown in Figure 1;
- Figure 3 is a distal end view of the base member shown in Figure 2;
- Figure 4 is a perspective view of a proximal side of a coupled guide of the apparatus shown in Figure 1;
- Figure 5 is a top view of the coupled guide shown in Figure 1;
- Figure 6 is an exploded view of two coupled guides of the apparatus shown in Figure 1, including the coupled guide shown in Figures 4 and 5;

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- Figure 7** is a side view of the coupled guides of Figure 6 shown engaged;
- Figure 8** is a perspective view of the apparatus shown in Figure 1 illustrating a bended configuration of the tool positioner shown in Figure 1;
- Figure 9** is a perspective view of a proximal face of an intermediate member of the apparatus shown in Figure 1;
- Figure 10** is a perspective view of a distal face of the intermediate member shown in Figure 9;
- Figure 11** is a perspective view of a proximal side of an end member of the apparatus shown in Figure 1;
- Figure 12** is a perspective view of a distal side of the side member shown in Figure 11;
- Figure 13** is a perspective view of a proximal side of a tool holder of the apparatus shown in Figure 1;
- Figure 14** is a perspective view of a distal side of the tool holder shown in Figure 13;
- Figure 15** is a side view of a tool apparatus for use with the tool positioner shown in Figure 1;
- Figure 16** is a perspective view of a tool assembly comprised of the apparatus shown in Figure 1 with the tool apparatus shown in Figure 15 connected thereto;
- Figure 17** is a perspective view of a tool controller shown connected to the tool assembly shown in Figure 16;
- Figure 18** is a perspective view of a laparoscopic surgical apparatus employing the device shown in Figure 17;
- Figure 19** is a side view of a head of the apparatus shown in Figure 18 and a coupler operable to be coupled to the head;
- Figure 20** is a side view of the head and coupler of Figure 19 with the coupler connected to the head;

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- Figure 21 is a side view of the coupler connected to the head of Figures 19 and 20 with a sterile cover connected to the coupler draped over the head and nearby components;
- Figure 22 is a side view of the head and coupler of Figures 19 - 21 and a camera/delivery tube assembly operable to be coupled to the coupler;
- Figure 23 is a detailed view of the camera/delivery tube assembly shown in Figure 22;
- Figure 24 is a side view of the camera/delivery tube assembly shown in Figure 23 coupled to the coupler shown in Figures 19 - 22;
- Figure 25 is a side view of the camera/delivery tube assembly coupled to the coupler and a tool positioning device of the type shown in Figure 17 being engaged therewith;
- Figure 26 is a perspective view from below of the tool controller of Figure 17 connected to the coupler of Figures 19 - 22 with a tube associated with the tool positioning device inserted in the delivery tube shown in Figure 23;
- Figure 27 is a side view of the delivery tube of Figure 23 with a first tube supporting the tool positioner of Figure 1 extending therethrough;
- Figure 28 is a side view of the apparatus of Figure 27 further including a second tool support tube supporting a second tool positioner extending through the delivery tube of Figure 23;
- Figure 29 is a side view of a laparoscopic surgical apparatus employing the apparatuses described in Figures 1 - 28; and
- Figure 30 is a perspective view of a surgeon's work-station for controlling the apparatus shown in Figure 29.
- Figure 31 is a perspective view from below of two tool controllers of the type shown in Figure 17 on a coupler according to an alternative embodiment of the invention;

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Figure 32 is a fragmented side view of first and second articulated tool positioning apparatuses extending at different distances from an end of a delivery tube of the coupler shown in Figure 31, when first and second tool controllers thereon are disposed at different linear distances from the delivery tube.

DETAILED DESCRIPTION

Referring to Figure 1, an articulated tool positioning apparatus according to a first embodiment of the invention is shown generally at 20. In this embodiment, the apparatus 20 includes a base member 22, an intermediate member 24, an end member 26 and a first tool holder 28 arranged in succession as shown in Figure 1. The base member 22 may be considered to be in a proximal position while the tool holder may be considered to be in a distal position. Thus, the base member 22, intermediate member 24, end member 26 and first tool holder 28 are arranged in succession from a proximal position to a distal position.

The apparatus 20 further includes a first plurality 30 of coupled guides, disposed between the base member 22 and the intermediate member 24. At least one (32) of the first plurality 30 of coupled guides is coupled to the base member 22 and another one (34) of the first plurality 30 of coupled guides is coupled to the intermediate member 24. Each of the coupled guides of the first plurality 30 is coupled to an adjacent guide or to the base member 22 or intermediate member 24.

The tool positioning apparatus 20 further includes a second plurality 36 of coupled guides between the intermediate member 24 and the end member 26. At least one (38) of the second plurality 36 of coupled guides is coupled to the intermediate member 24 and another one (40) of the second plurality 36 of coupled guides is coupled to the end member 26. Each of the coupled guides of

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the second plurality **36** of coupled guides is thus connected to an adjacent guide of the second plurality or to the intermediate member **24** or the end member **26**.

The apparatus **20** further includes a third plurality **42** of coupled guides between the end member **26** and the tool holder **28**. At least one (**44**) of the third plurality **42** of coupled guides is coupled to the end member **26** and another one (**46**) of the third plurality **42** of coupled guides is coupled to the tool holder **28**. Each of the coupled guides of the third plurality **42** is thus connected to an adjacent coupled guide of the third plurality or to the end member **26** or to the tool holder **28**.

Referring to Figure 2, the base member **22** has a generally circular cylindrical first outer surface portion **50** having a first diameter and a second coaxial, generally circular cylindrical surface portion **52** having a second diameter smaller than the first diameter. The surface portion **52** having the smaller diameter facilitates connection to an adjacent support conduit as will be described below.

Referring back to Figure 1, the intermediate member **24** also has a generally circular cylindrical outer surface portion **54**, the end member **26** has a similar outer surface portion **56** and the tool holder **28** has a similar outer surface portion **58** all having a diameter the same as the diameter of the first outer surface portion **50** of the base member **22**. In addition, each coupled guide of the first, second, and third pluralities **30**, **36** and **42** of coupled guides has an outer circular cylindrical surface portion, exemplary ones of which are shown at **60**, **62** and **64** respectively. Thus, the tool positioning apparatus **20** has a plurality of generally coaxially aligned components all having outer surfaces of the same common diameter.

Referring to Figures 2 and 3, the base member **22** has a generally cylindrical body having a distal-facing end face **66** having an axially extending projection **68**

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with a truncated spherical portion **70** through which a central opening **72** is formed. The central opening **72** extends axially through the entire base member **22**. The distal-facing end face **66** also has receptacles **74** and **76** disposed diametrically opposite each other and extending into the outer surface portion **50** to receive corresponding projections on coupled guide **32** shown in Figure **1**.

Referring to Figures **1** and **2** as will be explained below, the truncated spherical portion **70** and the receptacles **74** and **76** serve to couple the base member **22** to coupled guide **32** of the first plurality **30** of coupled guides.

Referring back to Figures **2** and **3**, the distal-facing end face **66** further has a first plurality of guide openings **80, 82, 84, 86** through which a first plurality of flexible control links **88, 90, 92, 94** connected to the intermediate member **24** extend through the base member **22**.

In the embodiment shown, the distal-facing end face **66** also has a plurality of receptacles **96, 98, 100** and **102** to which ends of respective ones of a second plurality of flexible control links **104, 106, 108, 110** extending between the base member **22** and the end member **26** are connected. In an alternate embodiment, the plurality of receptacles **96, 98, 100** and **102** may instead be a plurality of openings extending through the base member **22**, allowing the second plurality of flexible control links **104, 106, 108, 110** to extend through and away from the base member **22**. In this alternate embodiment, the ends of respective ones of the second plurality of flexible control links **104, 106, 108, 110** are connected to a fixed object (not shown), spaced apart from the base member **22**. The fixed object may be a tool controller of the type described at **602** in Figure **17**, suitably modified such that the ends of respective ones of the second plurality of flexible control links **104, 106, 108, 110** are connected to the base plate **612** thereof, for example.

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The distal-facing end face **66** also has a third plurality of guide openings **112, 114, 116, 118** through which respective ones of a third plurality of flexible control links **120, 122, 124, 126** connected to the tool holder **28** extend through the base member **22**.

Each link of the first, second and third pluralities of flexible control links may be a single nitinol wire capable of about 200N in tension or compression without permanent deformation and capable of experiencing up to about **4%** strain. Nitinol is an alloy of nickel and titanium having shape memory and superelasticity and its ability to support both tension and compression allows the links to be selectively pushed or pulled with similar forces without permanent deformation, which provides for precise control of the flexible control links, actuation redundancy and increased structural stiffness. Accordingly, only two flexible control links are required in each of the first, second, and third plurality of flexible control links to achieve a full range of movement of the tool holder relative to the base member **22**.

Referring back to Figure 1, the first plurality **30** of coupled guides are configured to cause the tool positioning apparatus **20** to have a flexible section while at the same time maintaining the first, second and third flexible control links **88, 90, 92, 94, 104, 106, 108, 110, 120, 122, 124, 126** in a pre-defined spaced apart relation relative to each other. Generally, the individual flexible control links in each plurality of flexible control links are spaced apart angularly on a circle such that the flexible control links of a given plurality are spaced apart from each other as far as possible. This reduces and balances actuation loads, increases the stiffness of the flexible section and reduces backlash effects as the direction of force on the flexible control links is changed in response to pushing and pulling of the flexible control links.

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In the embodiment shown, the first plurality **30** of coupled guides includes fourteen coupled guides. Coupled guide **32** is an exemplary coupled guide of the first plurality **30** and is shown in greater detail in Figure 4.

Referring to Figure 4, coupled guide **32** has a body having proximal and distal-facing sides **130** and **132** and first and second annular segments **134** and **136**.

The proximal facing side **130** has first and second projections **138** and **140** disposed diametrically opposite each other, the annular segments **134** and **136** being defined between the projections **138** and **140**. The projections **138** and **140** are operably shaped to be received in receptacles **74** and **76** on the base member **22**. The annular segments **134** and **136** have receptacles **142** and **144** disposed diametrically opposite each other and disposed in positions angularly offset by 90 degrees from the first and second projections **138** and **140**.

The proximal facing side **130** also has a socket **146** having a shape complementary to the truncated spherical shape of the projection **68** on the base member **22** to receive that projection therein. The projection **68** on the base member **22** and the socket **146** on the coupled guide **32** allow the coupled guide to pivot about the projection **68** and such pivoting is constrained in a vertical or pitch direction (e.g. up and down in the plane of the drawing, Figure 7) by the projections **138** and **140** received in the receptacles **74** and **76** on the distal facing end face **66** of the base member **22**.

The socket **146** terminates in a cylindrical wall **148** disposed in a truncated spherical projection **150** seen in Figure 5 extending from the distal facing side **132**. The cylindrical wall **148** defines central opening **152** in the body of the coupled guide **32**.

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Referring back to Figure 4, the annular segments 134 and 136 have a first plurality of guide openings 160, 162, 164 and 166 which are generally aligned with first guide openings 80, 82, 84 and 86 in the base member 22 to guide the first plurality of flexible control links (88, 90, 92 and 94) through the coupled guide 32.

The annular segments 134 and 136 also have a second plurality of guide openings 168, 170, 172 and 174 which are generally aligned with the second receptacles 96, 98, 100 and 102 (shown in Figures 2 and 3) in the base member 22 to guide the second plurality of flexible control links (104, 106, 108 and 110 shown in Figures 2 and 3) through the coupled guide 32.

The annular segments 134 and 136 also have a third plurality of guide openings 176, 178, 180 and 182 which are generally aligned with the third plurality of guide openings 112, 114, 116, 118 in the base member 22 to guide the third plurality of flexible control links (120, 122, 124, 126) through the coupled guide 32.

Referring to Figure 5, the coupled guide 32 is shown from above looking in the direction of arrow 189 in Figure 1. Annular segments 134 and 136 have portions 190 and 192 respectively having angled surfaces 194 and 196 that form an obtuse angle in a horizontal plane intersecting the axis 200 of the coupled guide 32. These surfaces 194 and 196 extend symmetrically at about a 6 degree angle to a first plane 198 perpendicular to the axis 200 of the coupled guide 32.

Referring back to Figure 4, the coupled guide 32 also has proximal facing surfaces 202 and 204 defined between the receptacles 142 and 144 that form an obtuse angle in a vertical plane intersecting the axis 200 of the coupled guide 32. This can be seen as a slight incline in proximal facing surface 202 in Figure 5, which forms an angle of about 6 degrees with a second plane 199 perpendicular

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to the axis **200** of the coupled guide **32** and provides for rotation of up to 6 degrees in the pitch direction, relative to the base member **22**.

Referring to Figure **6**, the distal facing side **132** of the coupled guide **32** is shown along with an immediately distally-adjacent coupled guide **60**. Immediately distally adjacent coupled guide **60** is similar to coupled guide **32** in that it includes annular segments having the same first plurality of guide openings **160**, **162**, **164** and **166**, the same second plurality of guide openings **168**, **170**, **172** and **174** and the same third plurality of guide openings **176**, **178**, **180** and **182**. It also has a truncated spherical projection **207** having a bore **209**. It also has a socket (not shown) like socket **146** in the coupled guide **32**, in its proximal facing side.

The immediately adjacent coupled guide **60** is different than the coupled guide **32** in that it has receptacles **210** and **212** where the projections **138** and **140** of the coupled guide **32** are located and has projections, only one of which is shown at **214**, where the receptacles **142** and **144** of the coupled guide **32** are located.

In addition, referring to Figure **7**, the immediately adjacent coupled guide **60** has annular segments **216** and **218** extending between the receptacles **210** and **212** having portions **220** and **222** having distal facing surfaces **224** and **226** that form an obtuse angle in a vertical plane intersecting the axis of the immediately distally adjacent coupled guide **60** and proximal facing surfaces only one of which is seen at **227** in Figure **7**, extending between the receptacles **210** and **212** that form an obtuse angle in a horizontal plane intersecting the axis **230**. The distal facing surfaces **224** and **226** are disposed at about a 6 degree angle to a first vertical plane **228** intersecting the axis **230** and perpendicular thereto and the proximal facing surfaces, only one of which is shown at **227**, are

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disposed at about a 6 degree angle to a second vertical plane **229** intersecting the axis **230**.

Still referring to Figure 7, it can be seen that the coupled guide **32** and immediately distally adjacent coupled guide **60** are coupled together to form a pair of coupled guides by receiving the projection **150** of the coupled guide **32** in the socket (not shown) of the immediately distally adjacent coupled guide **60** and receiving the proximal facing projections of the immediately distally adjacent coupled guide **60**, only one of which is shown at **214**, in corresponding receptacles, only one of which is shown at **144** of the coupled guide **32**. The projection **150** and socket arrangement provides for pivoting in any direction and the proximally facing projections **214** received in corresponding receptacles **144** prevent torsional movement about the axis **230**, of the immediately distally adjacent coupled guide **60** relative to the coupled guide **32** and limit relative rotational movement to what is shown as a horizontal or yaw direction, i.e. into and out of the plane of the page. The angled surface **227** of the immediately distally adjacent coupled guide **60** faces angled surface **196** of the coupled guide **32** and this provides clearance for relative movement pivoting about the truncated spherical projection **150** of up to a total of 12 degrees in the yaw direction.

Similarly, the angled distal facing surfaces **224** and **226** on the immediately distally adjacent coupled guide **60** will face proximally facing surfaces like surfaces **202** and **204** on a next distally adjacent coupled guide **205** and this will provide for relative rotational movement between the immediately adjacent coupled guide **60** and the next distally adjacent coupled guide **205** of up to 12 degrees in the pitch direction. Thus each pair of coupled guides provides for limited defined movement in the pitch and yaw directions. More generally, every odd numbered coupled guide is operable to rotate in a vertical plane (pitch

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direction) and every even numbered coupled guide is operable to rotate in a horizontal plane (yaw direction).

Referring back to Figure 1, in the embodiment shown the first plurality 30 of coupled guides includes seven pairs of coupled guides which enables the first plurality of coupled guides to have pitch and yaw bend components sufficient to define a continuous arc extending through up to 90 degrees. Thus, the intermediate member 24 can be positioned in an orientation in any direction relative to the axis of the base member 22 up to an angle of about 90 degrees off the axis of the base member such as shown in Figure 8.

Referring to Figure 9, the intermediate member 24 has a body having proximal and distal facing sides 250 and 252. The proximal facing side 250 has first and second annular segments 254 and 256 disposed between first and second projections 258 and 260 that project proximally toward the first plurality 30 of coupled guides. These projections 258 and 260 are received in receptacles like those shown at 210 and 212 in Figure 6 in the immediately adjacent coupled guide 34 of the first plurality 30 of coupled guides as seen in Figure 1. Referring back to Figure 9, the proximal facing side 250 has a socket 262 terminating in an annular wall 264 defining a central opening 266 through the body. A projection like the one shown at 207 in Figure 6 of the immediately adjacent coupled guide 32 of the first plurality 30 of coupled guides is operable to be received in the socket 262 and the projections 258 and 260 are received in receptacles similar to those shown at 210 and 212 in Figure 6 of the immediately adjacent coupled guide 34. This permits the immediately adjacent coupled guide 34 to pivot about the projection 207 in a pitch direction.

The intermediate member 24 further includes first, second, third and fourth receptacles 270, 272, 274 and 276 disposed at locations aligned with the first set of guide openings 160, 162, 164 and 166 respectively in the immediately

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adjacent coupled guide **34** to receive and hold ends of the first plurality of flexible control links **88**, **90**, **92** and **94** respectively, extending through the first set of guide openings **160**, **162**, **164** and **166** of the immediately adjacent coupled guide **34**.

The proximal facing side **250** further includes a second plurality of openings **280**, **282**, **284** and **288** which extend entirely through the intermediate member **24** for guiding the second plurality of flexible control links **104**, **106**, **108** and **110** therethrough. In addition, the proximal facing side **250** includes a third plurality of guide openings **290**, **292**, **294** and **296** that extend through the entire intermediate member **24** for guiding the third plurality of flexible control links **120**, **122**, **124**, and **126** therethrough.

Referring to Figure **10**, the intermediate member **24** further includes a projection **300** projecting from the distal facing side **252** and has first and second receptacles **302** and **304** diametrically opposed and disposed in the outer surface portion **54** and terminating on an end face **306** of the distal facing side **252**. Referring back to Figure **1**, the receptacles **302** and **304** receive corresponding projections on the immediately adjacent coupled guide **38** of the second plurality **36** of coupled guides. The second plurality **36** of coupled guides is the same as the first plurality of coupled guides, described above, in connection with Figures **4** through **7**.

Referring to Figure **11**, the end member **26** has a body having proximal and distal facing sides **350** and **352**. The proximal facing side **350** has first and second annular segments **354** and **356** disposed between first and second projections **358** and **360** that project proximally toward the second plurality **36** of coupled guides. These projections **358** and **360** are received in receptacles like those shown at **210** and **212** in Figure **6** in the immediately adjacent coupled guide **40** of the second plurality of coupled guides **36** as seen in Figure **1**.

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Referring back to Figure 11, the proximal facing side **350** has a socket **362** terminating in an annular wall **364** defining a central opening **366** through the body. A projection like the one shown at **207** in Figure 6 of the adjacent coupled guide **40** of the second plurality of coupled guides **36** is operable to be received in the socket **362** and the projections **358** and **360** are received in receptacles similar to those shown at **210** and **212** in Figure 6 of the immediately adjacent coupled guide **40**. This permits the immediately adjacent coupled guide **40** to pivot about the projection **(207)** in a pitch direction.

The end member **26** further includes first, second, third and fourth receptacles **370**, **372**, **374** and **376** disposed at locations aligned with the second set of guide openings **168**, **170**, **172** and **174** respectively in the adjacent coupled guide **40** to receive and hold ends of the second plurality of flexible control links **104**, **106**, **108** and **110** respectively, extending through the second guide openings **168**, **170**, **172** and **174** of the immediately adjacent coupled guide **40**.

The proximal facing side **350** further includes a third plurality of openings **380**, **382**, **384** and **386** which extend entirely through the end member **26** for guiding the third plurality of flexible control links **120**, **122**, **124** and **126** therethrough.

Referring to Figure 12, the end member **26** further includes a projection **400** projecting from the distal facing side **352** and has first and second receptacles **402** and **404** disposed in the outer surface portion **56** and terminating on a flat annular end face **406** of the distal facing side **352**. Referring back to Figure 1, the receptacles **402** and **404** receive corresponding projections on the immediately adjacent coupled guide **44** of the third plurality **42** of coupled guides.

The third plurality **42** of coupled guides includes coupled guides the same as those shown in Figures 4 through 7 with the exception that the surfaces **194** and **196** extend symmetrically at about an **8.5** degree angle to the first plane **198**

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perpendicular to the axis of the coupled guide and the proximal facing surfaces **202** and **204** form angles of about **8.5** degrees with the second plane **199** perpendicular to the axis of the coupled guide. With the angles of the indicated surfaces on the third plurality of coupled guides being slightly greater than the angles on the first and second plurality of coupled guides, the third plurality of coupled guides can include fewer elements such as shown in this embodiment where there are only about **10** coupled guides and enable the portion extending from the end member **26** to be bent in a tighter radius than the coupled guides of the first and second pluralities **30** and **36** can be bent as shown in Figure **8**.

Referring to Figures **13** and **14**, the tool holder **28** has a body having proximal and distal facing sides **450** and **452**. The proximal facing side **450** has first and second annular segments **454** and **456** disposed between first and second projections **458** and **460** that project proximally toward the third plurality **42** of coupled guides. These projections **458** and **460** are received in receptacles like those shown at **210** and **212** in Figure **6** in the immediately adjacent coupled guide **46** of the third plurality **42** of coupled guides as seen in Figure **1**. Referring back to Figure **13**, the proximal facing side **450** has a socket **462** terminating in an annular wall **464** defining a central bore **466** through the body. A projection like the one shown at **207** in Figure **6** of the adjacent coupled guide **46** of the third plurality of coupled guides **42** is operable to be received in the socket **462** and the projections **458** and **460** are received in receptacles similar to those shown at **210** and **212** in Figure **6** of the immediately adjacent coupled guide **46**. This permits the immediately adjacent coupled guide **46** to pivot about the projection **207** in a pitch direction.

The tool holder **28** further includes first, second, third and fourth receptacles **470**, **472**, **474** and **476** disposed at locations aligned with the third set of guide openings **176**, **178**, **180** and **182** respectively in the adjacent coupled guide **46** to receive and hold ends of the third plurality of flexible control links **120**, **122**, **124**

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and **126** respectively, extending through the second set of guide openings **176**, **178**, **180** and **182** of the immediately adjacent coupled guide **46**.

Referring to Figure **14**, the tool holder **28** has a flat annular end face **500** on the distal facing side **452** and the bore **466** is coterminous with the annular end face **500**. Aligned openings **502** and **504**, are aligned on a chord extending through the wall **464** and are operable to receive a threaded fastener, for example, for securing a tool in the tool holder **28**, so that the tool can rotate axially in the tool holder.

Referring to Figure **15**, an exemplary tool for use in the tool holder shown in Figures **13** and **14** is shown generally at **550**. In the embodiment shown, the tool **550** includes an end effector **552**, which, in the embodiment shown includes a gripper having fixed and pivotal opposing jaws **554** and **556** extending from a base **558**. Other tool arrangements could alternatively be employed. For example, the tool may alternatively be a cauterizing device, a suction device, a retraction device or a grasping device. In the embodiment shown a flexible tool control link **560** is connected to the pivotal jaw **556** and extends through an axial opening in the base **558** to open and close the pivotal jaw **554** on the fixed jaw **556** in response to linear movement of the flexible control link **560**.

The tool **550** further includes a coupler comprised of first and second spaced apart cylinders **562** and **564** rigidly connected to the base **558** and having outer cylindrical surfaces **563** and **565** slightly smaller than a diameter of the bore **466** in the tool holder **28** so that the tool **550** can be held snugly in the tool holder **28**. A flexible conduit **566** having a length approximately equal to a distance between the tool holder **28** and the base member **22** has a first end **568** connected to the cylinder **564** and a second end **570** connected to a first end **572** of a rigid conduit **574** by a crimp connector **576**. The flexible tool control link **560** extends through

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the cylinders **562** and **564**, through the flexible conduit **566** and through the rigid conduit **574** and has a second end **578** that extends outwardly from a proximal end **580** of the rigid conduit **574**. Accordingly, linear movement of the second end **578** of the flexible tool control link **560** relative to the proximal end **580** of the rigid conduit **574** opens and closes the pivotal jaw **556**.

Referring to Figures **15** and **16**, the tool **550** is shown installed in the tool holder **28** whereby only the base **558** and jaws **554** and **556** project distally from the tool holder and the flexible conduit **566** extends through the central openings **152** in the third plurality of coupled guides **42**, the central opening **266** in the end member **26**, the central openings **152** in the second plurality of coupled guides **36**, the central opening **266** in the intermediate member **24**, and the central openings **(152)** in the first plurality **30** of coupled guides. The crimp connector **576** is located in the central opening **72** in the base member **22** and is about the same length as the base member and the rigid conduit **574** extends outwardly from the base member in a proximal direction. The tool **550** installed in the tool holder thus forms a tool assembly **600** comprised of the tool **550** and the tool positioning apparatus **20**.

Referring to Figure **17**, the tool assembly **600** is connected to a tool controller **602** comprising a second rigid conduit **604** having a first end **606** rigidly connected to the outer surface portion **52** of reduced diameter of the base member **22** and having a second end **608** connected to a drive mechanism **610**. The drive mechanism **610** includes a base plate **612** having a conduit coupling **614** for rigidly connecting the second rigid conduit **604** to the base plate **612**. In addition the drive mechanism includes a rotational coupling **616** connected to the proximal end **580** of the rigid conduit **574** whereupon rotation of the rotational coupling **616** causes a corresponding rotational movement of the rigid conduit **574** about its axis. A rotational flexible control link **618** is connected to the rotational coupling **616** and is routed to a rotational spool **620** which is connected

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to a gear segment **622** such that when the gear segment is rotated the rigid conduit **574** is rotated by a corresponding amount. Such rotation of the rigid conduit **574** rotates the tool **550** by a corresponding amount.

The first, third and tool flexible control links **88, 90, 92** and **94; 120, 122, 124** and **126; and 560** extend through the interior of the second rigid conduit **604** and emanate from the second end **608** of the second rigid conduit **604**. The drive mechanism **610** has a link guide shown generally at **624** for guiding the tool control link **560** to a tool spool **626** connected to a tool gear segment **628**. The tool control link **560** is wound on the tool spool **626** such that rotation of the tool gear in a first direction opens the end effector **552** of the tool **550** and rotation of the tool spool **626** in a second, opposite direction closes the end effector.

Two of the third flexible control links in a horizontal plane at the tool holder **28** such as links **120** and **126** or links **122** and **124** are wound in opposite directions on a horizontal tool control spool **630** connected to a horizontal tool control gear **632**, such that rotation of the horizontal tool control gear **632** in a first direction pulls on, say, a left side link **120** or **122** while pushing on a corresponding right side link **126** or **124** and rotation of the horizontal tool control gear **632** in a second direction opposite to the first direction pushes on the left side link **120** or **122** while pulling the corresponding right side link **126** or **124**. This has the effect of moving the tool holder **28** to the left or right.

Two of the third flexible control links in a vertical plane at the tool holder **28** such as links **120** and **122** or links **124** and **126**, depending on which of these links are not already connected to the horizontal tool control spool **630**, are wound in opposite directions on a vertical tool control spool **634** connected to a vertical tool control gear **636**, such that rotation of the vertical tool control gear **636** in a first direction pulls on, say, an upper link **120** or **126** while pushing on a corresponding lower link **122** or **124** and rotation of the vertical control gear **636**

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in a second direction opposite to the first direction pushes on the upper link **120** or **122** while pulling the corresponding lower link **122** or **124**. This has the effect of moving the tool holder **28** up or down.

Two of the first flexible control links in a horizontal plane at the intermediate member **24** such as links **88** and **94** or links **90** and **92** are wound in opposite directions on a horizontal s-curve control spool **638** connected to a horizontal s-curve gear **640**, such that rotation of the horizontal s-curve control gear **640** in a first direction pulls on, say, a left side link **88** or **90** while pushing on a corresponding right side link **92** or **94** and rotation of the horizontal s-curve control gear **640** in a second direction opposite to the first direction pushes on the left side link **88** or **90** while pulling the corresponding right side link **92** or **94**. This has the effect of moving the intermediate member **24** to the left or right.

Two of the first flexible control links in a vertical plane at the intermediate member **24** such as links **88** and **90** or links **92** and **94**, depending on which of these links are not already connected to the horizontal s-curve control spool **638**, are wound in opposite directions on a vertical s-curve control spool **642** connected to a vertical s-curve control gear **644**, such that rotation of the vertical s-curve control gear **644** in a first direction pulls on, say, an upper link **88** or **94** while pushing on a corresponding lower link **90** or **92** and rotation of the vertical s-curve control gear **644** in a second direction opposite to the first direction pushes on the upper link **88** or **94** while pulling the corresponding lower link **90** or **92**. This has the effect of moving the intermediate member **24** up or down.

While spools **626**, **620**, **630**, **634**, **638** and **642**, and corresponding gear segments **628**, **622**, **632**, **636**, **640** and **644** are arranged in a particular order as depicted in Figure **17**, the ordering is not important. Thus, for example, spool **626** and corresponding gear segment **628** may be arranged such that they are

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positioned between spool **620** and corresponding gear segment **622**, and spool **630** and corresponding gear segment **632**.

The second flexible control links **104**, **106**, **108** and **110**, being connected between the base member **22** and the end member **26**, act as a kind of parallelogram in two dimensions, tending to keep the end member **26** at the same orientation as the base member **22**. The first plurality of flexible control links **88**, **90**, **92** and **94** move the intermediate member **24** but parallelogram effect of the second plurality of control links tends to keep the end member **26** at the same orientation as the base member **22**. Similarly, the third plurality of control links **120**, **122**, **124** and **126** moves the tool holder **28**, but again the end member **26** is held under the constraints of the parallelogram formed by the second plurality of flexible control links and maintains the same orientation as the base member **22**.

While the second plurality of flexible control links **104**, **106**, **108** and **110** have been shown as being connected between the base member **22** and the end member **26**, it is only necessary that the proximal ends of the second plurality of flexible control links be fixed to some reference point. Thus, for example, they need not be connected to the base member **22** but could alternatively be connected to some other fixed structure located in the proximal direction away from the base member **22**.

Therefore by rotating gear segments **622**, **628**, **632**, **636**, **640** and **644**, the end effector can be moved with 5 degrees of freedom and the jaws can be opened and closed. As described below a suitable gear drive mechanism may be used to drive the gear segments **622**, **628**, **632**, **636**, **640** and **644** to manipulate the end effector **550** in space to perform an operation. Such operation may be a medical operation for example.

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For example, the apparatus described herein may be used in performing laparoscopic surgery such as shown in Figure 18. To do this, there is provided a movable platform 700 on which is secured a cabinet 702 housing a computer 704 either wired or wirelessly connected to a computer network such as an ethernet network. A gross positioning mechanism shown generally at 706 is connected to the cabinet 702 and has a head 708 to which the tool controller 602 shown in Figure 17 is ultimately secured. The gross positioning mechanism 706 and the movable platform 700 allow the head 708 to be positioned at a location in space such that the tool positioning apparatus 20 can be placed inside the patient's body at a position that allows the desired laparoscopic surgery to be performed.

Referring to Figure 19, to facilitate connection of the tool controller (602) to the head 708 while maintaining a sterile environment, the head is provided with a first portion 712 of a mechanical connector and first and second pluralities of spaced apart coaxial drive gear segments, only one gear segment of each plurality being shown at 710 and 711 in Figure 19. As will be described below, the first plurality of drive gear segments controls the position of a camera and the second plurality of drive gear segments controls the tool controller (602). In this embodiment, respective separate motors, only two of which are shown at 714 and 715 are provided to independently drive each drive gear in a direction, at a speed and for a time responsive to control signals received from the computer 704 shown in Figure 18.

The computer 704 may receive commands from the network to control the motors and a separate computer (shown in Figure 30) connected to an input device controlled by a surgeon performing the surgery may generate the commands and transmit them on the network in response to hand, finger and arm movements, for example of the surgeon performing the surgery. The

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surgeon performing the surgery may be located in the operating room near the patient or may be located remotely anywhere in the world.

A coupler 720 comprising a housing 722 and having a second connector portion 724 of the mechanical connector has a plastic cover 726 connected around the perimeter of the housing 722 just below the second connector portion 724 of the mechanical connector. Before the second portion 724 of the mechanical connector is connected to the first connector portion 712, the plastic cover 726 is arranged to drape downwardly such that an open end portion 728 of the plastic cover 726 faces downwardly. The coupler 720 is then moved into place such that the second connector portion 724 mates with the first connector portion 712 as shown in Figure 20. Then, referring to Figure 21, the plastic cover 726 is raised up over the head 708 and onto a portion of the gross positioning arm 706, leaving only the portion of the coupler 720 below the perimeter line at which the plastic cover 726 is attached to the housing 722, exposed to the patient.

Referring to Figure 22, the coupler 720 serves to couple a camera/delivery tube assembly 730 to the head 708 and further serves to connect one or more tool controllers of the type shown at 602 in Figure 17 to the head 708.

The camera/delivery tube assembly comprises a base 732 having a connector portion 734 that mates with a corresponding connector portion 736 on the coupler 720. A clear plastic delivery tube 738 approximately about 1 inch (2.5cm) in diameter, about 20 (51cm) inches long and having a wall thickness of about 0.035 (0.1cm) inches has a proximal end portion 740 connected to the base 732 and has a distal second end portion 742. A camera assembly 748 comprising a camera 750 and a camera positioner 752 are located at the distal end of the delivery tube and a rigid camera positioner support tube 754 extends from the camera positioner 752 up the delivery tube 738 from the distal second end portion 742 of the delivery tube 738 and is rigidly connected to the base 732.

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Referring to Figure 23 the camera positioner 752 may be the same as the tool positioner 20 and coupled to a camera controller 760 like the tool controller shown at 602 in Figure 17 to enable the camera 750 to be positioned on or off the axis 762 of the delivery tube 738. The camera 750 need not have the same range of movement as the formerly described tool positioner 20 and therefore fewer flexible control links may be used in the camera positioner 752. For example, only two of the first flexible control links may be required to move the camera positioner 752 in a vertical direction off-axis of the delivery tube 738 and the flexible control link for rotating the tool may not be required. This simplifies the camera controller 760 in that it has fewer spools and gear segments. Only one gear segment is shown at 761 in Figure 23 but there are as many gear segments as there are flexible control links for controlling the camera position. Referring back to Figure 19, each gear segment is engaged with a corresponding linear gear rack 763 on the coupler. The linear gear rack 763 on the coupler 720 has a gear portion that faces upwardly so as to engage with the gear segment 711 on the head 708 and has a gear portion that faces downwardly to engage with the gear segment 761 shown in Figure 23 on the camera/delivery tube assembly 730.

Referring back to Figure 19, the coupler 720 also has a plurality of linear gear racks having upwardly facing gear portions 765 for engaging corresponding gear segments 710 on the head 708 and has downwardly facing gear portions 767 for engaging corresponding gear segments on at least one tool controller such as 602 in Figure 17, as will be described below.

Referring back to Figure 23, the base 732 further has an optical connector 770 and an electrical connector 772 that project in a proximal direction from the base 732 so that when the base is coupled to the coupling 720 shown in Figure 22, they mate with corresponding optical and electrical connectors 774 and 776 on

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the head **708**. The optical connector **774** on the head **708** provides light by way of an optical fiber **778** and a corresponding optical fiber **780** connected to the optical connector **770** on the base **732** is routed in the camera positioner and terminates at a location above a lens **781** on the camera **750** so as to illuminate the subject of the image taken by the camera **750**. The electrical connector **772** on the base is connected to the camera **750** to receive image signals and passes these image signals to the electrical connector **776** on the head **708**, which communicates them to the computer **704** shown in Figure **18**. The camera **750** may have two lenses or be otherwise configured to produce 3D image signals, for example. The computer **704** formats the image signals as necessary and transmits them on the network to enable capture of the image signals by devices connected to the network, including a display that may be located at or near the input device being operated by the surgeon.

Referring back to Figure **23**, the delivery tube **738** has a proximal end portion **782** that extends rearward of the base **732**.

Referring to Figure **24**, the base **732** is shown coupled to the coupler **720**, whereupon the gear segments, one of which is shown at **711**, for controlling the camera positioner **752** engage with the linear gear racks **763** on the coupler **720**. In addition the gear segments **710** associated with the tool positioner engage with corresponding linear gear racks **765** on the coupler **720**. A space is provided adjacent the linear gear racks **765** to enable at least one tool controller to be mounted in the space in a manner in which the gear segments (**628**, **622**, **632**, **636**, **640** and **644** on a tool controller **602**) are engaged with corresponding linear gear racks, only one of which is shown at **765** in Figure **24**. Also in the position shown in Figure **24**, the optical connectors (**770**) and (**774**) and electrical connectors (**772**) and (**776**) are connected to permit light to be transmitted to the camera head and to permit the camera to send image signals to the computer **704** in Figure **18**. Also when the camera/delivery tube assembly **730** is

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connected to the coupler **720**, the proximal end portion **782** of the delivery tube is disposed adjacent the space adjacent the linear gear racks **765**.

Referring to Figure **25**, with the camera/delivery tube assembly **730** connected to the coupler **720**, the tool controller **602** can be installed. Referring to Figure **26**, to install the tool controller **602**, the tool controller is positioned such that the tool **550** is inserted into the proximal end portion **782** of the delivery tube (**738**) and is pushed all the way through the delivery tube until the tool **550** and tool positioner **20** extend outwardly from the distal second end portion **742** of the delivery tube as shown in Figure **27**. Thus, the second rigid conduit **606** extends inside the delivery tube parallel to the camera positioner support tube **754** and the tool positioner **20** can be freely moved about in the space adjacent the distal second end portion **742** of the delivery tube. Referring to Figures **26** and **27**, the length of the second rigid conduit **606** is pre-configured so that when the gear segments **628**, **622**, **632**, **636**, **640** and **644** are engaged with their corresponding linear gear racks (**629**, **623**, **633**, **637**, **641** and **645**), the tool positioner **20** is completely outside the delivery tube **738**.

Referring to Figure **26**, in the embodiment shown, the coupler **720** has first and second linear gear rack assemblies **800** and **802** that are operable to receive first and second tool controllers respectively. A first tool controller is shown at **602** and a second tool controller is shown in broken outline at **804**. In the above-described design of the first tool controller **602** each gear segment **628**, **622**, **632**, **636**, **640** and **644** has a symmetrically opposite gear segment **928**, **922**, **932**, **936**, **940**, and **944** on the same hub. These gear segments **928**, **922**, **932**, **936**, **940**, and **944** lie in respective parallel planes at pre-defined distances from a parallel plane in which the base plate **612** lies and protrude beyond an edge **950** of the base plate **612** by the same amount by which their corresponding opposite gear segments protrude beyond an opposite edge **952** of the base plate **612**. In the embodiment shown, the first tool controller **602** is installed on the

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coupler 720 to cooperate with the first linear gear rack assembly 800 and when installed to effect this cooperation, edge 952 of the first tool controller 602 is facing the first linear gear rack assembly 800.

The second tool controller 804 is the same as the first tool controller 602 but is installed in a mirror image orientation relative to the first tool controller 602 as shown in broken outline in Figure 26. In this orientation, an edge 954 of the second tool controller 804 corresponding to edge 950 of the first tool controller 602 faces the second linear gear rack assembly 802 and gear segments (equivalent to 928, 922, 932, 936, 940, and 944 of the first tool controller 602) of the second tool controller 804 engage with corresponding linear gear racks of the second linear gear rack assembly 802. Thus, a second tool positioner 812 connected to a second tool controller 804 may be fed through the delivery tube 738 to extend outside the delivery tube as shown in Figure 28.

Referring to Figure 29, with the above described components connected together as described, the laparoscopic surgical apparatus shown in Figure 18 is further described. The movable platform 700 can be used to move the head 708 into a position such as shown, wherein the tools 550 and 810 and camera 750 are positioned inside a patient (not shown) through a single, relatively small incision. Initially, the camera 750 and first and second tool positioners are positioned so as to be closely adjacent each other within the diameter of the delivery tube 738 to facilitate inserting the camera and first and second tool positioners 20 and 812 and tools 550 and 810 thereon into the patient through the small incision. Then the patient can be inflated with CO₂ in the conventional manner and then the camera can be positioned off-axis of the delivery tube, upwardly, for example and positioned to have a field of view that encompasses the locations of the tools 550 and 810, for example. The camera 750 may also have zoom capability to zoom in on any area of particular interest inside the patient in the vicinity of the tools 550 and 810. Then, the tools 550 and 810 may

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be positioned and manipulated to perform surgery while the actions of the tools are viewed by the camera **750**.

The positioning and manipulation of the tools **550** and **810** is directed by a surgeon operating a workstation such as shown at **860** in Figure **30**, having a 3D portal **862**, for example, for viewing three-dimensional images produced by the camera **750** on a screen and having left and right input devices **864** and **866**, a handrest **868** and a support cabinet **870** mounted on a movable platform **872**. The movable platform may have first and second footswitches **874** and **876**. The support cabinet **870** may include a computer **878** operably configured to receive signals from the left and right input devices **864** and **866** and from the first and second footswitches **874** and **876** and to produce and transmit command signals on the network to the computer of the laparoscopic surgical apparatus **850** shown in Figure **29** to cause the liner gear racks to move in directions and distances that will effect a desired movement of the tool.

Above it was mentioned that the end effector or tool can be moved with **5** degrees of freedom by pulling or pushing on various links of the first, second and/or third pluralities of flexible control links **88, 90, 92, 94, 104, 106, 108, 110, 120, 122, 124, 126** by moving corresponding ones of the linear gear rack assemblies. A 6th degree of freedom of movement is provided by causing the tool assembly **600** and the tool controller **602** to move in a direction along the axis of the second rigid conduit **604**. Such motion may be provided by moving the head **708** in a linear direction along a line coincident with the delivery tube **738**, for example.

Alternatively, referring to Figures **26** and **31**, in an alternative embodiment of the coupler **720** the first and second linear gear rack assemblies **800** and **802** can be formed on separate bases **900** and **902** and the cooperating gear racks (**765** on the coupler **720**) can be made long enough to permit the first and second linear

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gear racks 800 and 802 to be moved linearly relative to a base 904 of the coupler 720 to provide a 6th degree of freedom of movement in the direction of the axis of the delivery tube 738. To effect this movement, the base 904 can be provided with first and second gear racks 906 and 908 that engage with corresponding linear gear segments (not shown) on undersides of the first and second bases 900 and 902. The first and second gear racks can be actuated by corresponding mating gear racks (not shown) on the head (708) in a manner similar to that described in connection with the way individual racks of the first and second linear gear rack assemblies 800 and 802 are actuated.

In the alternative embodiment of the coupler 720 shown in Figure 31, referring to Figure 32, when the first and second tool controllers 602 and 804 are disposed at different distances from the proximal end portion 782 of the delivery tube, the respective tool positioners 20 and 812 are disposed at different distances from the distal end portion 742 of the delivery tube which positions the respective tools 550 and 810 at different distances from the distal end portion of the delivery tube.

Advantageously, the apparatus described herein provides for different types of tools to be held by the same type of tool positioning apparatus which separates the tool positioning function from the tool operation function. Thus, a single type of tool positioner can be provided and different types of tools can selectively be used in that tool positioning apparatus, as desired. In addition, the apparatus provides for left and right surgical tools to be received through the same incision in the patient and allows these tools to be positioned on opposite sides of an axis defined by the delivery tube. This enables access to the area in which surgery is taking place from either side, making it seem to the surgeon quite like directly performing the surgery in the conventional manner. In addition the same tools that are being used to perform the functions of the end effector are rotatable

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about their longitudinal axes which provides for more convenient and independent positioning of the end effectors.

While specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. An articulated tool positioning apparatus, the apparatus comprising:

a base member, an intermediate member, an end member and a first tool holder arranged in succession, each of said base member, intermediate member, end member and tool holder having a respective central opening;

a first plurality of coupled guides between the base member and the intermediate member wherein at least one of said first plurality of coupled guides is coupled to the base member and at least one of said first plurality of coupled guides is coupled to the intermediate member and wherein each coupled guide of said first plurality of coupled guides has a respective central opening;

a second plurality of coupled guides between the intermediate member and the end member wherein at least one of said second plurality of coupled guides is coupled to the intermediate member and at least one of said second plurality of coupled guides is coupled to the end member and wherein each coupled guide of said second plurality of coupled guides has a respective central opening;

a third plurality of coupled guides between the end member and the tool holder wherein at least one of said third plurality of coupled guides is coupled to the end member and at least one of said third plurality of coupled guides is coupled to the tool holder and wherein

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each coupled guide of said third plurality of coupled guides has a respective central opening;

first guide openings in said base member and corresponding generally-aligned first guide openings in each coupled guide of said first plurality of coupled guides;

a first plurality of flexible control links disposed in parallel spaced apart relation and extending through respective openings of said first guide openings in said base member and through respective openings of said corresponding first guide openings in said first plurality of coupled guides, each of said first plurality of flexible control links having respective first end portions connected to said intermediate member and respective second end portions extending away from said base member;

second guide openings in said intermediate member and corresponding generally-aligned second guide openings in each coupled guide of said first and second pluralities of coupled guides;

a second plurality of flexible control links disposed in parallel spaced apart relation each having a first end connected to the end member, a second end connected to at least one of the base member and an object spaced apart from the base and having an intermediate portion between said first and second ends, each said intermediate portion extending through a respective second guide opening in said intermediate member and through a respective second guide opening in each guide of said first and second pluralities of coupled guides;

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third guide openings in said base member and in each coupled guide of said first plurality of coupled guides and in said intermediate member and in each coupled guide of said second plurality of coupled guides and in said end member and in each coupled guide of said third plurality of coupled guides; and

a third plurality of flexible control links disposed in parallel spaced apart relation and extending through respective said third guide openings in said base member through respective said third guide openings, in each coupled guide of said first plurality of coupled guides through respective said third guide openings, in said intermediate member through respective said third guide openings, in each coupled guide of said second plurality of coupled guides through respective said third guide openings, in said end member and through respective said third guide openings in each coupled guide of said third plurality of coupled guides, each said flexible control link of said third plurality of flexible control links having a first end connected to the tool holder and a second end extending away from said base member;

wherein pushing or pulling control links of said first plurality of control links causes said base member, said first plurality of coupled guides, said intermediate member, said second plurality of coupled guides and said end member to assume positions that selectively define a continuous curve;

wherein said second plurality of control links causes said end member to maintain an orientation generally the same as said base member when any of said first and third flexible control links is pushed or pulled; and

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wherein pushing or pulling control links of said third plurality of control links causes said tool holder to be selectively moved into any of a plurality of orientations, such that said third plurality of coupled guides between said end member and said tool holder defines a continuous curve from said end member to said tool holder.

2. The apparatus of claim 1 wherein said first, second and third pluralities of flexible control links include wires capable of experiencing about 200N of tension and compression without yielding and up to about 2% to 4% strain.
3. The apparatus of claim 1 or 2 wherein at least one of said wires is comprised of a metal alloy of nickel and titanium having shape memory and superelasticity.
4. The apparatus of any one of claims 1-3 wherein said second plurality of control links includes wires having a common stiffness.
5. The apparatus of any one of claims 1-4 wherein said base member, said intermediate member, said end member, said tool holder and said coupled guides of said first, second and third pluralities of coupled guides each have a generally circular cylindrical outer surface portion, each said generally circular cylindrical outer surface portion having a common diameter.
6. The apparatus of claim 5 wherein said base member, said intermediate member, said end member, said tool holder and said coupled guides of

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said first, second and third pluralities of coupled guides each have generally annular segments and wherein:

at least one annular segment of said base member and at least one annular segment of each coupled guide of said first plurality of coupled guides have said first guide openings;

at least one annular segment of each coupled guide of said first and second pluralities of coupled guides and at least one annular segment of said intermediate member have said second guide openings; and

at least one annular segment of each of said base member, said intermediate member, said end member, and each coupled guide of said first, second and third pluralities of coupled guides have said third guide openings.

7. The apparatus of claim 6 wherein each of said annular segments of said coupled guides of said first plurality of coupled guides has opposite faces disposed at acute angles to an axis of said central opening in said coupled guide.
8. The apparatus of claim 7 wherein each of said annular segments of said second plurality of coupled guides has opposite faces disposed at acute angles to an axis of said central opening in said coupled guide.
9. The apparatus of claim 8 wherein each of said annular segments of said third plurality of coupled guides has opposite faces disposed at acute angles to an axis of said central opening in said coupled guide.

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10. The apparatus of claim 9 wherein said opposite faces of annular segments of said coupled guides of said first and second pluralities of coupled guides are disposed at a first acute angle to the axis and wherein said opposite faces of annular segments of said coupled guides of said third plurality of said coupled guides are disposed at a second acute angle to the axis, said second acute angle being different from said first acute angle.
11. The apparatus of claim 10 wherein said second acute angle is greater than said first acute angle.
12. The apparatus of any one of claims 6-11 wherein adjacent pairs of coupled guides of said first, second and third pluralities of coupled guides are coupled by at least one projection on one guide of said pair and a receptacle for receiving the projection on the other guide of said pair.
13. The apparatus of any one of claims 1-12 wherein each of said coupled guides of said first, second and third pluralities of coupled guides has an axially extending projection having a truncated spherical portion and has an axially aligned socket for receiving an axially extending projection of an adjacent coupled guide to permit adjacent coupled guides to spherically pivot relative to each other, said central opening of said coupled guide having a first terminus on said projection and a second terminus in said socket so that central openings of adjacent coupled guides are in communication with each other so as to define a central channel operable to receive a portion of a tool held by said tool holder.
14. The apparatus of any one of claims 1-13 and further comprising a first support conduit having first and second open ends, said base being connected to said first open end of said support conduit to support said

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base and said second end portions of said first and third control links extending through said first support conduit to extend out of said second open end of said first support conduit.

- 15.** A tool assembly comprising the apparatus of claim **14** and further comprising a first tool comprising a first end effector, a first coupler for coupling the first end effector to the first tool holder, a first flexible shaft portion having a length approximately the same as a length defined between said base member and said tool holder, a first rigid shaft portion having a length approximately equal to a length of said first support conduit and a first tool control link having a first end connected to the first end effector and a second end extending from said first rigid shaft portion, said first rigid shaft portion being received in said central opening of said first tool holder and extending through said central openings in said third plurality of coupled guides, said central opening in said end member, said central openings in said second plurality of coupled guides, said central opening in said intermediate member, said central openings in said first plurality of coupled guides, said central opening in said base member and said first support conduit such that said first flexible shaft portion is coaxial with said tool positioning apparatus and said first rigid shaft portion is generally coaxial with said first support conduit and such that said second end portion of said first tool control link extends from said second end portion of said first support conduit.
- 16.** A tool controller assembly comprising the tool assembly of claim **15** and further comprising a first control mount, said first support conduit of said tool positioning apparatus being connected to said first control mount such that said first control mount is on a first side of a first longitudinal axis of said first support conduit, and wherein said first control mount has a first plurality of actuators connected to respective flexible control links of said

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first and third pluralities of said flexible control links of said first tool positioning apparatus, for selectively pushing and pulling on said second end portions of said respective flexible control links to cause said base member, said first plurality of coupled guides, said intermediate member, said second plurality of coupled guides and said end member to selectively define a continuous curve and to selectively cause said tool holder to be moved into any of a plurality of orientations, such that said third plurality of coupled guides between said end member and said first tool holder apparatus defines a continuous curve from said end member to said first tool holder; and

wherein said first control mount includes a first tool actuator connected to said first tool control link of said first tool, for selectively pushing and pulling on said second end portion of said first tool control link to effect operation of said end effector.

- 17.** The tool controller assembly of claim **16** wherein each actuator of said first plurality of actuators and said first tool actuator comprises:

a respective rotatable spool portion to which a respective control link is connected to permit a portion of said respective control link to be taken up or payed out from said spool portion in response to corresponding rotation of said spool portion; and

a respective driver for selectively rotating said spool portion in first and second opposite directions, wherein said respective control link is pulled when said spool portion is rotated in said first direction to take up said portion of said respective control link and wherein said respective control link is pushed when said spool portion is rotated

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in said second direction to pay out said portion of said respective control link.

18. The tool controller assembly of claim 17 wherein each said driver includes a gear segment.
19. The tool controller assembly of claim 18 wherein said first control mount has a first mounting surface and wherein each said gear segment has a portion that projects beyond said first mounting surface to engage a corresponding drive gear on a first tool controller mount.
20. A tool controller mount comprising a first tool controller mounting interface for holding a first tool controller assembly as claimed in claim 19 and further comprising a first plurality of drive gears for engaging respective gear segments on said first tool controller assembly.
21. The tool controller mount of claim 20 wherein said drive gears of said first plurality of drive gears include respective linear gear racks operably configured to slide linearly in parallel spaced apart relation.
22. The tool controller mount of claim 21 further including a first plurality of linear actuators connected to respective said linear gear racks for sliding said linear gear racks linearly to impart movement to corresponding gears of said second plurality of drive gears.
23. The tool controller mount of any one of claims 20 - 22 further comprising a second tool controller mounting interface comprising a second plurality of drive gears for engaging respective gear segments on a second tool controller assembly as claimed in claim 19.

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24. The tool controller mount of claim 23 wherein said drive gears of said second plurality of drive gears include respective linear gear racks operably configured to slide linearly in parallel spaced apart relation.
25. The tool controller mount of claim 24 further including a second plurality of actuators connected to respective said linear gear racks for sliding said linear gear racks linearly to impart movement to corresponding drive gears of said second plurality of drive gears.
26. A tool supervisory apparatus comprising:
- a positioning tube positioned to receive at least one support conduit of a tool controller assembly as claimed in claim 19, wherein said positioning tube has a length approximately the same as or less than a length of said at least one support conduit so that a tool holder supported by said at least one support conduit extends from a distal end of said positioning tube; and
- a camera holder in a position off an axis of said positioning tube such that said camera is directed toward an end effector of a tool held by said at least one tool holder to facilitate visual monitoring of movement of said end effector.
27. The tool supervisory apparatus of claim 26 wherein said camera holder comprises the tool holder as claimed in any one of claims 1-19 and wherein said support conduit of said camera holder extends inside said positioning tube and a tool positioner of said camera holder extends from said distal end of said positioning tube and is operably configured to hold and position the camera in said position off said second axis, wherein said

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second axis is generally perpendicular to said longitudinal axis of said support conduit.

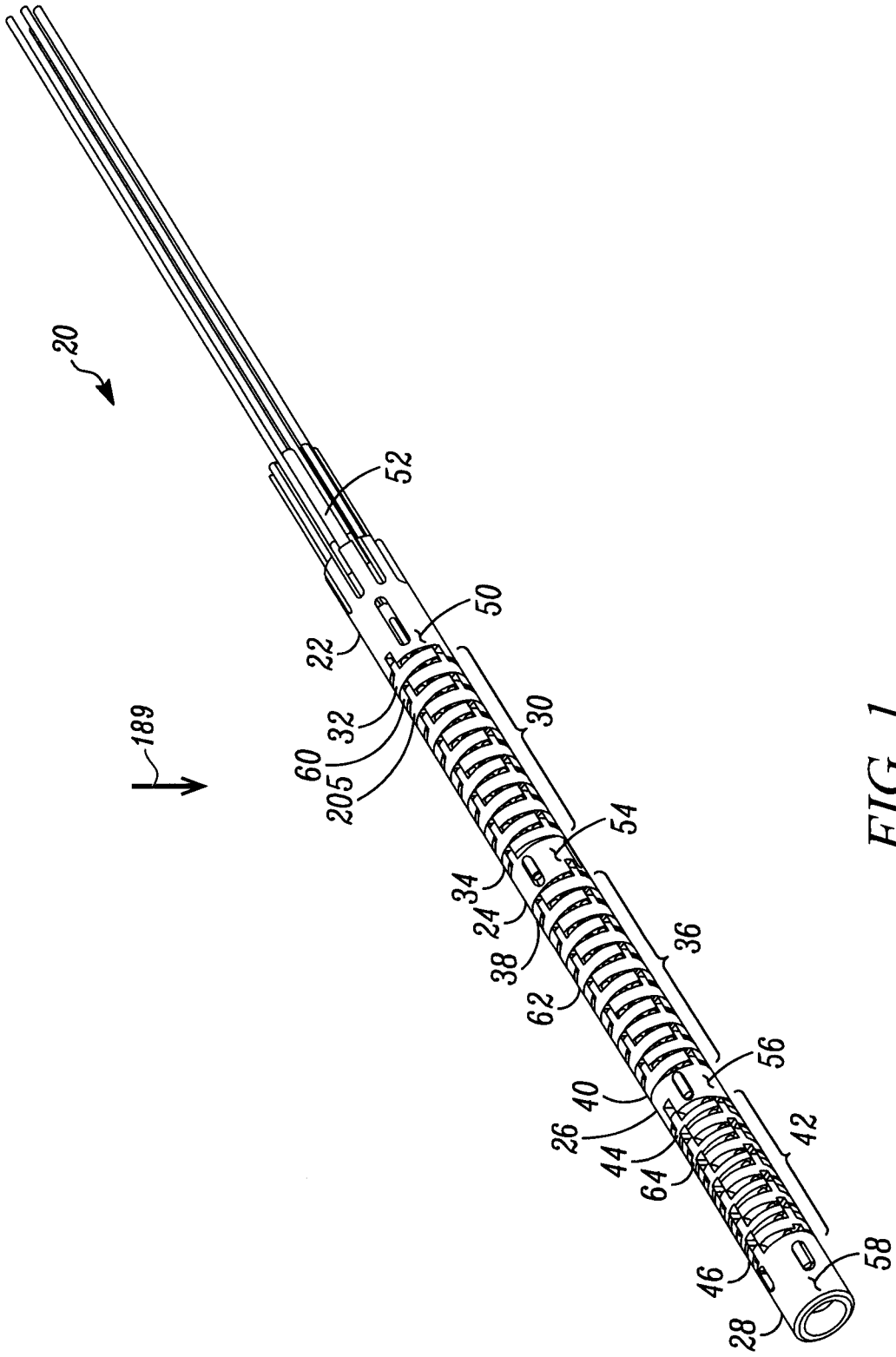


FIG. 1

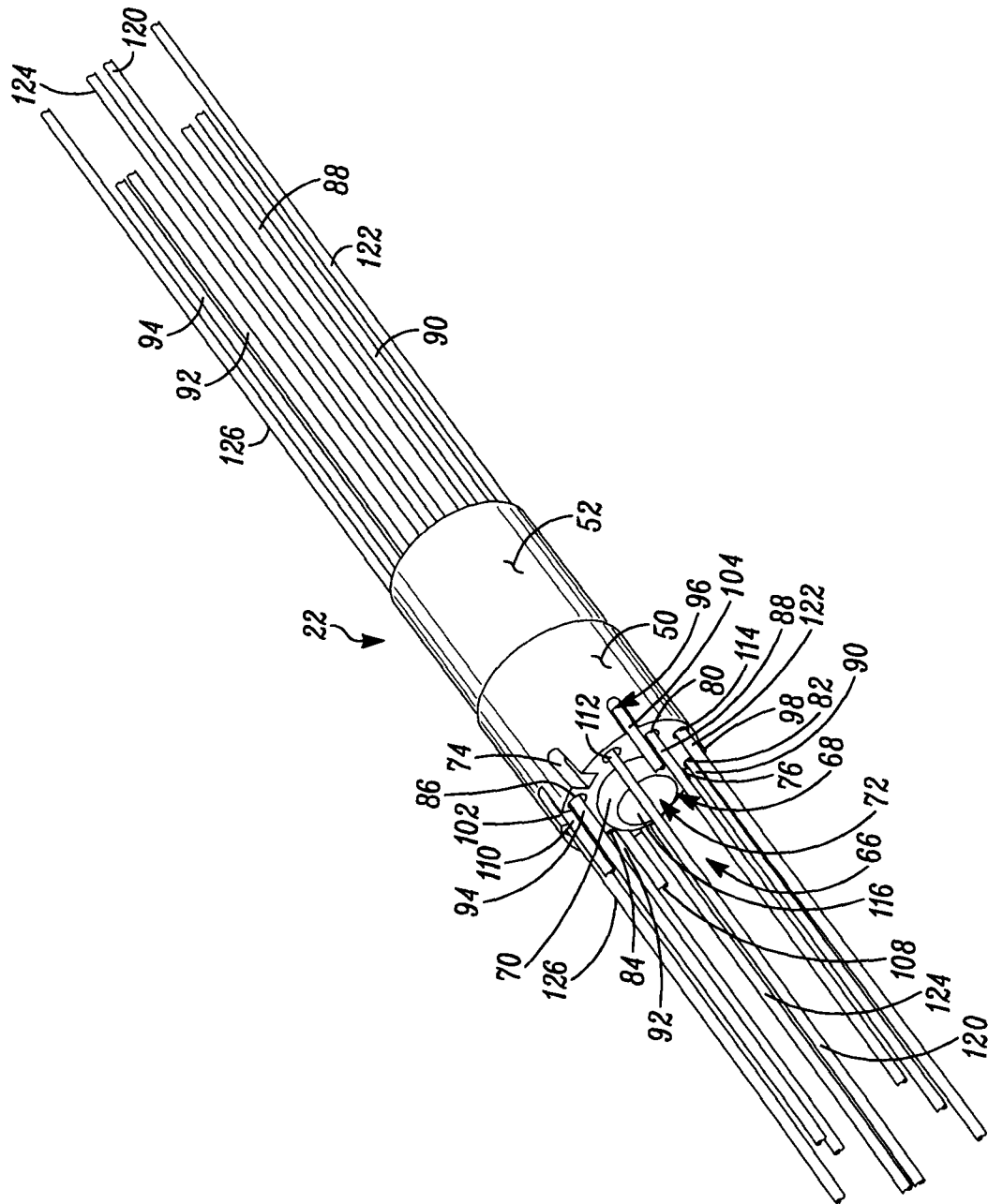


FIG. 2

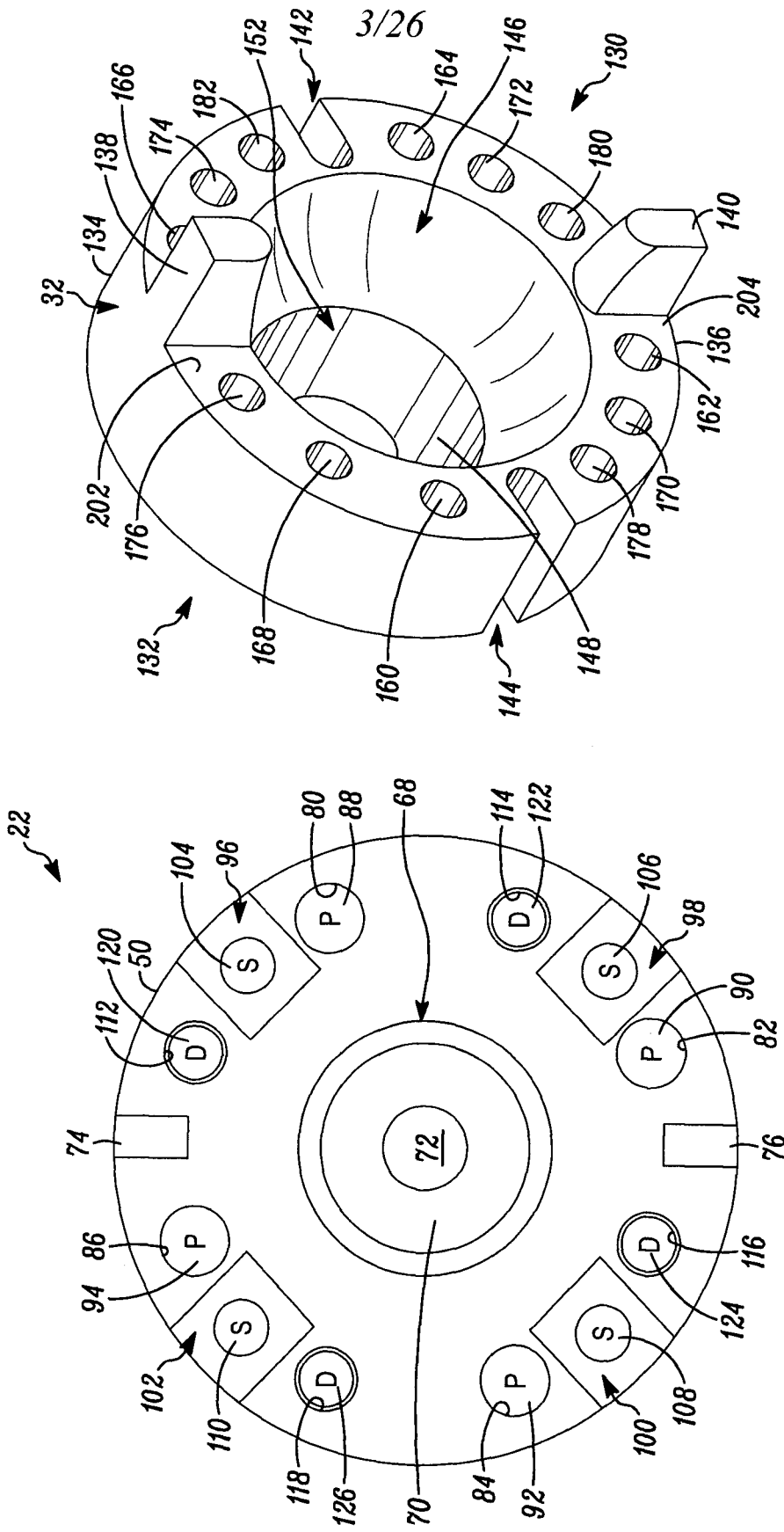


FIG. 4

FIG. 3

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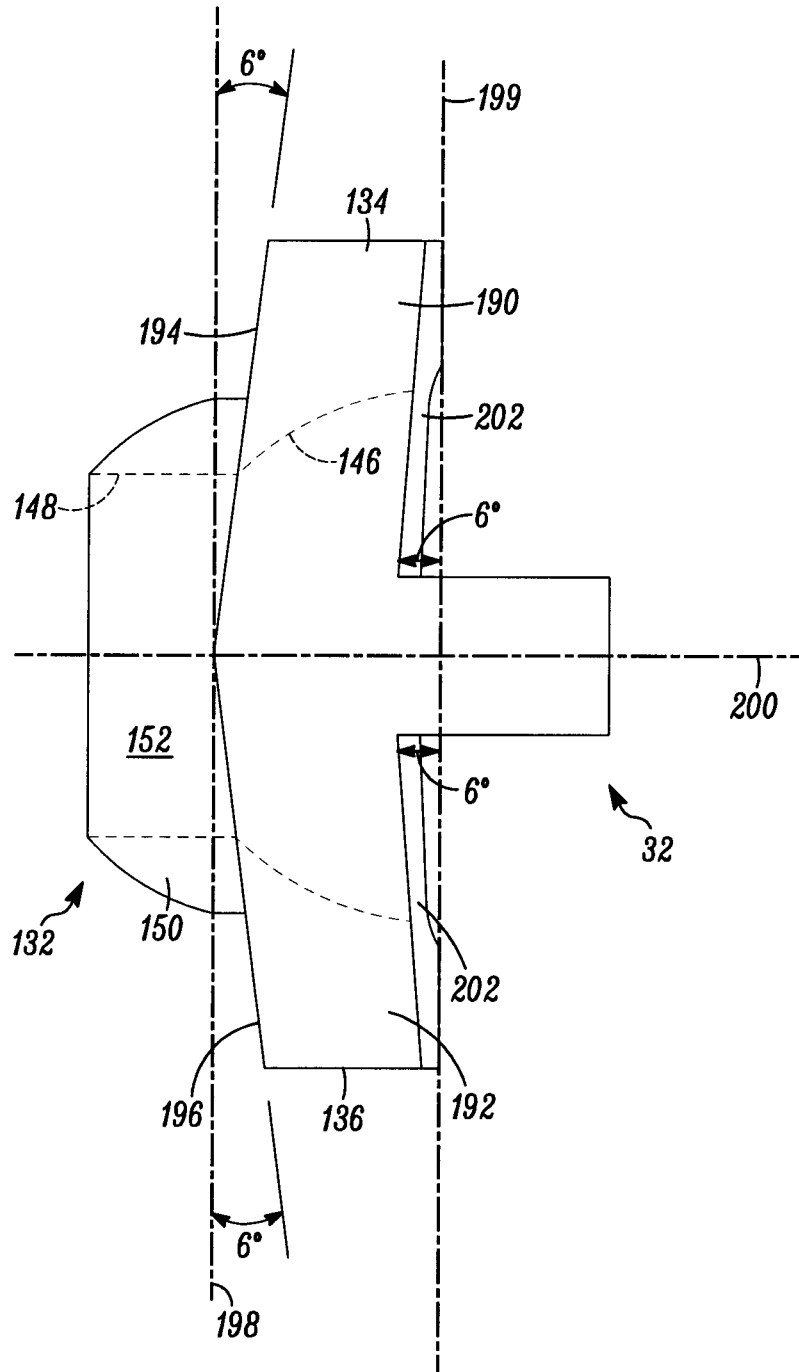


FIG. 5

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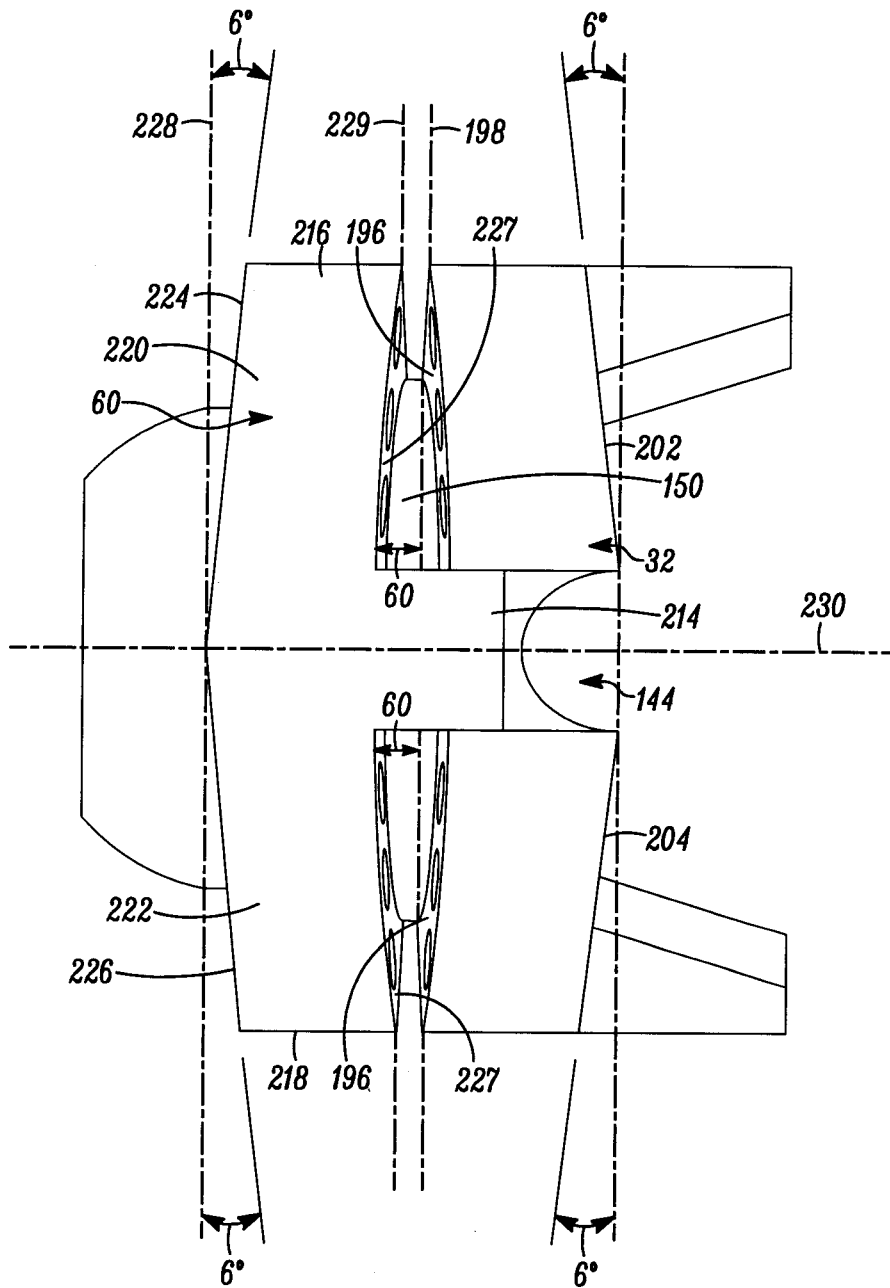


FIG. 7

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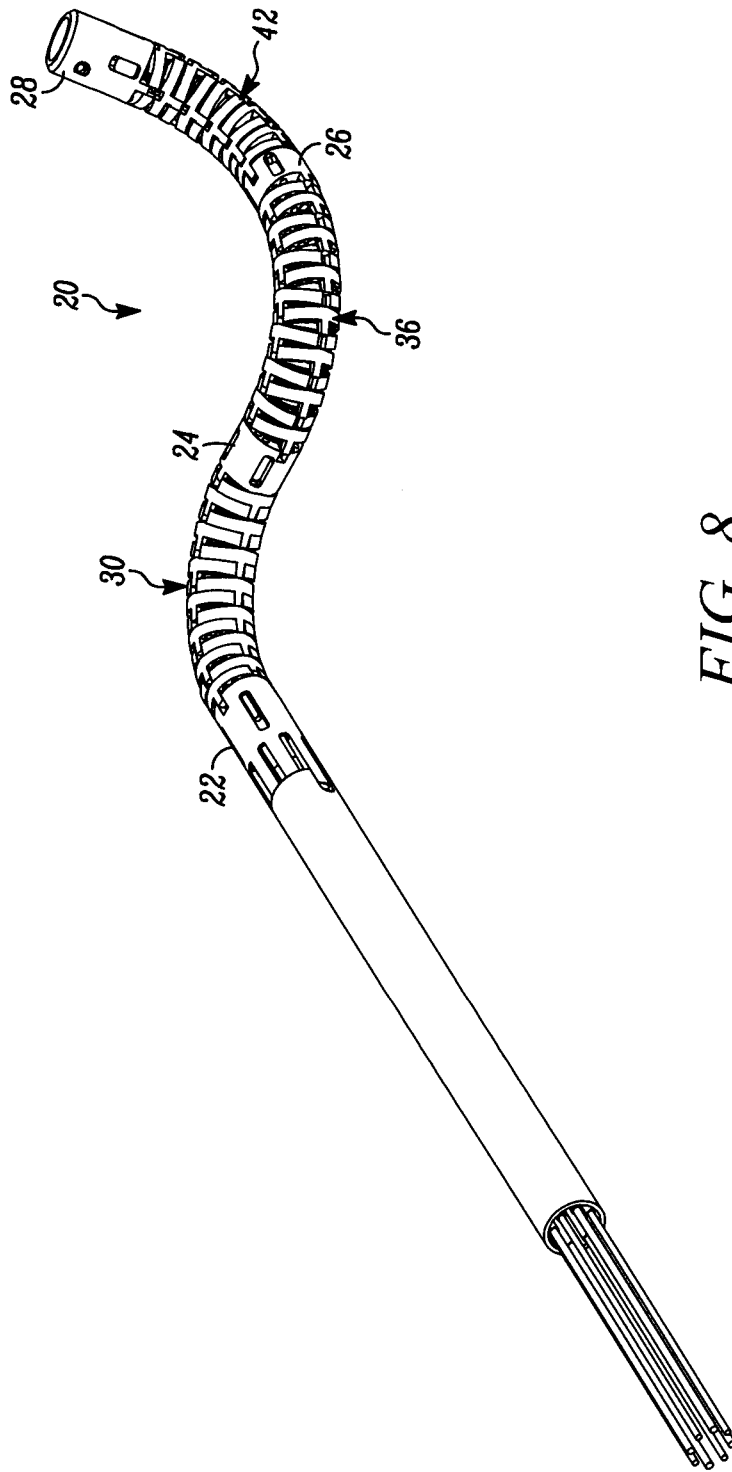


FIG. 8

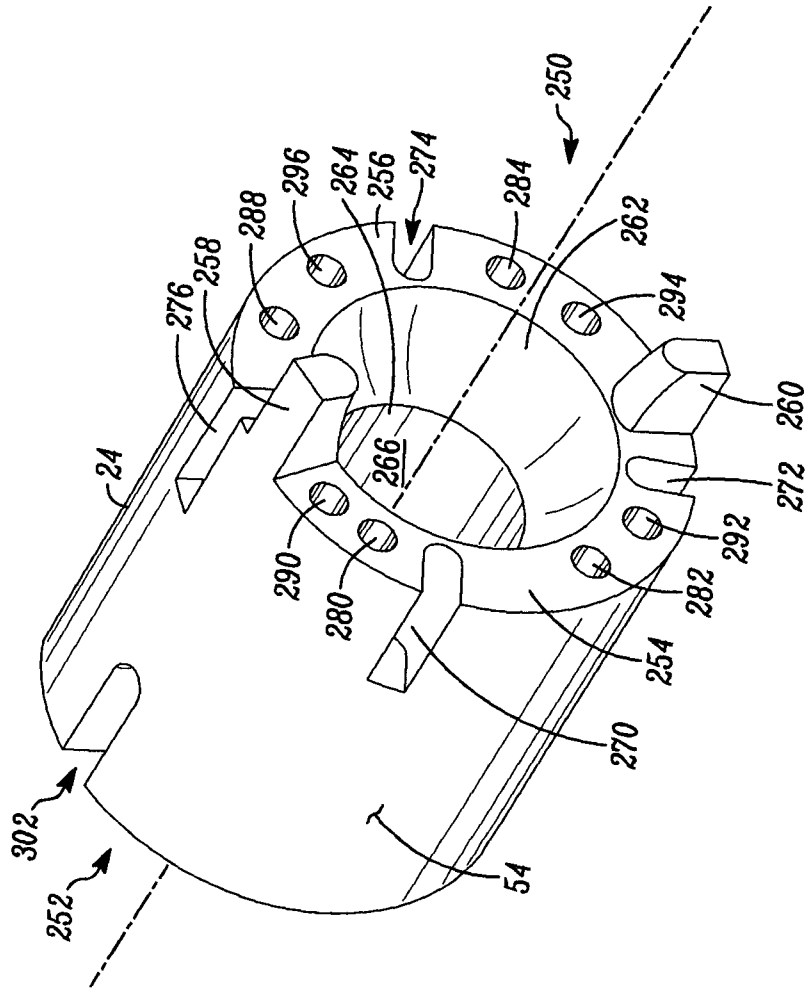


FIG. 9

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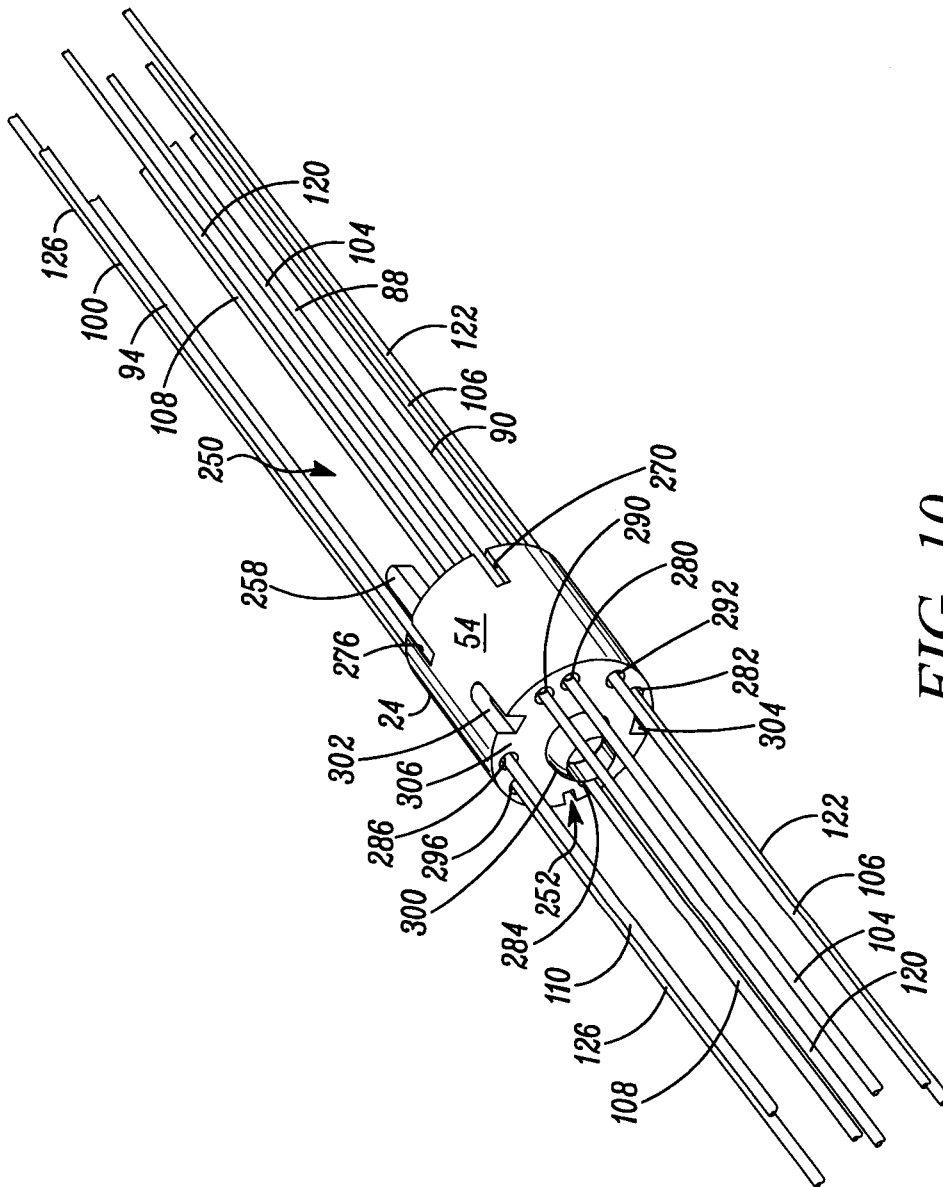
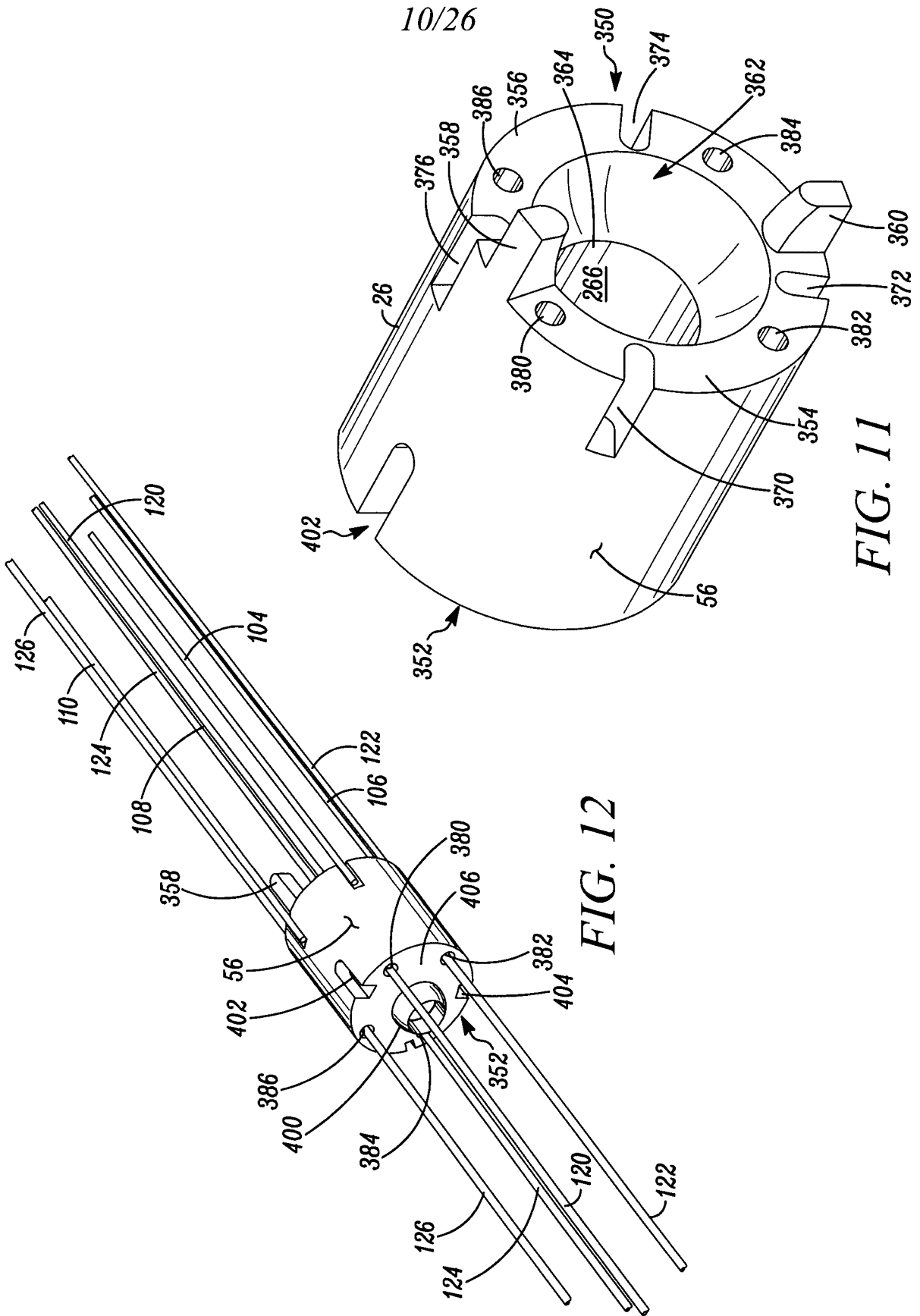


FIG. 10



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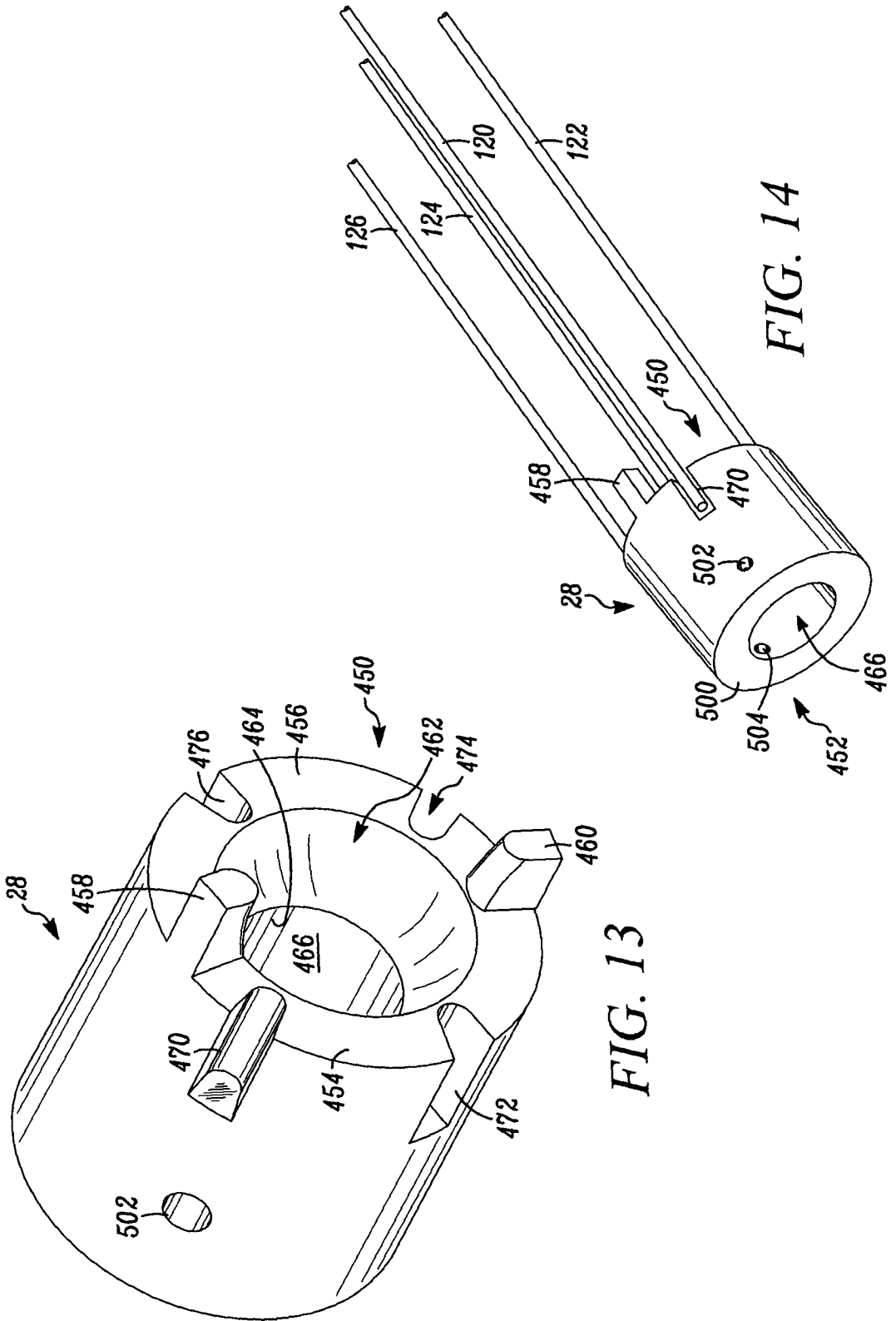


FIG. 14

FIG. 13

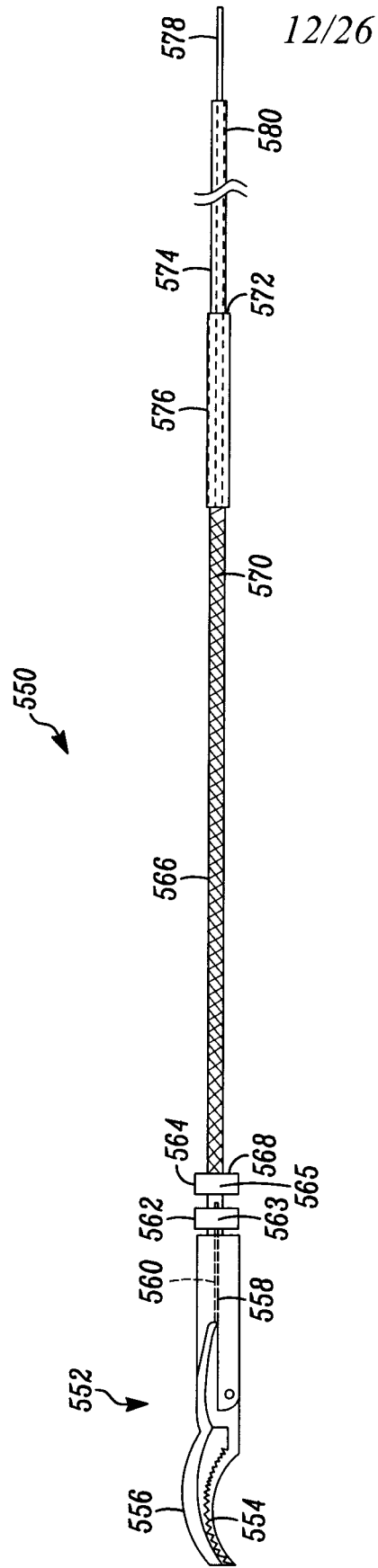


FIG. 15

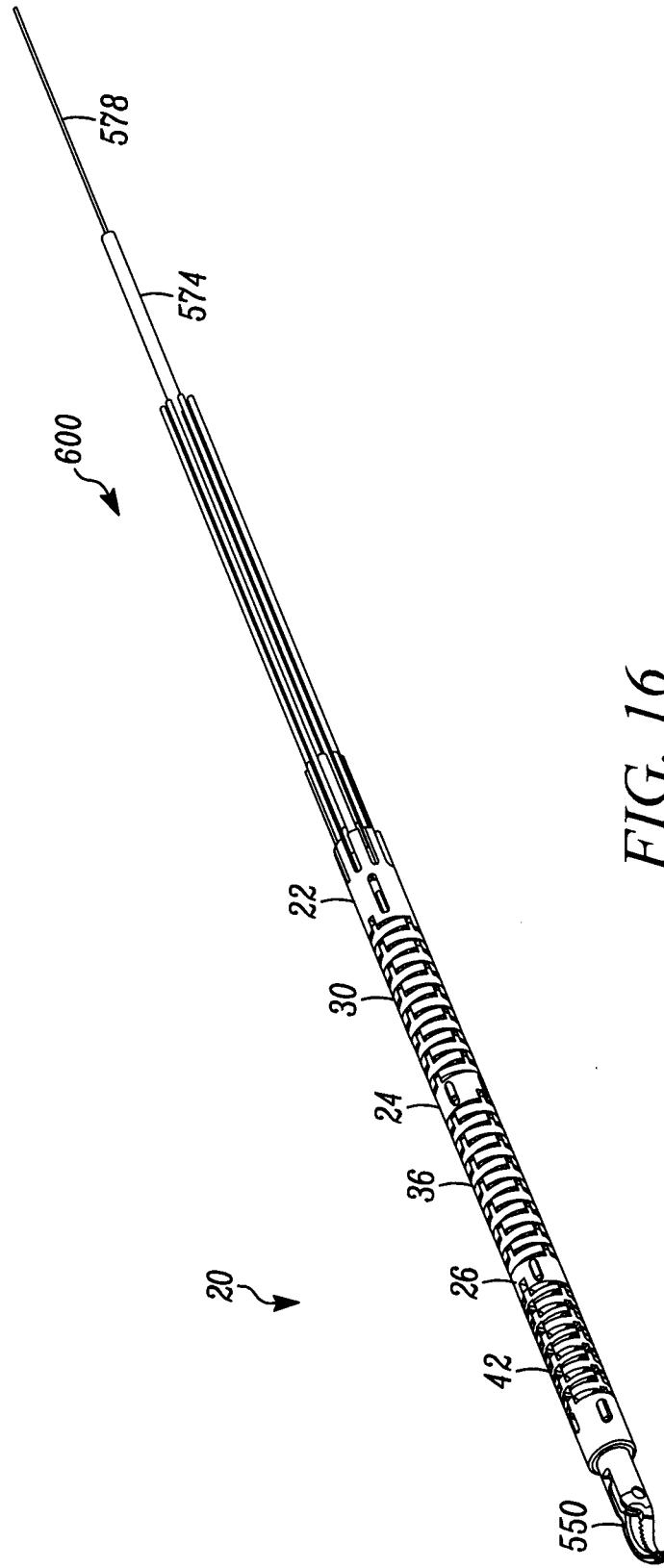


FIG. 16

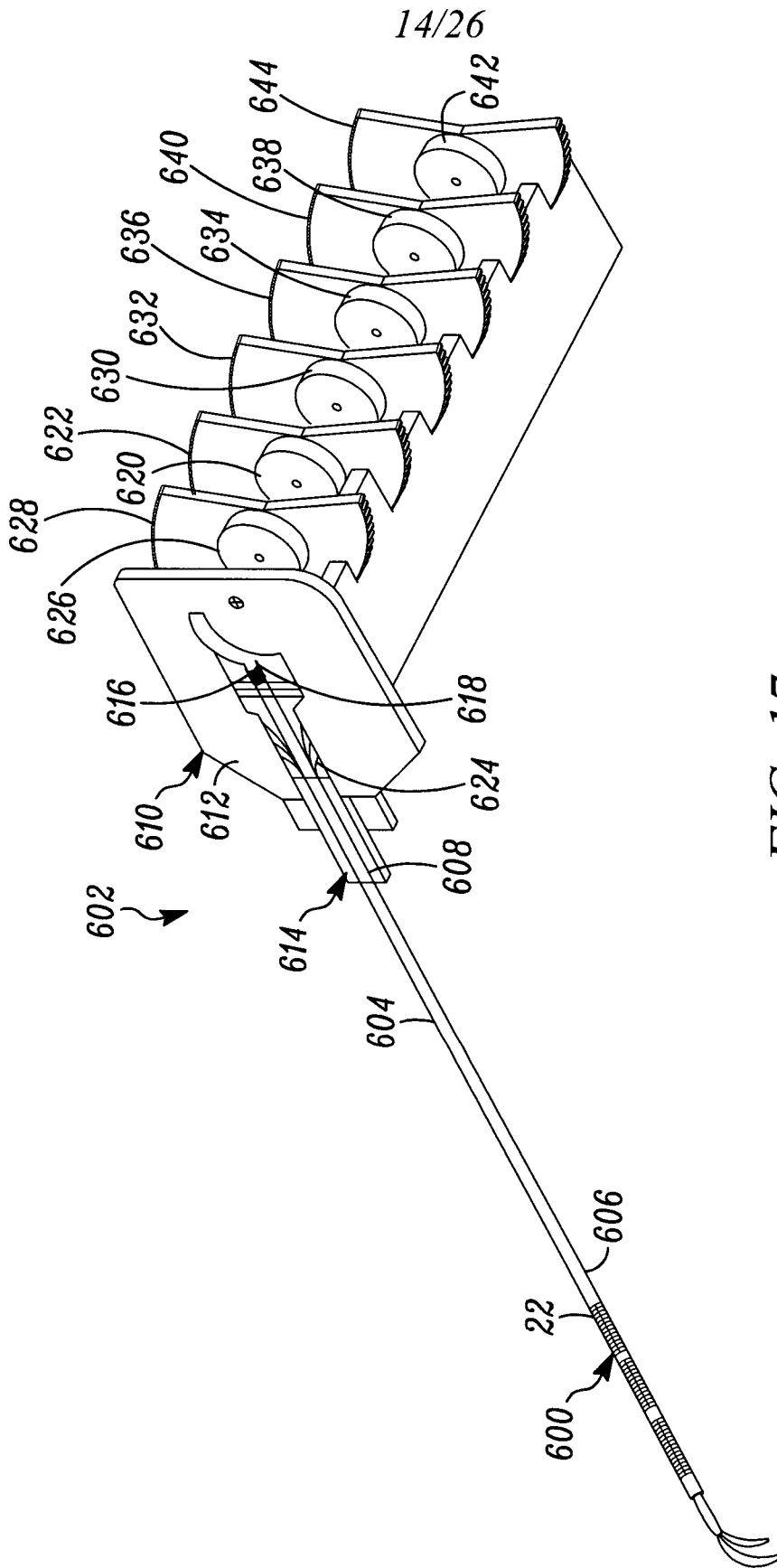


FIG. 17

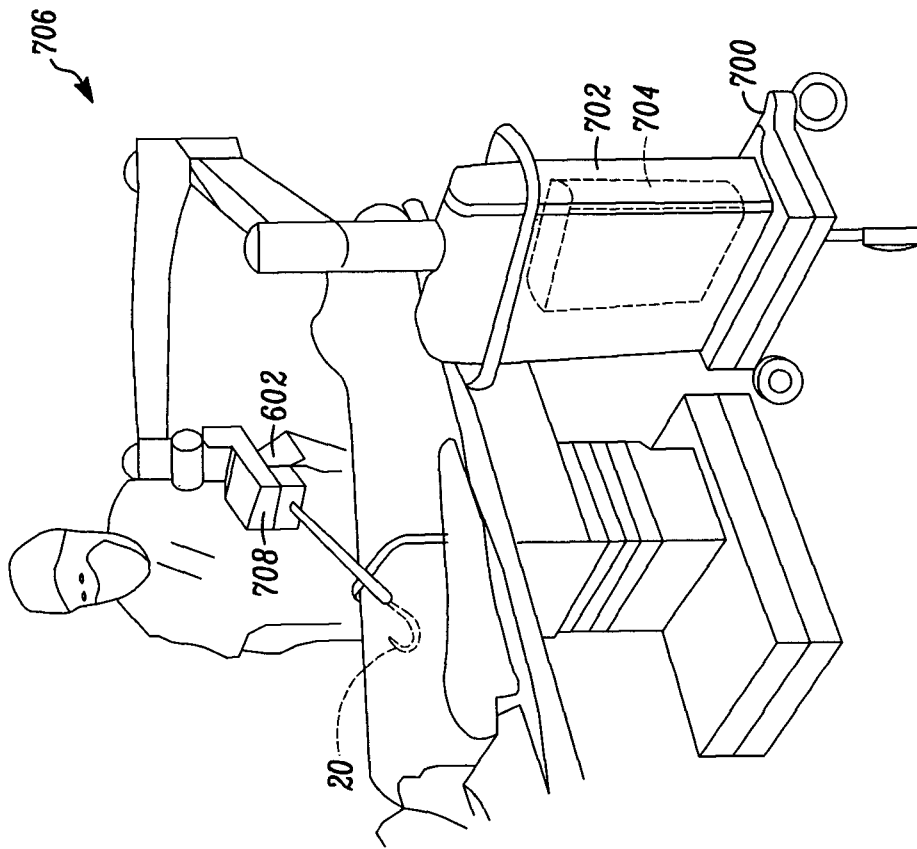


FIG. 18

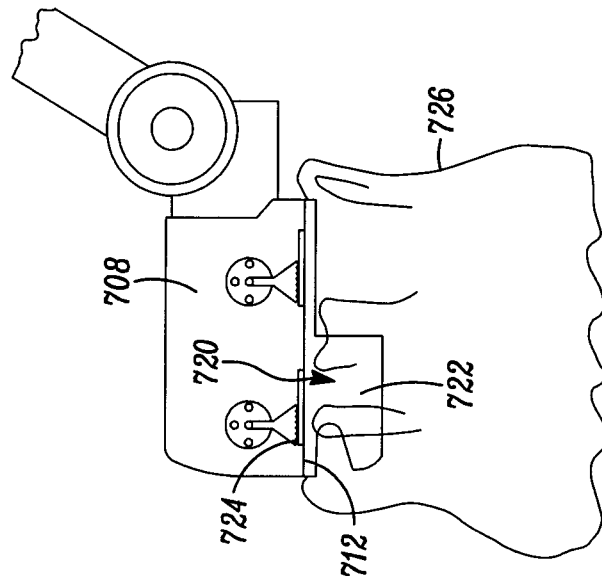


FIG. 19

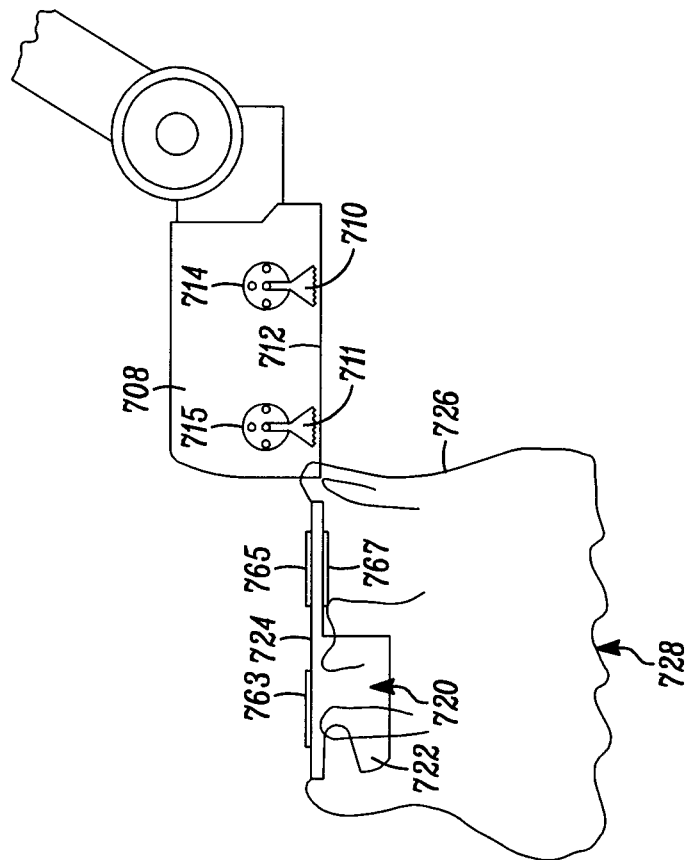


FIG. 20

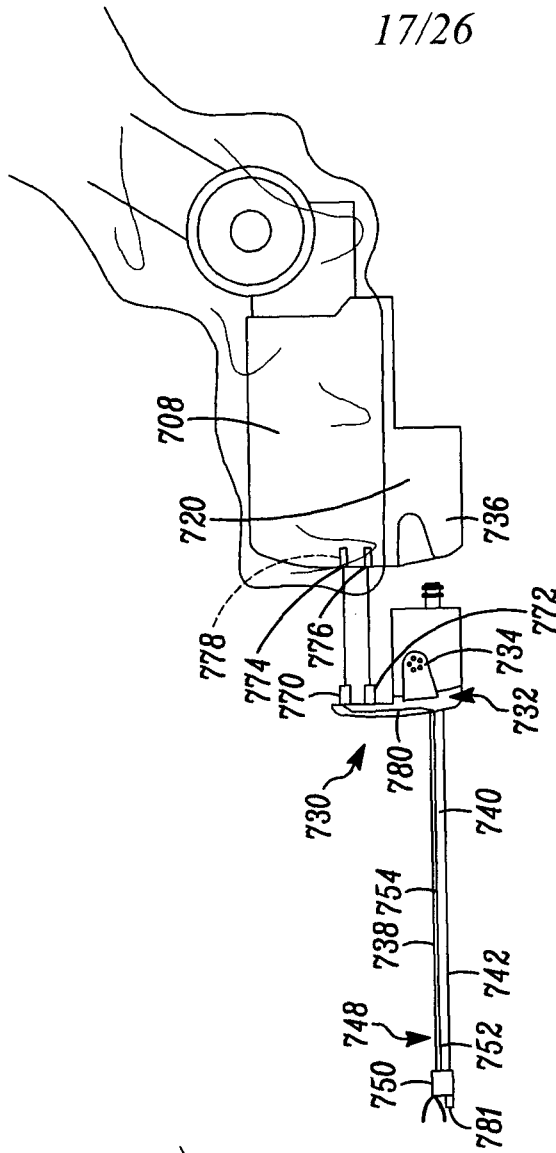


FIG. 22

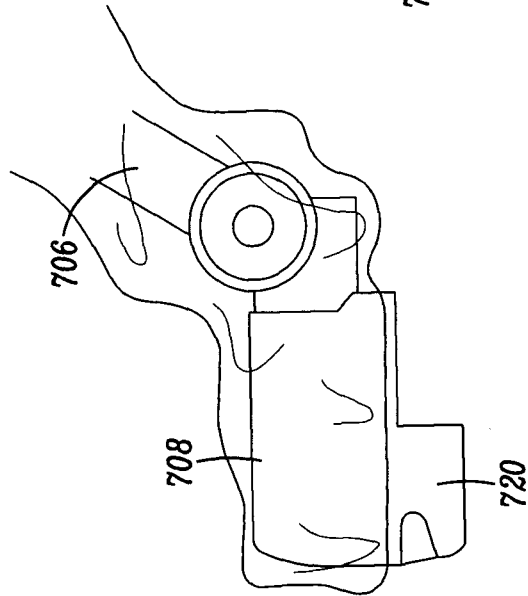


FIG. 21

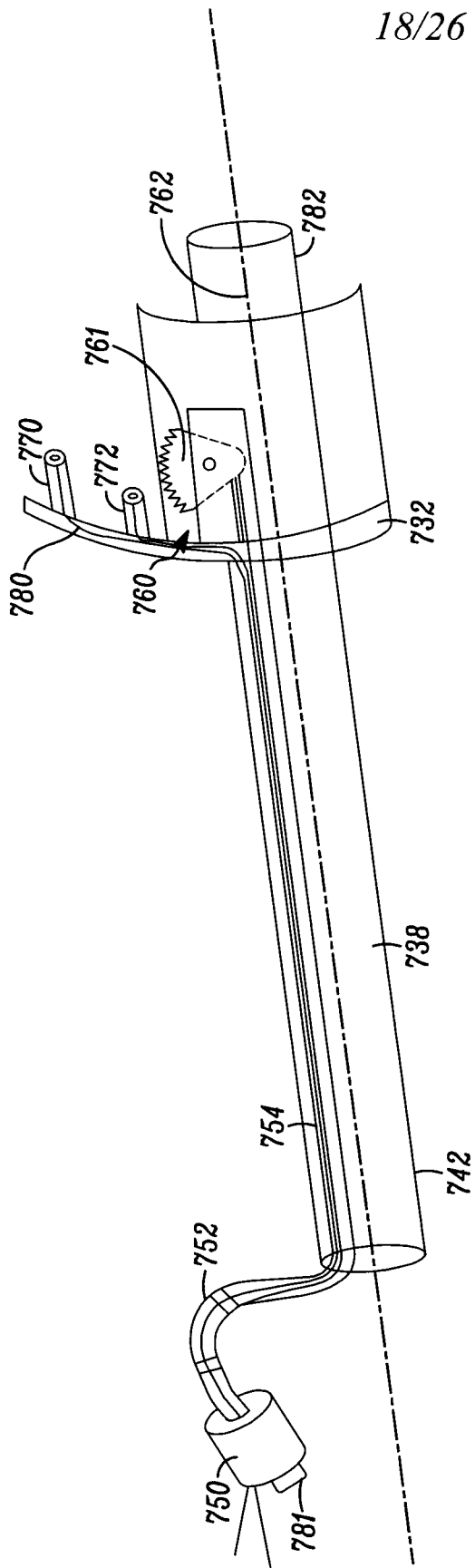


FIG. 23

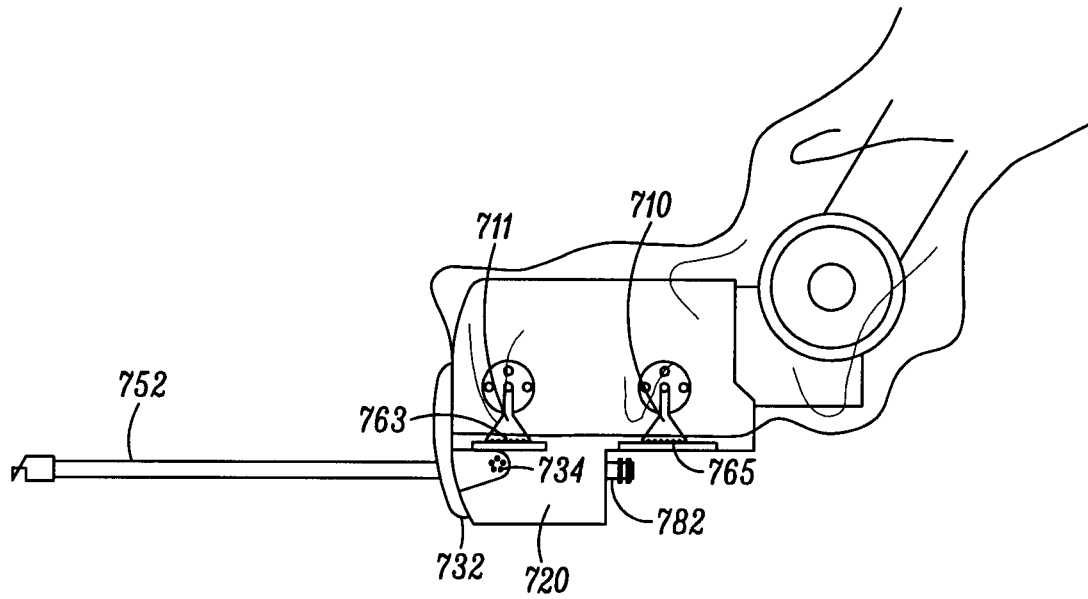


FIG. 24

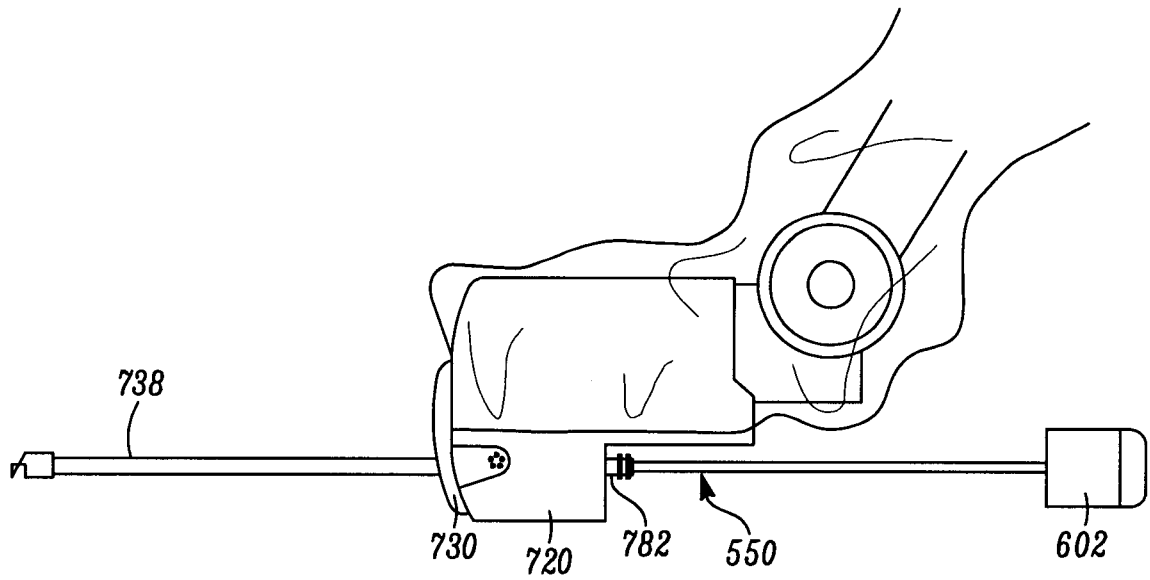


FIG. 25

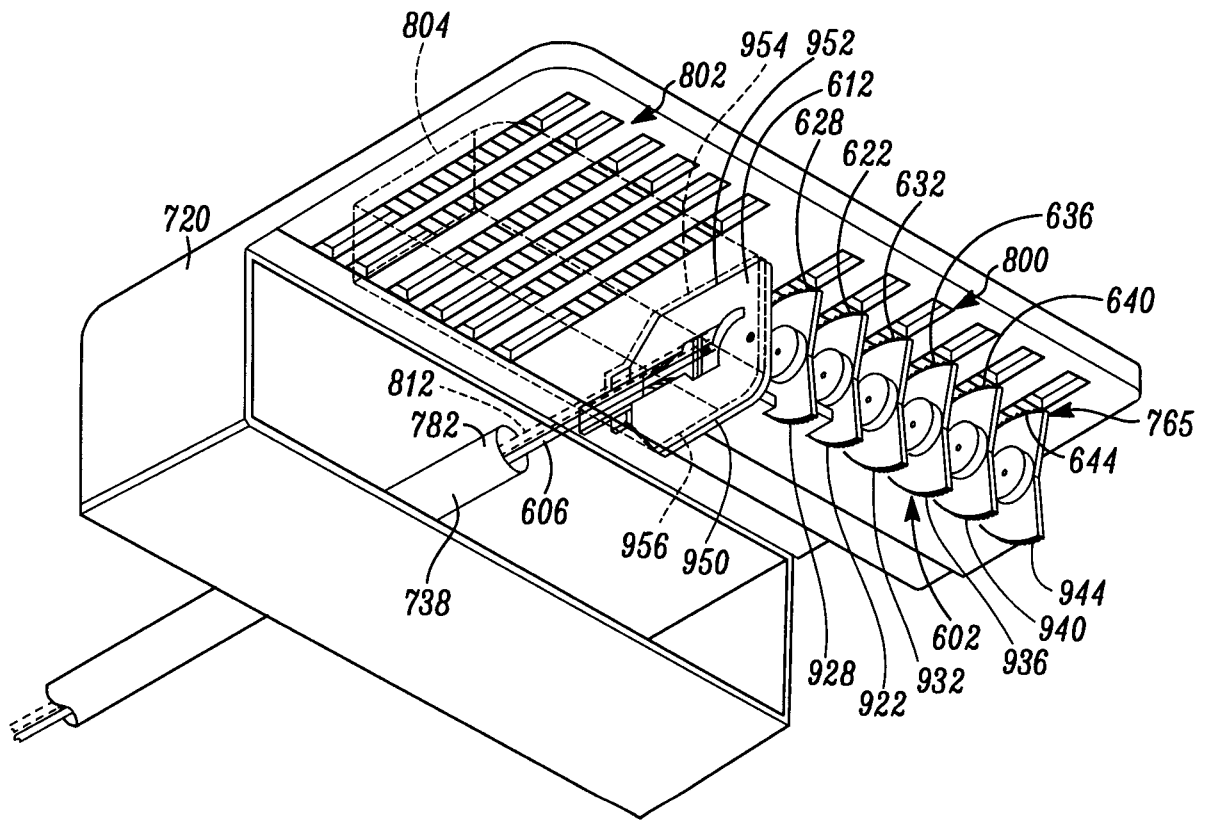


FIG. 26

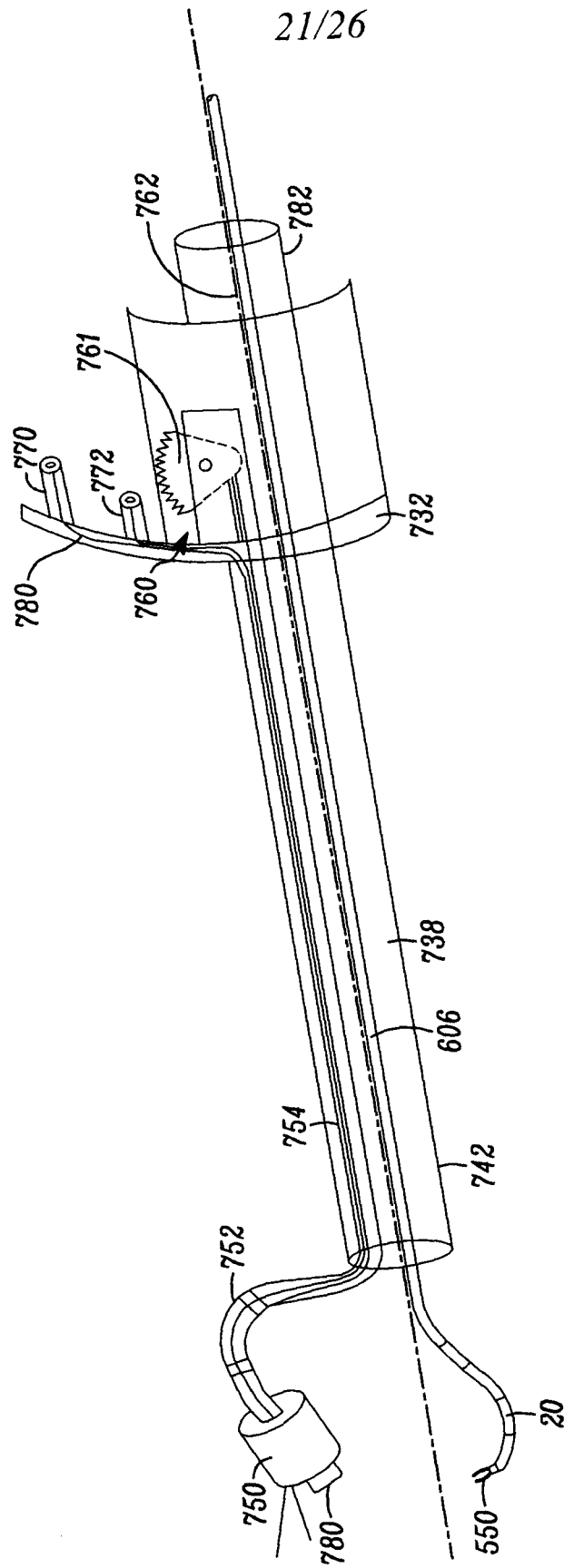


FIG. 27

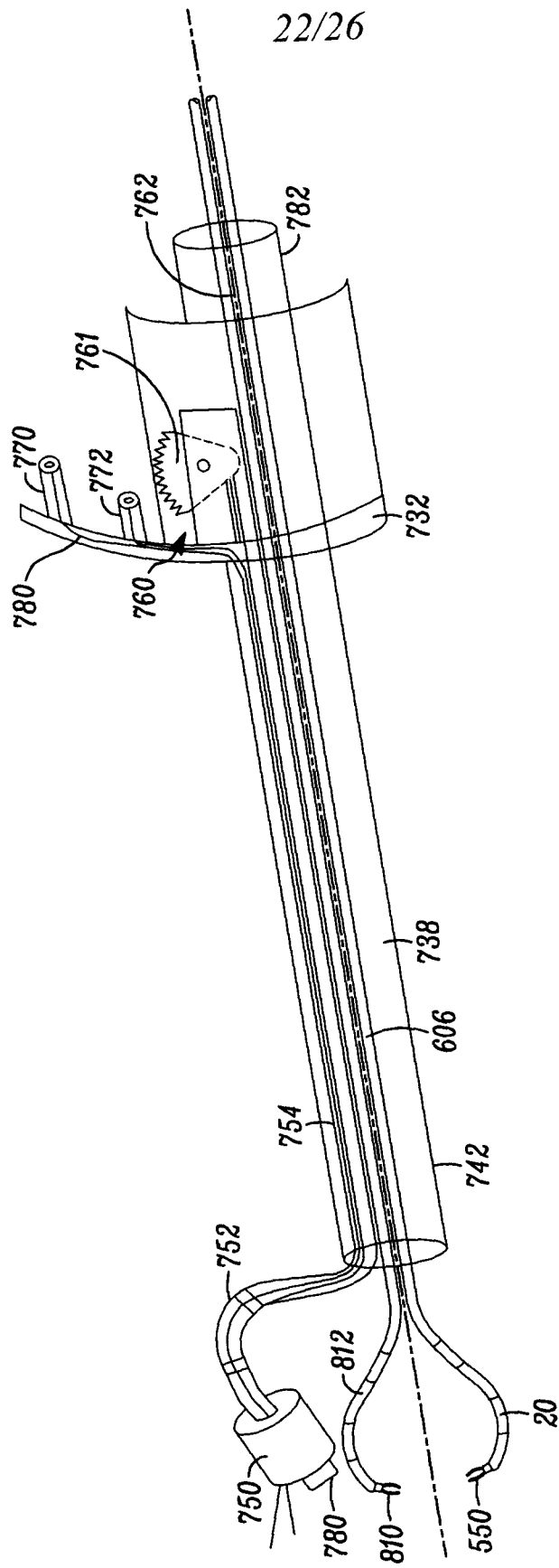


FIG. 28

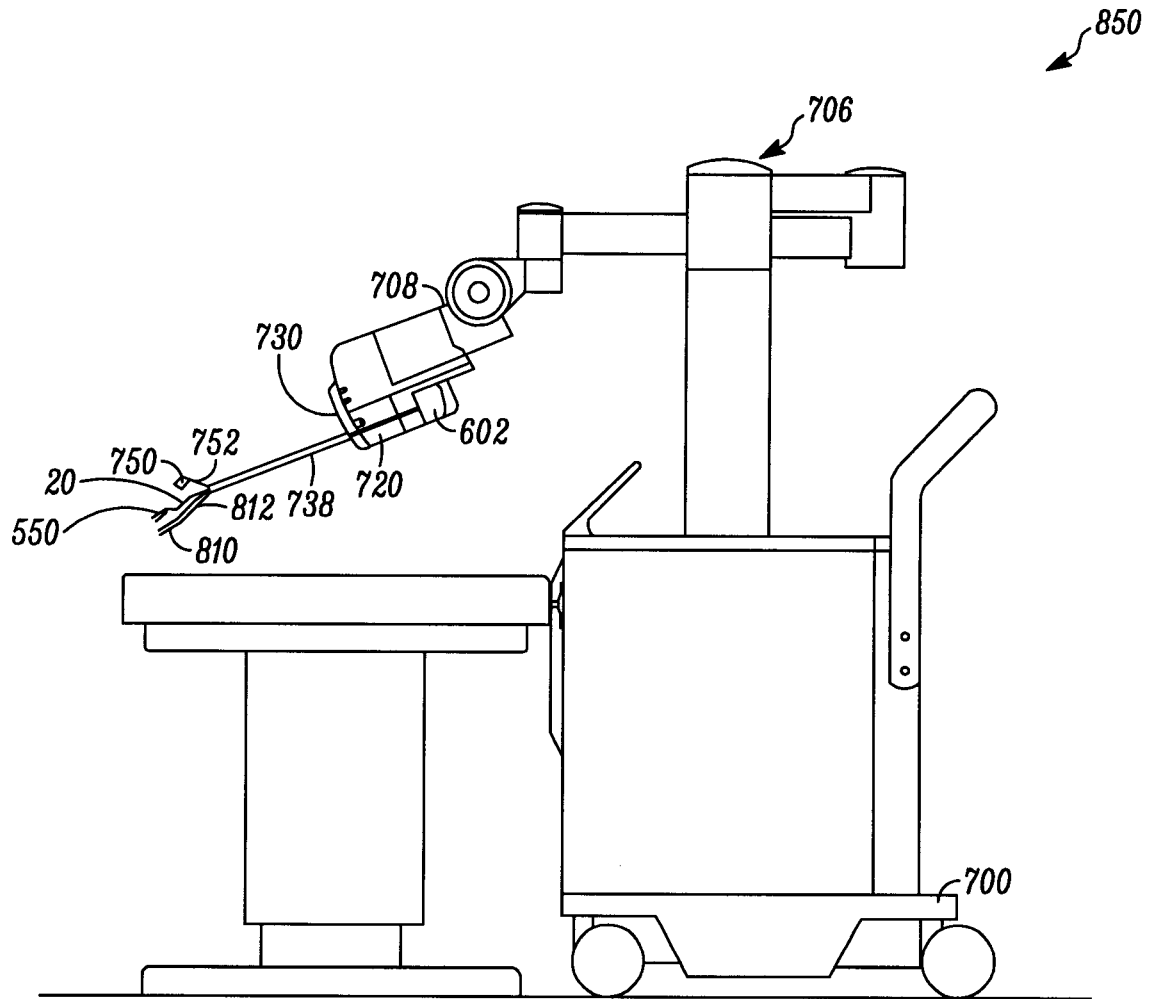


FIG. 29

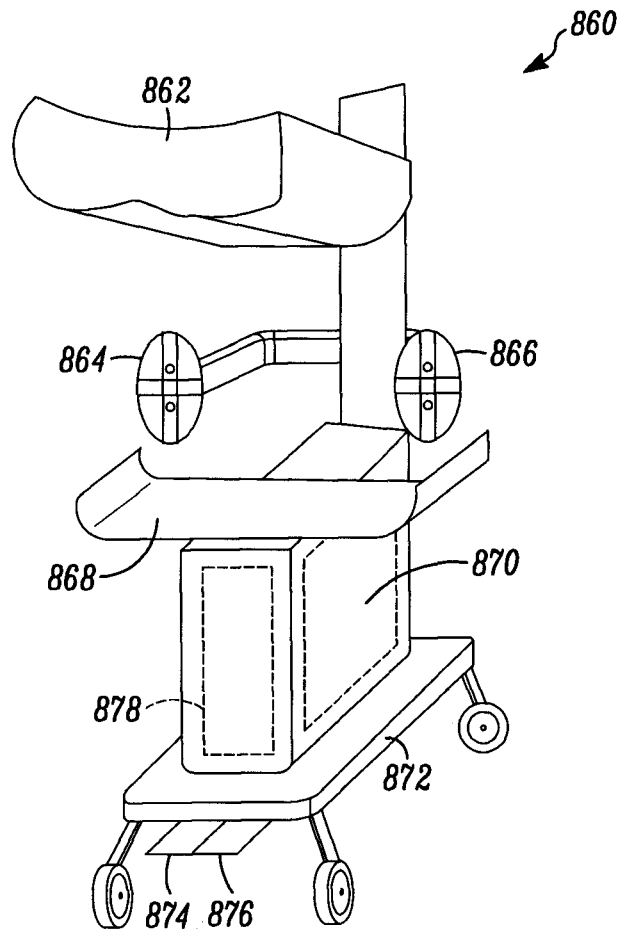


FIG. 30

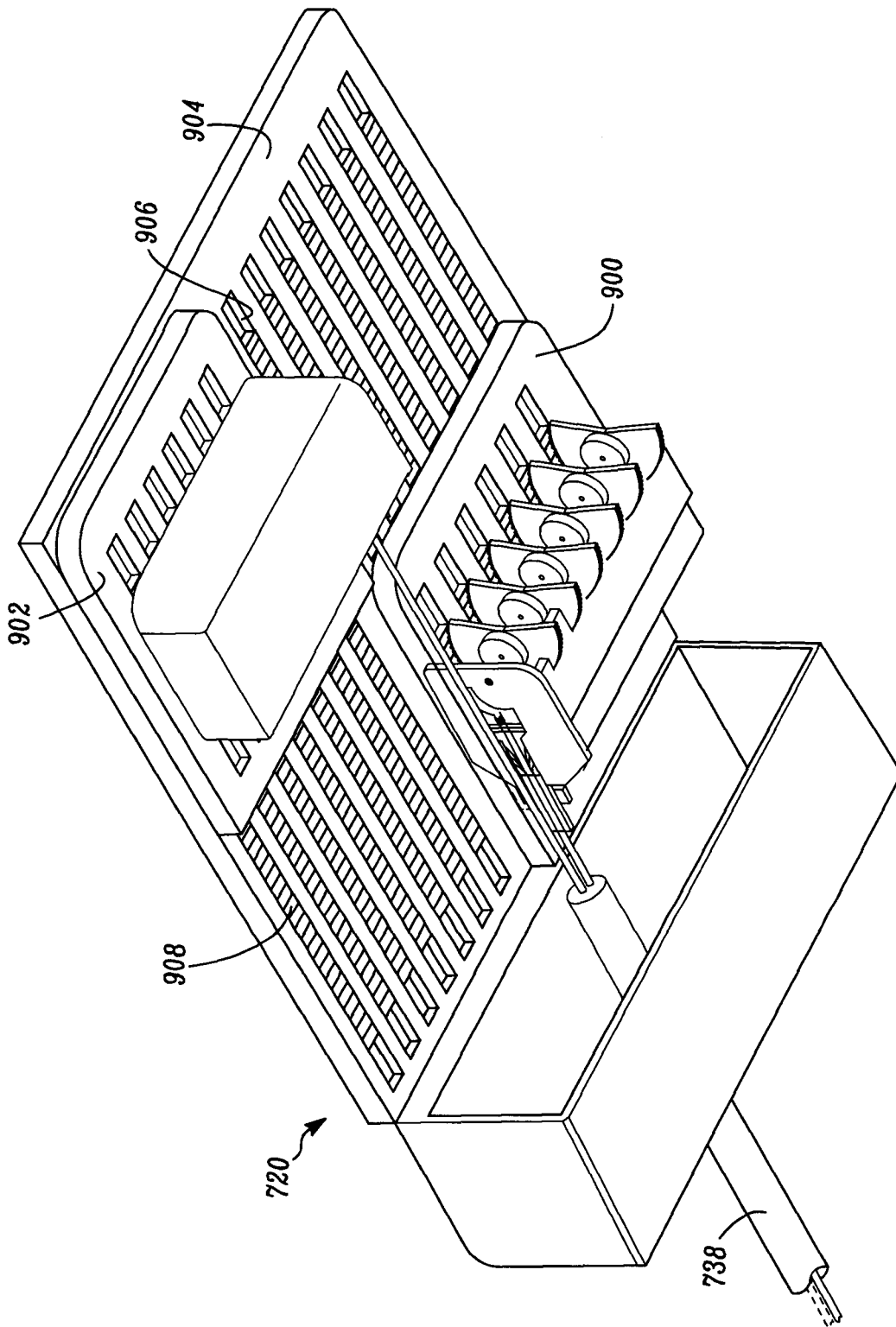


FIG. 31

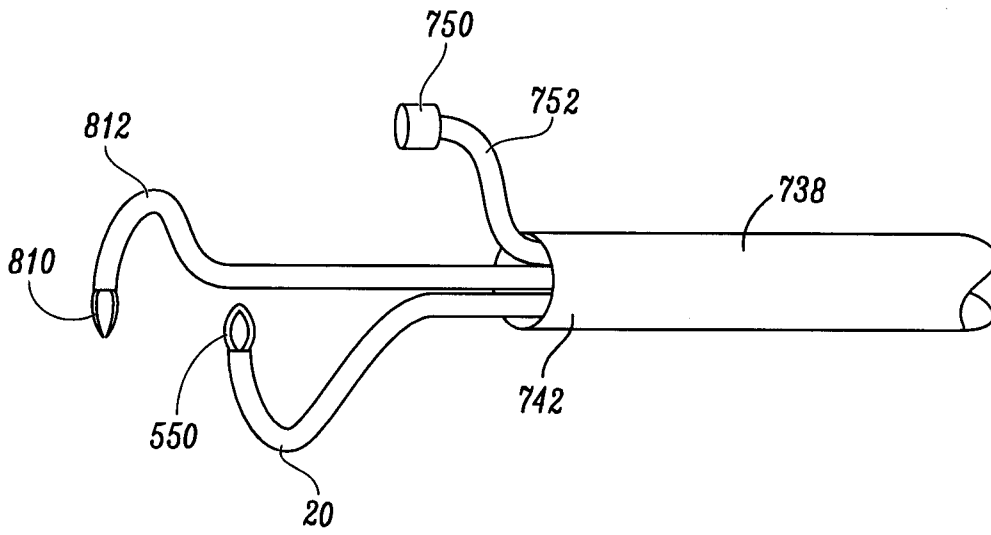


FIG. 32

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA20 13/00 1076

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2004/199052 A1 (BANK et al.) 07 October 2004 (07-10-2004) *Fig. 3A-4D; paragraphs [0058]-[0059]*	17-18
A	US 2012/232339 A1 (CSIKY) 13 September 2012 (13-09-2012) *Fig. 1A-3B, 6; paragraphs [0150]-[0155]*	1
A	US 7 147650 B2 (LEE) 12 December 2006 (12-12-2006) *Fig. 1-9B, 11A-15; paragraph [0085]*	1

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA20 13/00 1076

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2012253131A1	04 October 2012 (04-10-2012)	None	
US2006199999A1	07 September 2006 (07-09-2006)	AT547992T AT551964T AU2002318461A1 AU2002318461A8 CA2451824A1 CA2792000A1 CN1728972A CN100389730C EP1575439A4 EP1575439B1 EP1585425A2 EP1585425A4 EP1853193A1 EP1965718A2 EP2338434A2 FR2895665A1 JP2005502398A JP4332031 B2 JP2005507679A JP4347043B2 JP2006508765A JP4486503B2 KR101026692B1 US6699235B2 US6817974B2 US2004162547A1 US7066926B2 WO03001986A2 WO03001986A8 WO03001987A3	15 March 2012 (15-03-2012) 15 April 2012 (15-04-2012) 03 March 2003 (03-03-2003) 23 April 2009 (23-04-2009) 09 January 2003 (09-01-2003) 09 January 2003 (09-01-2003) 01 February 2006 (01-02-2006) 28 May 2008 (28-05-2008) 05 August 2009 (05-08-2009) 04 April 2012 (04-04-2012) 19 October 2005 (19-10-2005) 23 February 2011 (23-02-2011) 14 November 2007 (14-11-2007) 10 September 2008 (10-09-2008) 29 June 2011 (29-06-2011) 06 July 2007 (06-07-2007) 27 January 2005 (27-01-2005) 16 September 2009 (16-09-2009) 24 March 2005 (24-03-2005) 21 October 2009 (21-10-2009) 16 March 2006 (16-03-2006) 23 June 2010 (23-06-2010) 07 April 2011 (07-04-2011) 02 March 2004 (02-03-2004) 16 November 2004 (16-11-2004) 19 August 2004 (19-08-2004) 27 June 2006 (27-06-2006) 09 January 2003 (09-01-2003) 04 December 2003 (04-12-2003) 20 November 2003 (20-11-2003)
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA20 13/00 1076

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专利名称(译)	铰接式工具定位器和采用该工具定位器的系统		
公开(公告)号	EP2996613A1	公开(公告)日	2016-03-23
申请号	EP2013887243	申请日	2013-12-20
[标]申请(专利权)人(译)	提坦医疗公司		
申请(专利权)人(译)	TITAN MEDICAL INC.		
当前申请(专利权)人(译)	TITAN MEDICAL INC.		
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发明人	ROBERT, RENE ZITNICK, DAVID ALLEN CAMERON, PETER JOHN KENNETH FARIA, LEONARD M. BAJO, ANDREA		
IPC分类号	A61B90/00 A61B1/05 A61B17/29 A61B34/30		
CPC分类号	A61B1/00193 A61B1/0055 A61B1/0057 A61B17/29 A61B34/30 A61B46/10 A61B50/13 A61B90/361 A61B2017/00314 A61B2017/00323 A61B2017/2903 A61B2017/2905 A61B2017/2906 A61B2034/301 A61B2034/306 A61B17/00234 A61M25/0147		
优先权	61/837112 2013-06-19 US		
其他公开文献	EP2996613B1 EP2996613A4		
外部链接	Espacenet		

摘要(译)

一种铰接工具定位装置，包括依次布置的基座构件，中间构件，端部构件和第一工具架，每个基座构件，中间构件，端部构件和工具架具有相应的中心开口。定位在基部构件和中间构件之间的第一多个联接导向件以及第二多个联接导向件定位在中间构件和端部构件之间。第三多个联接的引导件设置在端部构件和工具架之间。基部构件，中间构件，端部构件，第一工具保持器和第一，第二，第三多个联接的引导件都具有中心开口和引导开口或固定点，用于将多个柔性控制连杆固定到基部构件或固定到与基底构件。推动或拉动第一多个控制连杆的控制连杆使得基部构件，第一多个联接的引导件，中间构件，第二多个联接的引导件和端部构件选择性地限定连续的曲线。当任何其它柔性控制连杆被推动或拉动时，第二多个控制连杆使得端部构件保持与基部构件大致相同的取向。推动或拉动第三多个控制连杆的控制连杆使得工具保持器选择性地移动到多个方向中的任一个，使得端部构件和工具架之间的第三多个连接的引导器限定了从端部构件到工具架。描述了用于推动和拉动柔性控制连杆的至少一个机构，并且描述了用于定位用于腹腔镜手术应用的工具的装置的使用。