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(54) Title: CENTER ROBOTIC ARM WITH FIVE-BAR SPHERICAL LINKAGE FOR ENDOSCOPIC CAMERA

(57) Abstract: A robotic arm including a parallel spherical five-bar linkage with a remote center of spherical rotation. The robotic arm movably supports an endoscopic camera. Two outboard links are pivotally coupled together. At least one of the two outboard links supports the endoscopic camera. Two inboard links are respectively pivotally coupled to the two outboard links such that the two inboard links are able to cross over one another. The two inboard links moveably support the two outboard links. A ground link is pivotally coupled to the two inboard links. The ground link moveably supports the two inboard links.

CENTER ROBOTIC ARM WITH FIVE-BAR SPHERICAL LINKAGE FOR ENDOSCOPIC CAMERA

FIELD

The embodiments of the invention relate generally to robotic surgical systems. More particularly, the embodiments of the invention relate to linkage in robotic arms.

BACKGROUND OF THE INVENTION

Minimally invasive surgery (MIS) provides surgical techniques for operating on a patient through small incisions using a camera and elongated surgical instruments introduced to an internal surgical site, often through trocar sleeves or cannulas. The surgical site often comprises a body cavity, such as the patient's abdomen. The body cavity may optionally be distended using a clear fluid such as an insufflation gas. In traditional minimally invasive surgery, the surgeon manipulates the tissues using end effectors of the elongated surgical instruments by actuating the instrument's handles while viewing the surgical site on a video monitor.

A common form of minimally invasive surgery is endoscopy. Laparoscopy is a type of endoscopy for performing minimally invasive inspection and surgery inside the abdominal cavity. In standard laparoscopic surgery, a patient's abdomen is insufflated with gas, and cannula sleeves are passed through small (generally 1/2 inch or less) incisions to provide entry ports for laparoscopic surgical instruments. The laparoscopic surgical instruments generally include a laparoscope (a type of endoscope adapted for viewing the surgical field in the abdominal cavity) and working tools. The working tools are similar to those used in conventional (open) surgery, except that the working end or end effector of each tool is separated from its handle by a tool shaft. As used herein, the term "end effector" means the actual working part of the surgical instrument and can include clamps, graspers, scissors, staplers, image capture lenses, and needle holders, for example. The end effector for the laparoscope may include lenses and light sources that may be optically couple to a camera and lamps through the tool shaft. To perform surgical procedures, the surgeon passes these working tools or instruments through the cannula sleeves to an internal surgical site and manipulates them from outside the abdomen. The surgeon monitors the procedure by means of a monitor that displays an image of the surgical site taken from the laparoscope. Similar endoscopic techniques are employed in other types of surgeries such as arthroscopy, retroperitoneoscopy, pelviscopy, nephroscopy, cystoscopy, cisternoscopy, sinoscopy, hysteroscopy, urethroscopy, and the like.

BRIEF SUMMARY

The embodiments of the invention are summarized by the claims that follow below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a surgical suite in which embodiments of the invention are used.

FIG. 2 is a plan view of a portion of the operating suite of FIG. 1.

FIG. 3 is a side view of a portion of the operating suite of FIG. 2.

FIG. 4 is a schematic view of a parallel five-bar linkage.

FIG. 5 is a schematic view of a parallel spherical five-bar linkage.

FIG. 6 is a schematic view of another parallel spherical five-bar linkage.

FIG. 7 is a pictorial view of an embodiment of the invention.

FIG. 8 is a view of a first side of an embodiment of the invention.

FIG. 9 is a bottom view of the embodiment of the invention shown in FIG. 8.

FIG. 10 is view of a second side of the embodiment of the invention shown in FIG. 8.

FIG. 11 is a top view of the embodiment of the invention shown in FIG. 8.

FIG. 12 is an end view of the embodiment of the invention shown in FIG. 8.

FIG. 13 is a pictorial view of a portion of the embodiment as shown in FIG. 12.

FIG. 14 is a bottom view of the embodiment of the invention as shown in FIG. 9 in a different operative position.

FIG. 15 is a bottom view of another embodiment of the invention.

FIG. 16 is an end view of another embodiment of the invention.

FIG. 17 is a schematic view of a parallel spherical five-bar linkage.

FIG. 18 is a schematic view of another parallel spherical five-bar linkage.

FIG. 19 is a pictorial view of another embodiment of the invention.

FIG. 20 is a schematic view of the parallel spherical five-bar linkage shown in FIG. 19.

FIG. 21 is a pictorial view of another embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTIION

The detailed description describes the invention as it may be used in a laparoscopic surgery. It is to be understood that this is merely one example of the types of surgeries in which the invention may be used. The invention is not limited to laparoscopy nor to the particular structural configurations shown which are merely examples to aid in the understanding of the invention. Traditional minimally invasive surgery requires a high degree of surgical skill

because the surgeon's hand movements are controlling a surgical tool at a substantial distance from the surgeon's hands, often requiring unnatural and non-intuitive hand motions. In robotically assisted surgery, a surgeon may operate a master controller to control the motion of surgical instruments at the surgical site. Servo mechanisms may move and articulate the surgical instrument based on the surgeon's manipulation of the hand input devices. The robotic assistance may allow the surgeon to control the motion of surgical instruments more easily and with greater precision.

Figure 1 shows a schematic plan view of a surgical suite in which the invention may be used. A patient 110 is shown on an operating table 112 undergoing robotically assisted laparoscopic surgery. A surgeon 120 may use a master controller 122 to view a video image of the internal surgical site provided by an endoscopic camera, a laparoscopic camera 104 in the case of abdominal surgery, and control one or more surgical instruments and the endoscopic camera by means of robotic servo mechanisms. The master controller 122 will typically include one or more hand input devices (such as joysticks, exoskeletal gloves, or the like) which are coupled by a servo mechanism to a surgical instrument.

A robotic arm 116 that embodies the invention may be used to support and move the laparoscopic camera 104 at the surgical site during robotically assisted surgery. It is desirable to support the laparoscopic camera 104 such that the tool shaft 118 of the instrument and the cannula 106 through which it passes pivot about a center of spherical rotation positioned in space along the length of the tool shaft and cannula. Additional robotic arms 100, 102 may support and move surgical instruments. The robotic arms 100, 102 for supporting the surgical instruments may be of a different form than the robotic arm 116 for supporting the laparoscopic camera.

Each robotic arm 100, 102, 116 may be supported by an articulated set-up arm 130, 132, 134. The set-up arms may be attached to the operating table 112. Each set-up arm may include a number of segments coupled by joints that provide one or more degrees of freedom that allow the robotic arm to be positioned within a defined range of motion. One or more locking mechanisms may be provided to fix the segments and joints of the set-up arm when the robotic arm is in the desired position. The set-up arms may allow the robotic arms 100,102, 116 to be fixed at an arbitrary position with respect to the operating table and the patient thereon. Joint angle sensors may be provided on the set-up arm to allow the pose of the set-up arm and the resulting position of the supported robotic arm to be determined.

Each robotic arm 100, 102, 116 may be fixed at a position where the center of spherical rotation is substantially at the access point to the internal surgical site (for example, with the

incision that provides entry for the trocar or cannula 106 at the abdominal wall during laparoscopic surgery). An end effector of the surgical instrument 104 supported by the robotic arm 116 can be positioned safely by moving the proximal end of the tool shaft 118 with the robotic arm 116 without imposing dangerous forces against the abdominal wall.

Each robotic arm 100, 102, 116 will support one surgical instrument which may be detachable from the robotic arm. While a variety of surgical instruments 108 may replace the surgical instrument on the robotic arm 100, 102 during the course of a single surgery, the laparoscopic camera 104 is generally left in place throughout the course of a surgery. Each robotic arm 116 may support a cannula 106 that passes through an incision into the body of the patient 110. The tool shaft 118 of the surgical instrument or laparoscopic camera 104 passes through the cannula 106 to the internal surgical site.

The robotic arm 116 may support the laparoscopic camera 104 such that the cannula 106 and the tool shaft 118 of the instrument pivot about a center of spherical rotation positioned in space along the length of the cannula 106. The center of spherical rotation may also be called the remote center of spherical rotation because it is the spherical center of rotational motion for the robotic arm while being spaced apart from the structure of the robotic arm. Motion about the center of spherical rotation may be described as spherical motion because a point at a radial distance from the center of spherical rotation will move on a spherical surface having the radial distance as its radius. The cannula 106 defines an insertion axis that passes through an access point, such as an incision in the abdominal wall of the patient 110, to the internal surgical site. The tool shaft 118 extends along the insertion axis.

Each robotic arm 100, 102, 116 may include one or more servo motors to move the arm to a desired position. Each robotic arm may include one or more additional servo motors to move the surgical instrument or laparoscopic camera 104 and/or an end effector on the surgical instrument or laparoscopic camera. One or more control cables 124 may provide signals between the computer 123 in the master controller 122 and the servo motors of the robotic arms 100, 102, 116. The master controller 122 may include a computer 123 to provide signals that control the servo mechanisms of the robotic arms, the surgical instruments, and laparoscopic camera based on the surgeon's input and received feedback from the servo mechanisms.

Figure 2 shows an enlarged view of a portion of Figure 1 including the patient 110 and the robotic arms 100, 102, 116. Figure 3 shows an side view of the robotic arm 116 that supports and moves the laparoscopic camera looking from the patient's left hand side. A schematic cross-section of the patient 110 is shown in the area where the cannula 106 is inserted through an incision 314 in the abdominal wall. The tool shaft 118 of the laparoscopic camera

104 may be seen emerging from the end of the cannula 106 internal to the patient 110. An end effector 300 at the distal end of the tool shaft 118 may provide lenses and light sources. The lenses and light sources may be optically coupled to a camera and lamps through the tool shaft. The camera and lamps may be supported by the robotic arm 116 at a proximal end of the tool shaft.

The robotic arm 116 includes a spherical linkage to support the laparoscopic camera, as will be discussed in greater detail below. The spherical linkage constrains the motion of the insertion axis to rotation about a remote center of spherical rotation 306 which may be located along the length of the cannula 106. By locating the remote center of spherical rotation 306 at or near the incision 314, the insertion axis may be moved without significant lateral motion at the incision.

The end effector 300 is passed through the cannula 106 to the internal surgical site along the insertion axis. The end effector 300 is supported by the tool shaft 118 and coupled to one or more of cameras, lamps, and servo mechanisms through the tool shaft. Translation of the end effector 300 may be accomplished by translation of the laparoscopic camera 104 with the tool shaft 118 and attached end effector.

The end effector 300 may be moved in two additional dimensions by moving the tool shaft 118 about its remote center of spherical rotation 306. The robotic arm 116 will control these two dimensions of motion by moving the tool shaft 118 to change its angular position in space. The motion of the tool shaft 118 may be described in terms of the position of the insertion axis in a spherical coordinate system. A point in space may be specified in terms of two angles and a distance from a center of a spherical coordinate system. It will be appreciated that only the two angles are necessary to specify an insertion axis that passes through the center of the spherical coordinate system.

The robotic arm 116 of the present invention includes a parallel spherical five-bar linkage to move and support the laparoscopic camera 104 such that the tool shaft 118 of the instrument pivots about a remote center of spherical rotation 306 positioned in space along the insertion axis and generally along the length of the cannula 106.

Figure 4A shows a simplified, 2-dimensional schematic diagram of a parallel five-bar linkage 400. This example illustrates the linkage operating in essentially a flat plane. The inventive linkage operates similarly in 3-dimensional space and will be described subsequently. A parallel five-bar linkage is a system of four rigid bars or links 401, 402, 403, 404 pivoted to each other and to a fixed base link 405. The fixed base link may be referred to as the ground link. It is to be understood that the ground link 405 is fixed only in the sense that it provides a

fixed frame of reference for the remaining four links. The ground link 405 may be positioned in space to move the entire five-bar linkage 400.

Each link includes two pivot axes. In the present invention, there is a substantial distance between the two pivot axes on each link. All of the pivot axes 411, 412, 413, 414, 415 are perpendicular to a common surface. The links are coupled at the pivot axes such that the links can rotate relative to each other about the pivot axis at which they are coupled. The rotatable coupling of the links at a pivot axis can take any of a variety of forms that limits the motion of the coupled links to rotation about the pivot axis. A number of axes are described for the parallel spherical five-bar linkage. The term "axis" may be used interchangeably to refer to a "joint" or a "pivot" except for the insertion axis.

The ground link 405 provides two inboard axes 412, 413. An inboard link 401, 404 is pivotally coupled to each of the inboard axes 413, 412. Each inboard link 401, 404 has an intermediate axis 414, 411 spaced apart from the inboard axis 413, 412. Each inboard link 401, 404 is pivotally coupled to an outboard link 402, 403 at the intermediate axis 414, 411. Each outboard link 402, 403 has an outboard axis 415 spaced apart from the intermediate axis 414, 411. The two outboard links 402, 403 are pivotally coupled together at the outboard axis 415. The outboard axis 415 can be positioned perpendicular to the common surface (in this 2-dimensional illustrative example) anywhere within its range of motion thus providing an endpoint motion at the outboard axis 415 with two degrees of freedom. If motors are provided to rotate each of the inboard links 401, 404 about their inboard axis 413, 412, as suggested by the arrows, the outboard axis 415 may be positioned anywhere within its range of motion by rotating the two inboard links with the motors. Conversely, movement of the outboard axis 415 within its range of motion translates into rotation of the two inboard links 401, 404 about their inboard axis 413, 412.

A linkage that couples rotation of two ground-referenced independent links with two dimensional movement of an axis is a parallel linkage. The rotary motion provided by the two motors to the two inboard links may be described as parallel rotary motion inputs. It should be noted that "parallel" is used here to indicate two inputs that are provided independently of one another and not in the geometric sense to indicate the direction of the inputs. In a parallel linkage, the two independent parallel inputs act upon the same body at some distal point where links coupled to the inputs join to drive the same object or link.

It will be appreciated that there are two possible positions for each of the inboard links 401, 404 in a five-bar linkage for most of the possible positions of the outboard axis. For example, the inboard links 401, 404 could also be positioned as indicated by the dashed lines

401', 404'. These positions for the inboard links are generally considered undesirable because the distance between the intermediate axes 414', 411' is reduced and the angle between the outboard links 402', 403' is reduced. It is normally desirable to maximize the distance between the intermediate axes to provide a broad base of support for the outboard axis 415. It is also normally desirable to have the outboard links 402', 403' as close to being at right angles to one another as possible to support the outboard axis 415. While the conventional configuration of a five-bar linkage provides good structural support for the outboard axis 415, the resulting structure requires a substantial amount of space in which to move. The alternative configuration as indicated by the links 401', 402', 403', 404' drawn with dashed lines occupies a smaller area (as projected onto the plane) and is therefore a more compact mechanical configuration.

Figure 4B shows the parallel five-bar linkage 400 after the inboard links 401, 404 have been rotated in a counter-clockwise direction. It may be seen that the outboard axis 415 has been moved generally to the left by the rotation of the inboard links 401, 404. The same position of the outboard axis 415 may also be produced by a similar rotation of the inboard links 401', 404' when the parallel five-bar linkage 400 is in the compact mechanical configuration illustrated by the dashed lines.

A spherical linkage for the purposes of this description is a 3-dimensional version of the 2-dimensional mechanical linkage described above. In the 3-dimensional linkage, all pivot axes pass through a common remote center of spherical rotation. "Pass through" includes axes that may be slightly displaced (due to slight errors in manufacturing of the physical links, for example) from the remote center of spherical rotation to accommodate the structural limitations of the robotic arm where the displacement is small enough that the linkage has substantially the same kinematics (characteristic motions) as if the axes actually included the precise, theoretical remote center of spherical rotation. Note that axes that pass through a remote center of spherical rotation are also perpendicular to a spherical surface centered on the remote center of spherical rotation.

Figure 5 shows a schematic diagram of a parallel spherical five-bar linkage 500. As with the previously discussed planar five-bar linkage, the parallel spherical five-bar linkage 500 is a system of four rigid links 501, 502, 503, 504 pivoted to each other and to a fixed base or ground link 505. When a parallel five-bar linkage is constructed in a spherical form, all of the pivot axes 511, 512, 513, 514, 515 are perpendicular to a common spherical surface and therefore pass through a remote center of spherical rotation 520 of the common spherical surface. In particular, the outboard axis 515 will always pass through the remote center of spherical rotation 520 within its range of motion. Thus, a parallel spherical five-bar linkage 500 provides the

desired constrained motion for a surgical instrument such that the tool shaft of the instrument pivots about a remote center of spherical rotation when supported and moved by the outboard axis 515 of the linkage 500. The motors to move the surgical instrument are placed at the inboard axes 513, 512 of the ground link 505. This avoids the need to move one motor with the other motor as might be required if a serial arm mechanism were used.

As shown schematically in Figure 6A, it has been discovered that a parallel spherical five-bar linkage 600 can be constrained so that the intermediate axes 614, 611 do not assume the conventional configuration where the intermediate axes are at their maximum possible separation and, surprisingly, provide good structural support for the outboard axis 615. This results in a more compact configuration that is better suited for use as a robotic arm to support an endoscopic camera where it is often necessary to have other robotic arms in close proximity within a limited amount of space as shown by the exemplary system in Figures 1 and 2.

The parallel spherical five-bar linkage 600 shown schematically includes a ground link 605, two inboard links 601, 604 pivotally coupled to the ground link, and two outboard links 602, 603 pivotally coupled to each other at one end and to the two inboard links 601,604 respectively at an opposite end. The first inboard link 601 is pivotally coupled to the ground link 605 at a first axis of rotation 613. The first inboard link 601 further includes a first intermediate axis 614 at a first distance from the first axis of rotation 613. A first outboard link 602 is pivotally coupled to the first inboard link 601 at the first intermediate axis 614. The first outboard link 602 has an outboard axis 615 at a second distance from the first intermediate axis 614.

The second inboard link 604 is pivotally coupled to the ground link at a second axis of rotation 612. The second inboard link 604 has a second axis of rotation 612 that is separated from the first axis of rotation 613 by a fourth distance. The second inboard link 604 further includes a second intermediate axis 611 at a fifth distance from the second axis of rotation 612. A second outboard link 603 is pivotally coupled to the second inboard link 604 at the second intermediate axis 611 and to the first outboard link 602 at the outboard axis 615. The outboard axis 615 is at a sixth distance from the second intermediate axis 611.

A mechanical stop may limit the rotation of the outboard links 602, 603 about the outboard axis 615 such that a minimum angle is maintained between the outboard links, perhaps a minimum angle in the range of 15 to 30 degrees. The links are assembled and constrained such that when the outboard axis 615 lies in a plane 622 that is the perpendicular bisector of the line segment from the first axis of rotation 613 to the second axis of rotation 612, each of the inboard links 601, 604 intersects 624 the bisecting plane 622. (The double dashed lines are

intended to suggest an edge of the portion of the imaginary bisecting plane 622 in the vicinity of the linkage 600. The dashed circle indicates the point of intersection between each of the inboard links 601, 604 and the bisecting plane 622, which is at the same place for the configuration and pose shown.) When an inboard link intersects the bisecting plane, the axis of rotation and the intermediate axis will lie on opposite sides of the plane. It will be appreciated that this requires the inboard links 601, 604 to be able to cross over one another.

A specific position assumed by a robotic arm may be referred to as a pose. Placing a robotic arm in a specific position may be referred to as posing the robotic arm. The parallel spherical five-bar linkage may be limited in its motion such that the two intermediate axes 614, 611 are relatively close together compared to the maximum separation possible for any given pose of the robotic arm 600. In particular, each inboard link 601, 604 may be in one of two positions for a given position of the outboard axis 615, except for the singularities where the axis of rotation 612, 613, the intermediate axis 611, 614, and the outboard axis 615 are coplanar. One of the two positions for each of the two inboard links 601, 604 will provide the maximum distance between the intermediate axes 611, 614. The pose where each of the two inboard links 601, 604 is in the other of the two positions will be described as the compact pose. It will be appreciated that this always results in less than the maximum distance between the intermediate axes 611, 614 although it may not result in the minimum possible distance. If the outboard links are constrained to maintain at least a minimum angle between the outboard links and the parallel five-bar spherical linkage is assembled in a compact pose, then the linkage will be limited to a range of compact poses.

Figure 6B shows the parallel spherical five-bar linkage 600 after one of the inboard links 601 has been rotated in a counter-clockwise direction. It may be seen that the outboard axis 615 has been moved generally to the left by the rotation of the inboard link 601. It may also been seen that points on the outboard axis 615 are constrained to move on a spherical surface. In the pose shown in Figure 6B neither of the two inboard links 601, 604 intersect the bisecting plane 622. It will be observed that the linkage 600 retains the compact configuration even though it has moved away from the pose where the outboard axis 615 lies in a plane 622 that is the perpendicular bisector of the line segment from the first axis of rotation 613 to the second axis of rotation 612.

Referring now to Figure 7A, the inboard links 701, 704 and the outboard links 702, 703 are illustrated for the embodiment shown in Figures 1-3. The ground link, which is provided by a motor assembly, is not shown in Figure 7 to allow the relationship between the four moving links to be better seen. The two inboard links 701, 704 each can rotate about one of the axes of

rotation 713, 712. Each inboard link 701, 704 is pivotally coupled to an outboard link 702, 703 at an intermediate axis 711, 714. The two outboard links 702, 703 are pivotally coupled together at an outboard axis 715. The outboard axis 715 may also be the insertion axis on which the cannula (not shown) is centered.

In some embodiments, the first axis 713 and second axis 712 of rotation are driven by motors connected to a controller that provides signals to the motors. A first motor may rotate the first inboard link 701 and a second motor may rotate the second inboard link 704. The controller may limit the motion of the links so that the parallel five-bar spherical linkage is limited to a range of compact poses. The controller may limit the motion of the inboard links 701, 704 such that each of the inboard links 701, 704 intersects a perpendicular bisecting plane of the line segment from the first axis of rotation 713 to the second axis of rotation 712 when the outboard axis 715 lies in the bisecting plane. When an inboard link intersects the bisecting plane, the axis of rotation and the intermediate axis will lie on opposite sides of the bisecting plane. The controller may also limit the rotation of the inboard links 701, 704 such that a minimum angular distance is maintained between the intermediate axes 711, 714, perhaps a minimum angular distance in the range of 15 to 30 degrees. The controller can provide the same constraint on the range of motion of the links 701-704 as a mechanical stop that limits the angle between the outboard links 702, 703 at the outboard axis 715.

The parallel spherical five bar linkage may be used to move the outboard axis 715 to a desired position by controllably rotating the inboard links 701, 704, such as by use of a servo motor or stepper motor. Figure 7B illustrates the parallel spherical five bar linkage after one of the inboard links 701 has been rotated in a counter-clockwise direction. The poses of the parallel spherical five bar linkage shown in Figures 7A and 7B are generally similar to the poses of the parallel spherical five bar linkage shown schematically in Figures 6A and 6B respectively.

In another embodiment, the parallel spherical five bar linkage may be used to sense a position of the outboard axis by determining the bearings of the two inboard axes that result from manipulation of the outboard axis. For example, rotary encoders, or other sensors, may be placed at the first 713 and second 712 axis of rotation of the parallel spherical five bar linkage illustrated by Figure 7. The controller may be replaced by a computer coupled to the two rotary encoders to receive the bearing of each of the inboard links 701, 704. The computer may then compute the position of the outboard axis, which may be manipulated by an operator to provide a position input. It will be appreciated that the outboard axis is constrained to rotate about the remote center of spherical rotation 720 of the spherical linkage. Thus, the parallel spherical five bar linkage may also be used in the control console 122 of Figure 1 to receive position input for

the outboard axis 715 from the surgeon 120. The position input will have the same constrained motion as the outboard axis of the robotic arm 116.

Referring now to Figures 8, 9, 10, 11, and 12, orthogonal views are shown for four sides and an end of the robotic arm 116 used to support the laparoscopic camera in the same pose as shown in Figures 1-3. Figure 8 is a first side view. Figure 9 is a bottom view. Figure 10 is a second side view of the side opposite the first side. Figure 11 is a top view. Figure 12 is a view of the end that is to the right in Figures 8-11.

Figures 8-12 show a robotic arm 116 that embodies the invention. The robotic arm includes a motor assembly 800 that serves as a ground link and four movable links 701, 702, 703, 704 to provide a parallel spherical five bar linkage. The relationship of the four movable links was discussed above in connection with Figure 7. The motor assembly 800 provides two rotatable shafts 802, 804. Each of the rotatable shafts is coupled to one of the two inboard links 701, 704 at one of the axes of rotation 713, 712 (shown in Figure 7). A cannula 106 is supported by the two outboard links 702, 703 in a position that is coaxial with the outboard axis 715 (shown in Figure 7). In this embodiment, the outboard axis 715 is coincident with the insertion axis for the tool shaft of an endoscopic camera.

Figure 13 shows the robotic arm 116 of Figure 12 with the two outboard links 702, 703 removed so that the relationship between the motor assembly 800 and the two inboard links 701, 704 can be seen. The motor assembly 800 and the two inboard links 701, 704 are shaped and coupled in a configuration that allows the two inboard links to pass over one another and the motor assembly. It may be seen that the two rotatable shafts 802, 804 emerge from the motor assembly 800 in substantially opposite directions in this embodiment. The two rotatable shafts 802, 804 may be driven by motors coupled to the shafts through right angle drives, such as a worm and helix drive.

One inboard link 701 moves within a spherical "shell" that is closer to the center of spherical motion than the motor assembly. The other inboard link 704 moves within a spherical "shell" that is further from the center of spherical motion than the motor assembly. The motor assembly 800 lies between these two spherical "shells." Thus one pair of links passes the motor assembly to the inside and the other pair of links passes to the outside.

Figure 14 shows the robotic arm 116' of Figure 9 in a pose with the outboard axis 806 close to the motor assembly 800. (The motor assembly 800 is drawn as though transparent as suggested by the dashed lines to allow the configuration of the movable links 701', 702', 703', 704' to be seen.) One inboard link 701', which is coupled to a first rotatable shaft 802 that extends toward the remote spherical center, and the coupled outboard link 702' have passed to

the inside of the motor assembly 800. These links lie between the motor assembly 800 and the remote spherical center. The other inboard link 704', which is coupled to a second rotatable shaft 804 that extends away from the remote spherical center, and the coupled outboard link 703' have passed to the outside of the motor assembly 800. The motor assembly 800 lies between these links and the remote spherical center.

Figure 15 shows another robotic arm 1500 that embodies the invention. The motor assembly includes two motors 1502, 1504 that are coupled by a support 1506 at a substantial distance from the two axes of rotation 1508, 1510. The motor assembly provides the ground link for the parallel spherical five bar linkage. This configuration of the support 1506 may permit the outboard axis 1512, which may also be the axis for the cannula 1514, to pass between the two axes of rotation 1508, 1510 and the two motors 1502, 1504 to provide a greater range of motion.

Figure 16 shows still another robotic arm 1600 that embodies the invention. The motor assembly includes two motors 1602, 1604 that are coupled by a support 1606 to provide the ground link for the parallel spherical five bar linkage. The two axes of rotation 1608, 1610 may coincide with axes of the two motors 1602, 1604 such that a right angle drive is not required. At least one of the inboard links 1614 has an angular length that is substantially less than the angular distance between the two axes of rotation 1608, 1610. This permits the inboard link 1614 to the motor 1604 that is coupled to the other inboard link 1616. The other inboard link 1616 may or may not have an angular length that is substantially less than the angular distance between the two axes of rotation 1608, 1610 as it may be configured to pass to the inside of the motor 1602, between the motor and the remote spherical center, that is coupled to the shortened inboard link 1614.

Figure 17 shows a schematic representation of a robotic arm 1700 that is similar to the robotic arm 1600 shown in Figure 16. A first pair of inboard and outboard links 1701, 1702 are pivotally coupled at a first intermediate axis 1714. A second pair of inboard and outboard links 1704, 1703 are pivotally coupled at a second intermediate axis 1711. The two outboard links 1702, 1703 are pivotally coupled at an outboard axis 1715. One of two motors 1733, 1734 is coupled to each of the inboard links 1701, 1704 to rotate the inboard link about an axis of rotation 1713, 1712. The two motors are coupled by a ground link 1705 to complete the parallel spherical five-bar linkage.

It may be observed that the first pair of inboard and outboard links 1701, 1702 may be constructed so that they move within a first spherical shell 1736. The second pair of inboard and outboard links 1704, 1703 move within a second spherical shell 1738 that is not shared with the first spherical shell 1736 except in the vicinity of the outboard axis 1715. This arrangement

permits the inboard links 1701, 1704 to cross over one another. The inboard links 1701, 1704 in this arrangement may also pass to the inside, closer to the remote center of spherical rotation 1720, of the ground link 1705 that couples the two motors 1733, 1734 if the ground link lies outside the second spherical shell 1738.

The arrangement of the linkage 1700 has the further characteristic that when the first inboard link 1701 lies in the same plane as the ground link 1705 as shown, a first directional vector 1721 from the first axis of rotation 1713 to the first intermediate axis 1714 has the same direction as a second directional vector 1722 from the first axis of rotation 1713 to the second axis of rotation 1712. Likewise, when the second inboard link 1704 lies in the same plane as the ground link 1705, a third directional vector 1723 from the second axis of rotation 1712 to the second intermediate axis 1711 has the same direction as a fourth directional vector 1724 from the second axis of rotation 1712 to the first axis of rotation 1713.

Figure 18 shows a schematic representation of a robotic arm 1800 that is similar to the robotic arm 116 as shown in Figure 11. A first pair of inboard and outboard links 1801, 1802 are pivotally coupled at a first intermediate axis 1814. A second pair of inboard and outboard links 1804, 1803 are pivotally coupled at a second intermediate axis 1811. The two outboard links 1802, 1803 are pivotally coupled at an outboard axis 1815. One of two motors 1833, 1834 is coupled to each of the inboard links 1801, 1804 to rotate the inboard link about an axis of rotation 1813, 1812. The two motors are coupled by a ground link 1805 to complete the parallel spherical five-bar linkage.

In the arrangement shown in Figure 18, the ground link 1805 is between the two inboard links 1801, 1804 when all three links are in the same plane. The first pair of inboard and outboard links 1801, 1802 may move within a first spherical shell 1836. The second pair of inboard and outboard links 1804, 1803 may move within a second spherical shell 1838 that is not shared with the first spherical shell 1836 except in the vicinity of the outboard axis 1815. If the ground link is within a third spherical shell 1837 that lies between the first and second spherical shells, then the inboard links 1801, 1804 may cross over one another and also cross over the ground link. The arrangement of the linkage 1800 has the same directionality characteristic when the inboard links 1801, 1804 lie in the same plane as the ground link 1805 as discussed above for the linkage 1700 shown in Figure 17.

In the arrangement shown in Figure 18, the axes of the motors 1833, 1834 may be perpendicular to the axes of rotation 1813, 1812. This may be done to allow all or part of the motors to be within the third spherical shell 1837 over which the inboard links 1801, 1804 may pass. A drive shaft 1840, 1842 may couple the motors 1833, 1834 to inboard links 1801, 1804

by means of a right angle drive 1844, 1846. In other embodiments, the drive shaft may be coupled to the motors in other arrangements or be a coaxial extension of the motor shaft. The end of the drive shaft 1840, 1842 coupled to the motors 1833, 1834 may be described as the driven end. In the arrangement shown, it may be observed that a first drive shaft 1840 extends from the driven end toward the remote center of spherical rotation 1820 and a second drive shaft 1842 extends from the driven end away from the remote center of spherical rotation 1820.

Figure 19 shows a parallel spherical five-bar linkage 1900 that embodies the invention with a structure similar to the robotic arm 116 shown in Figures 7-12. Figure 20 shows a schematic view of the parallel spherical five-bar linkage 1900 of Figure 19. Five pivot axes 1911-1915, about which the four movable links 1901-1904 rotate, all pass through a common remote center of spherical rotation 1920. The first inboard link 1901 and the second inboard link 1904 may be coupled to motors that can rotate the inboard links about the first 1913 and second 1912 axes of rotation. The two motors may be coupled together to form the fifth link (not shown), which is the ground link.

The movable links 1901, 1902, 1903, 1904 are shown as having a generally arcuate form. It will be appreciated that the links may have any desired form without affecting the function of the invention. The linkage will function as a spherical linkage as long as the axes of the pivoted connections 1921, 1922, 1923, 1924, 1925 all pass substantially through a common remote center of spherical rotation 1920. Any of the links may have an irregular shape, which may include arcuate segments, to accommodate placement of the pivoted connections such that the links and pivots can pass one another. It will be appreciated that the form of the links is unimportant as long as they support the pivot axes such that they pass substantially through the remote center of spherical rotation 1920.

In the compact configuration of the inventive parallel spherical five bar linkage, it may be desirable to configure the linkage such that the first pair of links 1901, 1902 coupling the first axis of rotation 1913 to the outboard axis 1915 can freely pass the second pair of links 1904, 1903 coupling the second axis of rotation 1912 to the outboard axis 1915. Since the only requirement of the parallel spherical five-bar linkage is that all the pivot axes pass substantially through the common remote center of spherical rotation 1920, the first pair of links 1901, 1902 and the first intermediate pivot 1914 may be configured so that a first volume swept out by the first pair does not intersect a second volume swept out by the second pair of links 1904, 1903 and the second intermediate pivot 1911. The only connections between the first and second volumes are in the vicinity of the outboard axis 1915 and the ground link 1905. The form of the

links in the embodiment illustrated by Figures 19 and 20 are an example of a configuration that permits the first pair of links 1901, 1902 to pass the second pair of links 1904, 1903.

Figure 21 shows another embodiment of a parallel spherical five-bar linkage 2100 for a robotic arm including two inboard links 2101, 2104, two outboard links, and a ground link provided by the motor assembly 2105. In comparison with the linkage 1900 of Figure 19, the parallel spherical five-bar linkage 2100 includes an outboard link 2103 having an insertion axis 2119 that is spaced apart from the outboard axis 2115 by an offset distance. Ideally the insertion axis 2119 is coincident with the outboard axis 2115. Mechanical packaging advantages can be obtained, however, by separating the insertion axis 2119 from the outboard axis 2115.

Preferably the insertion axis 2119 will be placed on the outboard link 2103 further from the intermediate axis 2111 than the outboard axis 2115. As long as the insertion axis 2119 is perpendicular to the surface of the sphere centered on the remote center of spherical rotation 2120 and therefore passes through the remote center of spherical rotation 2120, then the insertion axis will have the same kinematic characteristics as the pivot axes 2111-2115 of the parallel spherical five-bar linkage 2100. That is, the insertion axis 2119 will move relative to the remote center of spherical rotation 2120. The insertion axis 2119 may or may not lie in the plane defined by the intermediate axis 2114 and the outboard axis 2115.

The placement of the insertion axis 2119 outboard from the pivot axes of the parallel spherical five-bar linkage may allow the endoscopic camera (not shown) to be supported and manipulated without interfering with the motion of the linkage 2100. It may also simplify the construction, installation, removal, and sterile boundary construction of the cannula 2106 and its associated mechanical attachment means.

In some embodiments having a spaced apart insertion axis, such as the one illustrated in Figure 21, the insertion axis 2119, the outboard axis 2115, and the intermediate axis 2111 may be coplanar. This arrangement may simplify the relationship between the positions of the two inboard links 2101, 2104 and the position of the outboard axis 2115. Note that the insertion axis 2119 can be placed on either of the two outboard links 2102, 2103.

The parallel spherical five-bar linkage of the invention may be described using spherical geometry, which is a plane geometry on the surface of a sphere. While the links of the inventive linkage need not lie of the same spherical surface, or any spherical surface, they can be projected onto a common spherical surface for the purpose of describing the linkage. In spherical geometry, distances may be measured as angles because the geometric relationships on the spherical surface are unaffected by changing the radius of the sphere. Angular distance remains the same regardless of the radius of the sphere.

Navigation on the surface of the Earth is a common example of spherical geometry. Latitude and longitude as used in global navigation are a familiar system for describing locations and directions in a spherical system. The equator defines the points at 0° latitude. The north pole defines 90° latitude and the south pole defines -90° latitude. Longitude is the angular distance on a circle of constant latitude from an arbitrarily defined line of 0° longitude. Longitude is conventionally expressed as being in the range 180° west to 180° east of the 0° longitude line. Bearings are lines of direction from a point expressed as the angle between the bearing and a line of direction to the north pole. Westerly bearings can be expressed as positive angles and easterly bearings can be expressed as negative angles. The following is a description of an embodiment of the invention expressed in terms of a spherical geometry.

Referring again to Figure 6, the first axis of rotation 613 of the first inboard link 601 will be considered as being at 0° latitude and 0° longitude. The second axis of rotation 612 of the second inboard link 604 is shown as being at the same latitude and at a positive (easterly) longitude. The second axis of rotation 612 may be at a fixed position of 55° longitude and 0° latitude, for example. Thus, in this example the ground link has an angular length of 55°. It should be remembered that a fixed position means fixed within the frame of reference of the spherical geometry of the linkage and that the entire linkage with its frame of reference may be freely positioned in space.

All of the movable links 601-604 may have the same angular length as the ground link. For example, the first intermediate axis 614 may be spaced apart from the first axis of rotation 613 by 55°. The first outboard axis 615 may be spaced apart from the first intermediate axis 614 by 55°. The insertion axis 619 may be spaced apart from the outboard axis 615 by 30°. The second intermediate axis 611 may be spaced apart from the second axis of rotation 612 by 55°. The second intermediate axis 611 may be spaced apart from the outboard axis 615 by 55°.

The range of rotation of the inboard links 601, 604 about the axes of rotation 613, 612 may constrained such that a minimum angle of 15° is maintained between the outboard links 602, 603, for example. The range of rotation of the inboard links 601, 604 may further constrained such that when the outboard axis 615 has a longitude of 27.5°, for example, the first inboard link 601 has a negative (easterly) bearing and the second inboard link 604 has a positive (westerly) bearing. The line segment that most directly connects the axis of rotation 613, 612 to the intermediate axis 614, 611 on the common spherical surface will cross the longitude line of the outboard axis 615 for both of the inboard links. Thus, the inboard links will cross one another when the outboard axis is at or near the center of its east-west range of motion. The

constraints on the rotation of the inboard links prevents them from uncrossing when the outboard axis is in the central portion of its east-west range of motion.

These dimension are merely by way of example. The invention may be practiced with linkages having substantially different dimensions and substantially different ranges of motion. The invention is only limited by the claims. It may be desirable to use different dimensions and different ranges of motion to adapt the invention for needs of particular types of surgeries which have particular requirements for the range of motion of the insertion axis and for the space occupied by the device through its range of motion.

It is to be understood that the inventive parallel spherical five-bar linkage may be embodied in both powered and unpowered configurations. In powered embodiments, devices such as servo motors rotate the inboard links. The parallel spherical five-bar linkage translates those rotations into two dimensional movement of the outboard axis. In unpowered embodiments, two dimensional movement of the outboard axis is translated by the parallel spherical five-bar linkage into rotations of the inboard links. Devices such as rotary encoders may sense the bearings of the inboard links and that information may be used to compute the position of the outboard axis. Constraining the rotation of an intermediate axis as previously described is advantageous in unpowered embodiments because the constraint limits the position of the outboard axis to one of the two possible positions that correspond to the bearings of the inboard links.

While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and not restrictive on the broad invention, and that this invention not be limited to the specific constructions and arrangements shown and described, since various other modifications may occur to those ordinarily skilled in the art. Instead, the embodiments of the invention should be construed according to the claims that follow below.

CLAIMS

What is claimed is:

1. A robotic arm including a parallel spherical five-bar linkage with a remote center of spherical rotation, the robotic arm comprising:
an endoscopic camera;
two outboard links pivotally coupled together, at least one of the two outboard links to support the endoscopic camera;
two inboard links respectively pivotally coupled to the two outboard links such that the two inboard links are able to cross over one another, the two inboard links to moveably support the two outboard links; and
a ground link pivotally coupled to the two inboard links, the ground link to moveably support the two inboard links.

2. The robotic arm of claim 1, further including
two motors coupled by the ground link in spaced apart positions, each of the two motors respectively coupled to one of the two inboard links to rotate the coupled inboard link and thereby move the endoscopic camera about the remote center of spherical rotation.

3. The robotic arm of claim 2, wherein
each of the two motors is respectively coupled to one of the two inboard links by a right angle drive.

4. The robotic arm of claim 2, further including
a first drive shaft coupled to one of the two motors at a driven end and to one of the two inboard links at an opposite end, the first drive shaft extending from the driven end toward the remote center of spherical rotation; and
a second drive shaft coupled to one of the two motors at a driven end and to one of the two inboard links at an opposite end, the second drive shaft extending from the driven end away from the remote center of spherical rotation;
such that each of the two inboard links may cross over the ground link.

5. The robotic arm of claim 2, further including
a controller coupled to the two motors to provide signals to the motors.

6. The robotic arm of claim 5, wherein
the controller limits the rotation of the inboard links such that the robotic arm is limited to a range of compact poses.

7. The robotic arm of claim 1, wherein
the endoscopic camera is movable along an insertion axis passing through the remote center of spherical rotation.

8. The robotic arm of claim 1, wherein
the two outboard links are constrained to have a minimum angle between them.

9. The robotic arm of claim 4, wherein
the minimum angle between the two outboard links is fifteen degrees.

10. The robotic arm of claim 1, wherein
the robotic arm is limited to a range of compact poses.

11. A parallel spherical five-bar linkage with a remote center of spherical rotation, the linkage comprising:
a ground link having two spaced apart axes of rotation;
two inboard links, each inboard link pivotally coupled to the ground link at one of the two axes of rotation, each inboard link having an intermediate axis spaced apart from the axis of rotation;
two outboard links, each outboard link pivotally coupled to one of the inboard links at the inboard link's intermediate axis, the two outboard links pivotally coupled together at an outboard axis that is spaced apart from the intermediate axes; and
a constraint to limit the rotation of the outboard links about the outboard axis such that a minimum angle between the outboard links is at least fifteen degrees;
wherein all axes pass through the remote center of spherical rotation and each of the two inboard links is constrained such that the intermediate axis of the inboard link is disposed to a same side of the axis of rotation of the inboard link as the other axis of rotation when the inboard links lies in the same plane as the ground link.

12. The linkage of claim 11, wherein the constraint further includes a mechanical stop.

13. The linkage of claim 12, wherein the mechanical stop directly limits the rotation of one of the outboard links about the outboard axis relative to the other outboard link.

14. The linkage of claim 11, wherein the ground link and the two inboard links have substantially the same angular length.

15. The linkage of claim 14, wherein the two outboard links have substantially the same angular length.

16. The linkage of claim 14, wherein the two outboard links have substantially the same angular length as the ground link.

17. The linkage of claim 11, wherein the constraint includes:
two motors, each motor coupled to the ground link and to one of the two inboard links at one of the two axes of rotation; and
a controller to cause each of the two motors to rotate the coupled inboard link about one of the two axes of rotation with a limited range of rotation.

18. The linkage of claim 11, wherein the ground link and the two inboard links are constructed and coupled such that each one of the two inboard links and its coupled outboard link can freely pass the ground link and the other of the two inboard links and its coupled outboard link.

19. The linkage of claim 11, further comprising:
two rotary encoders, each rotary encoder coupled to one of the inboard links at its axis of rotation; and
a computer coupled to the two rotary encoders to receive the bearing of each of the inboard links and compute the position of the outboard axis.

20. The linkage of claim 11, wherein one of the outboard links further includes an insertion axis spaced apart from the outboard axis and the intermediate axis, the insertion axis passing through the remote center of spherical rotation.

21. The linkage of claim 11, wherein one of the outboard links further includes an insertion axis coincident with the outboard axis, the insertion axis passing through the remote center of spherical rotation.

22. A robotic arm comprising:
a first motor coupled to a first axis of rotation, the first axis of rotation extending from the first motor toward a remote center of spherical rotation;

a second motor coupled to a second axis of rotation, the second axis of rotation extending from the second motor away from the remote center of spherical rotation;

a ground link coupled between the first axis of rotation and the second axis of rotation;

a first pair of pivotally coupled links having a first end coupled to the first axis of rotation such that the first pair of links can pass a first side of the first and second motors;

a second pair of pivotally coupled links having a first end coupled to the second axis of rotation such that the second pair of links can pass a second side of the first and second motors, the second side of the first and second motors opposite the first side, a second end of the second pair of links pivotally coupled to a second end of the first pair of links;

wherein all joints that pivotally couple links together allow rotation around an axis that passes through the remote center of spherical rotation.

23. The robotic arm of claim 22, wherein one of the first and second pair of links further includes a support for a surgical instrument having a tool shaft with an insertion axis, the insertion axis being spaced apart from the joint that pivotally couples the first and second pair of links, the insertion axis passing through the remote center of spherical rotation.

24. The robotic arm of claim 23, wherein the joint that pivotally couples the first and second pair of links together is between the insertion axis and the first end of the pair of links that includes the support.

25. The robotic arm of claim 23, wherein the insertion axis, a first axis of rotation for the joint that pivotally couples the first and second pair of links together, and a second axis of rotation for the joint that pivotally couples the pair of links that includes the support are coplanar.

26. The robotic arm of claim 22, wherein the first outboard link further includes a support for a surgical instrument having a tool shaft with an insertion axis, the insertion axis being coincident with the outboard axis, the insertion axis including the remote center of spherical rotation.

27. The robotic arm of claim 22, wherein one of the first and second pair of links further includes a support for a surgical instrument having a tool shaft with an insertion axis, the

insertion axis being coincident with an axis of rotation for the joint that pivotally couples the first and second pair of links together, the insertion axis passing through the remote center of spherical rotation.

28. The robotic arm of claim 22, further comprising a constraint to limit the rotation of the links at the joint that pivotally couples the first and second pair of links such that a minimum angle between the links is at least fifteen degrees.

29. The robotic arm of claim 22, further comprising a constraint to limit the rotation of the links at the joint that pivotally couples the first and second pair of links such that a minimum angle between the links is at least thirty degrees.

30. The robotic arm of claim 22, wherein the first motor is coupled to the first axis of rotation at a first angle, and the second motor is coupled to the second axis of rotation at a second angle.

31. The robotic arm of claim 22, wherein the first motor is coupled to the first axis of rotation at a right angle, and the second motor is coupled to the second axis of rotation at a right angle.

32. A robotic arm comprising:

a first inboard link coupled to a first axis of rotation, the first inboard link having a first intermediate axis spaced apart from the first axis of rotation;

a first outboard link pivotally coupled to the first inboard link at the first intermediate axis, the first outboard link having an outboard axis spaced apart from the first intermediate axis;

a second inboard link coupled to a second axis of rotation spaced apart from the first axis of rotation, the second inboard link having a second intermediate axis spaced apart from the second axis of rotation;

a second outboard link pivotally coupled to the second inboard link at the second intermediate axis and to the first outboard link at the outboard axis;

a ground link coupling the first axis of rotation to the second axis of rotation;

a first motor coupled to the first axis of rotation;

a second motor coupled to the second axis of rotation;

wherein the five axes all pass through a remote center of spherical rotation that is spaced apart from all five links; and

a controller to provide signals to the first and second motors to respectively rotate the first inboard link and the second inboard link such that

a first directional vector from the first axis of rotation to the first intermediate axis has the same direction as a second directional vector from the first axis of rotation to the second axis of rotation when the first inboard link lies in the same plane as the ground link, and

a third directional vector from the second axis of rotation to the second intermediate axis has the same direction as a fourth directional vector from the second axis of rotation to the first axis of rotation when the second inboard link lies in the same plane as the ground link.

33. The robotic arm of claim 32, wherein the first outboard link further includes a support for a surgical instrument having a tool shaft with an insertion axis, the insertion axis being spaced apart from the outboard axis and the first intermediate axis, the insertion axis passing through the remote center of spherical rotation.

34. The robotic arm of claim 32, wherein the insertion axis is spaced further apart from the first intermediate axis than the outboard axis is spaced apart from the first intermediate axis.

35. The robotic arm of claim 34, wherein the insertion axis, the outboard axis, and the first intermediate axis are coplanar.

36. The robotic arm of claim 32, wherein the first outboard link further includes a support for a surgical instrument having a tool shaft with an insertion axis, the insertion axis being coincident with the outboard axis, the insertion axis including the remote center of spherical rotation.

37. The robotic arm of claim 32, further comprising a constraint to limit the rotation of the first outboard link about the outboard axis such that a minimum angle between the first outboard link and the second outboard link is at least fifteen degrees.

38. The robotic arm of claim 32, further comprising a constraint to limit the rotation of the first outboard link about the outboard axis such that a minimum angle between the first outboard link and the second outboard link is at least thirty degrees.

39. The robotic arm of claim 32, wherein the first motor is coupled to the first inboard link at a first angle to the first axis of rotation, and the second motor is coupled to the second inboard link at a second angle to the second axis of rotation.

40. The robotic arm of claim 32, wherein the first motor is coupled to the first inboard link at a right angle to the first axis of rotation, and the second motor is coupled to the second inboard link at a right angle to the second axis of rotation.

41. The robotic arm of claim 40, further comprising:

a first drive shaft coupled to the first motor at a driven end and to the first inboard link at an opposite end, the first drive shaft extending from the driven end toward the remote center of spherical rotation; and

a second drive shaft coupled to the second motor at a driven end and to the second inboard link at an opposite end, the second drive shaft extending from the driven end away from the remote center of spherical rotation.

42. A system comprising:

a first robotic arm including a first parallel spherical five-bar linkage having

a ground link;

two motors coupled to the ground link, each motor having an axis of rotation, the two axes of rotation intersecting at a first remote center of spherical rotation,

two inboard links, each inboard link coupled to one of the motors at the motor's axis of rotation, each inboard link having an intermediate axis spaced apart from the motor's axis of rotation, the two intermediate axes passing through the first remote center of spherical rotation, and

two outboard links, each outboard link pivotally coupled to one of the inboard links at the inboard link's intermediate axis, the two outboard links pivotally coupled together at an outboard axis that is spaced apart from the intermediate axes and passing through the first remote center of spherical rotation; and

a controller to cause each of the two motors of the first robotic arm to rotate the respectively coupled inboard links about the motors' axes of rotation such that the two intermediate axes are on the same side of a plane that includes the outboard axis and the axis of rotation of either one of the motors.

43. The system of claim 42, wherein one of the outboard links further includes a surgical instrument having an insertion axis spaced apart from the outboard axis, the insertion axis passing through the first remote center of spherical rotation.

44. The system of claim 43, wherein the insertion axis is spaced further apart from the intermediate axis of the one of the outboard links than the outboard axis is spaced apart from that intermediate axis.

45. The system of claim 44, wherein the insertion axis, the outboard axis, and the intermediate axis of the one of the outboard links are coplanar.

46. The system of claim 42, wherein one of the outboard links further includes a surgical instrument having an insertion axis coincident with the outboard axis, the insertion axis passing through the first remote center of spherical rotation.

47. The system of claim 42, wherein the first robotic arm further includes a mechanical stop to limit the rotation of one of the outboard links about the intermediate axis such that an angle between the motor's axis of rotation, the intermediate axis, and the outboard axis cannot exceed 160 degrees.

48. The system of claim 42, wherein the first robotic arm further includes a mechanical stop to limit the rotation of one of the outboard links about the intermediate axis such that an angle between the motor's axis of rotation, the intermediate axis, and the outboard axis cannot exceed 120 degrees.

49. The system of claim 42, wherein the two axes of rotation are spaced apart on the ground link.

50. The system of claim 42, wherein the two axes of rotation are coincident on the ground link.

51. The system of claim 42, further comprising a second robotic arm including a second parallel spherical five-bar linkage having:

two motors, each motor having an axis of rotation, the two axes of rotation intersecting at a second remote center of spherical rotation,

two inboard links, each inboard link coupled to one of the motors at the motor's axis of rotation, each inboard link having an intermediate axis spaced apart from the

motor's axis of rotation, the two intermediate axes passing through the second remote center of spherical rotation, and

two outboard links, each outboard link pivotally coupled to one of the inboard links at the inboard link's intermediate axis, the two outboard links pivotally coupled together at an outboard axis that is spaced apart from the intermediate axes and passing through the second remote center of spherical rotation;

the controller to further cause each of the two motors of the second robotic arm to rotate the respectively coupled inboard links about the motors' axes of rotation such that the two intermediate axes are on the same side of a plane that includes the outboard axis and one of the axes of rotation, and further such that the two intermediate axes of the second robotic arm are on the opposite side of the plane as they would be for the first robotic arm.

52. A robotic arm for a minimally invasive surgical system, the robotic arm comprising:

a parallel five-bar spherical linkage having a range of compact poses, the parallel five-bar spherical linkage to spherically rotationally move a robotic surgical tool coupled to the parallel five-bar spherical linkage about a remote center of spherical rotation; and

a constraint coupled to the robotic arm, the constraint to limit the parallel five-bar spherical linkage to the range of compact poses.

53. The robotic arm of claim 52, wherein

the robotic arm includes a first motor and a second motor to provide two parallel rotary motion inputs to the parallel five-bar spherical linkage; and

the constraint is a controller coupled to the first motor and the second motor to control the parallel five-bar spherical linkage to maintain the range of compact poses.

54. The robotic arm of claim 52, wherein

the parallel five-bar spherical linkage has an outboard joint, and

the constraint includes a mechanical stop coupled to the an outboard joint to limit the parallel five-bar spherical linkage to the range of compact poses.

55. The robotic arm of claim 52, wherein

the robotic arm further includes a ground link;

the first pair of links is coupled at a first end of the first pair of links to the ground link;

the second pair of serial pivotally coupled links is coupled at a first end of the second pair of links to the ground link; and

a second end of the first pair of links and a second end of the second pair of links are coupled together at an outboard joint.

56. The robotic arm of claim 52, wherein

the first pair of links and the second pair of links have arcuate shapes lying on a plurality of spheres of differing radii.

57. The robotic arm of claim 52, wherein

the constraint provides clearance for other surgical equipment around the robotic arm.

58. The robotic arm of claim 52, wherein

the parallel five-bar spherical linkage has a ground link to couple to a table to support the robotic arm over a patient.

59. The robotic arm of claim 58, further comprising:

a set-up arm coupled between the parallel five-bar spherical linkage and the table to support the robotic arm over a patient.

60. A method for a robotic arm in a minimally invasive surgical system, the method comprising:

posing a parallel five-bar spherical linkage into a compact pose;

moving the parallel five-bar spherical linkage with a spherical motion about a remote center of spherical rotation; and

constraining the spherical motion of the parallel five-bar spherical linkage within a range of compact poses.

61. The method of claim 60, wherein

points of the parallel five-bar spherical linkage move over differing spherical surfaces to spherically move the parallel five-bar spherical linkage.

62. The method of claim 60, wherein

the method further includes

coupling a link of the parallel five-bar spherical linkage to a table to support the robotic arm over a patient.

63. The method of claim 60, further comprising:

coupling a link of the parallel five-bar spherical linkage to a table with a set-up arm to support the robotic arm over a patient.

64. The method of claim 60, wherein

the robotic arm has a first motor and a second motor coupled to the parallel five-bar spherical linkage, and

in constraining the spherical motion of the parallel five-bar spherical linkage within the range of compact poses, controlling the first motor and the second motor to constrain the spherical motion of the parallel five-bar spherical linkage within the range of compact poses.

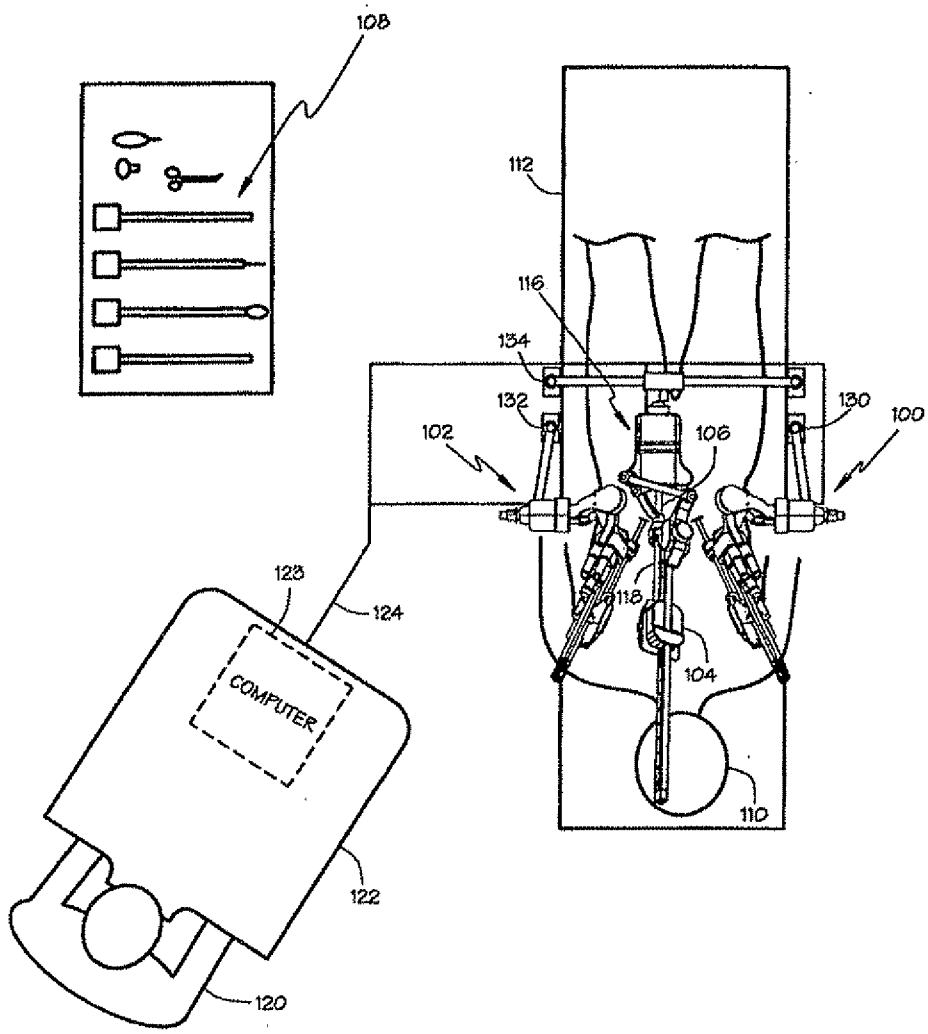

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120

FIG. 1

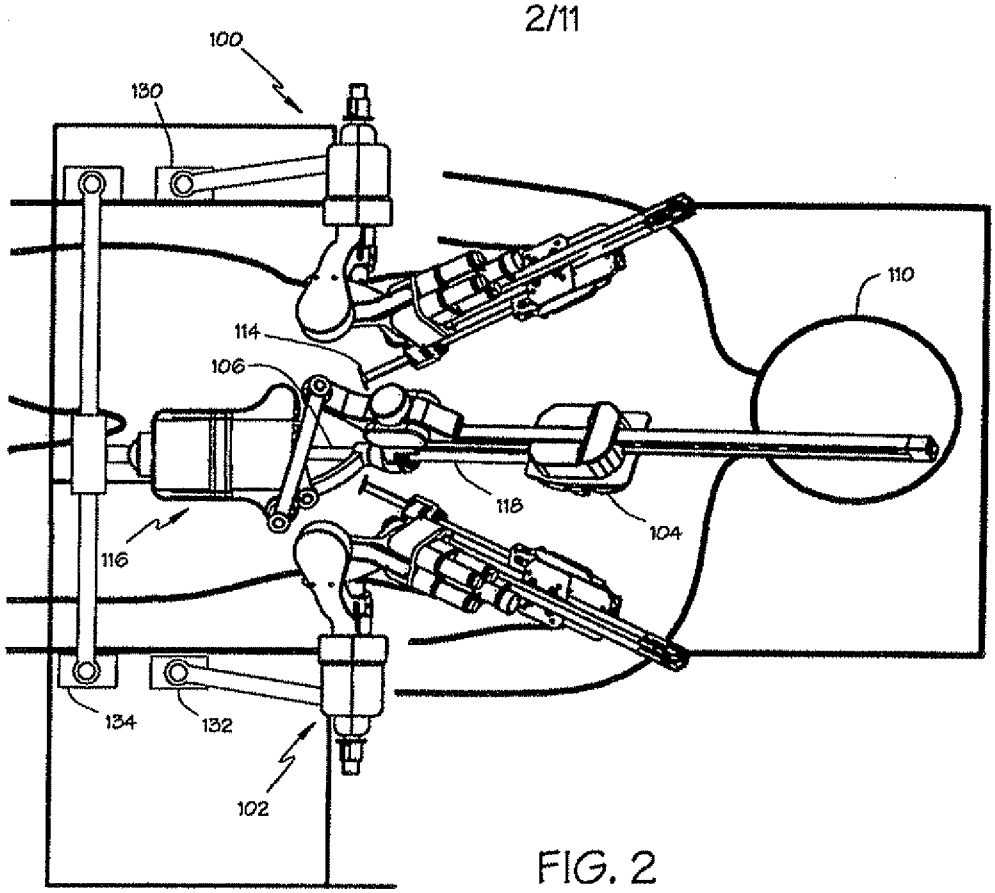

100
130
110
114
106
118
104
116
134
132
102

FIG. 2

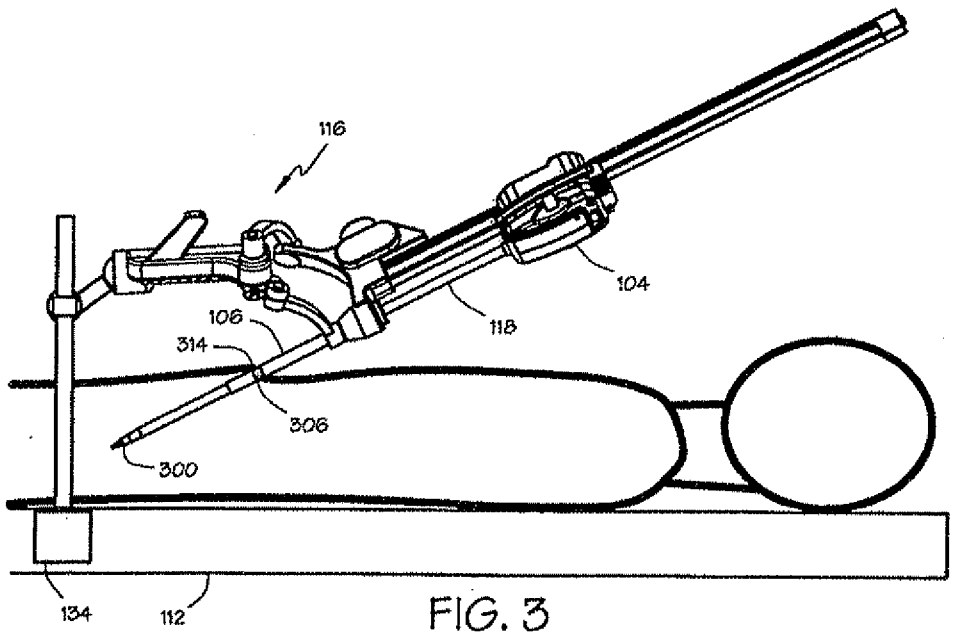

116
104
106
118
314
306
300
134
112

FIG. 3

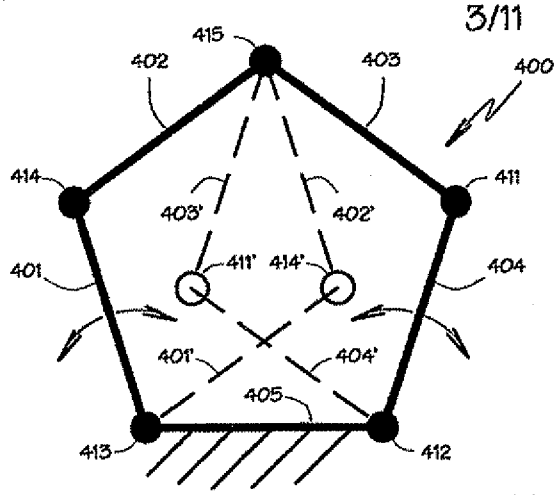


FIG. 4A

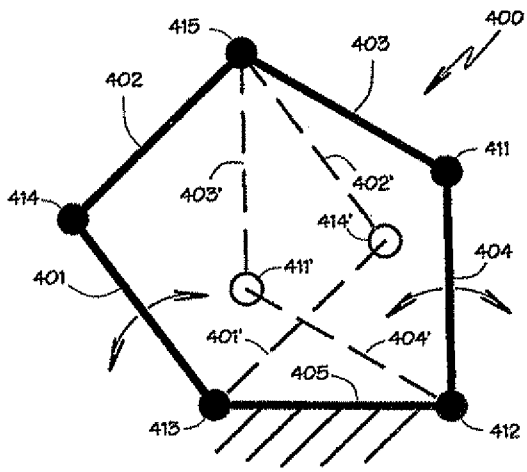


FIG. 4B

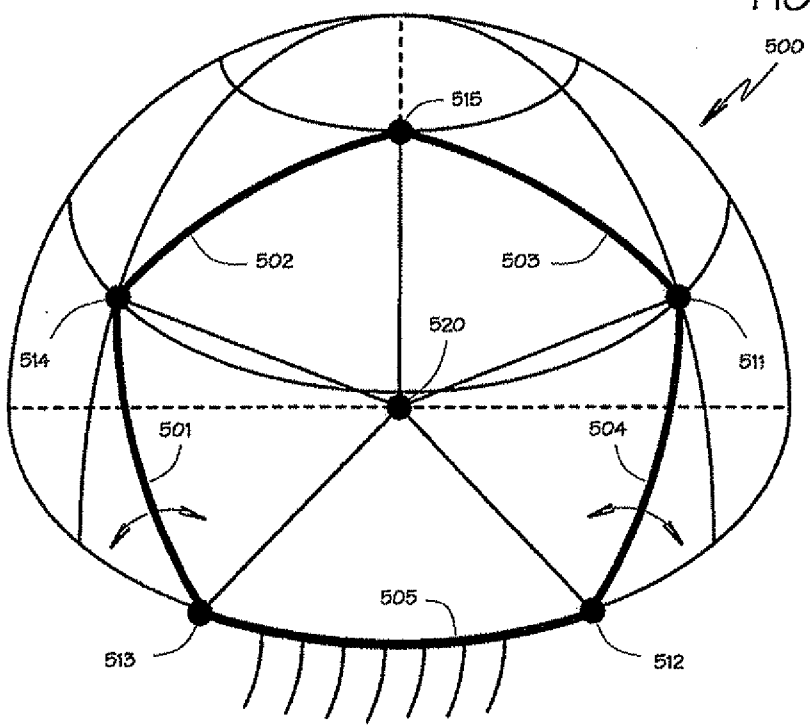


FIG. 5

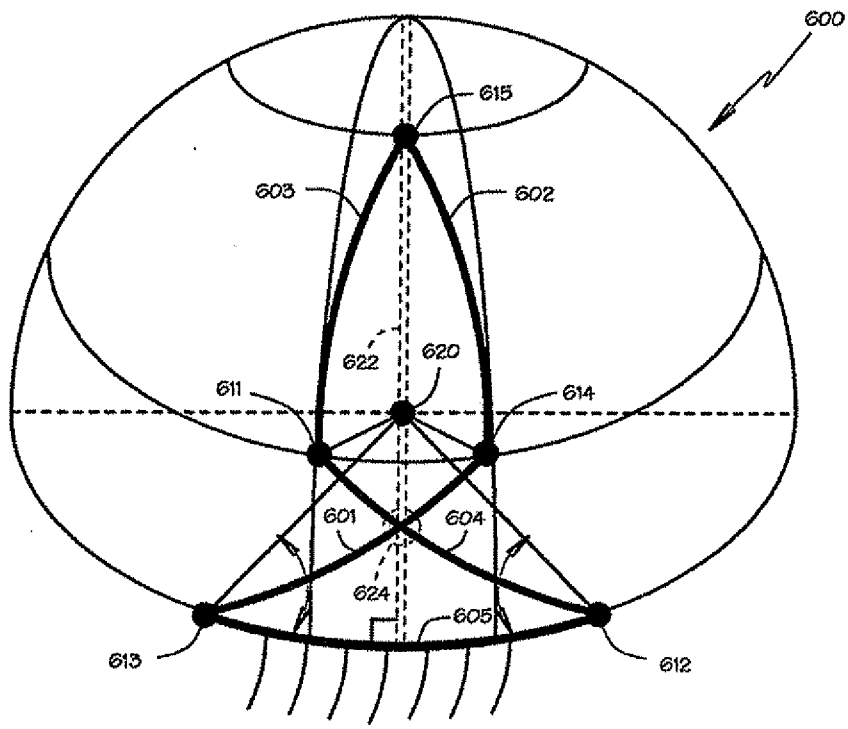

600
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622
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605
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612

FIG. 6A

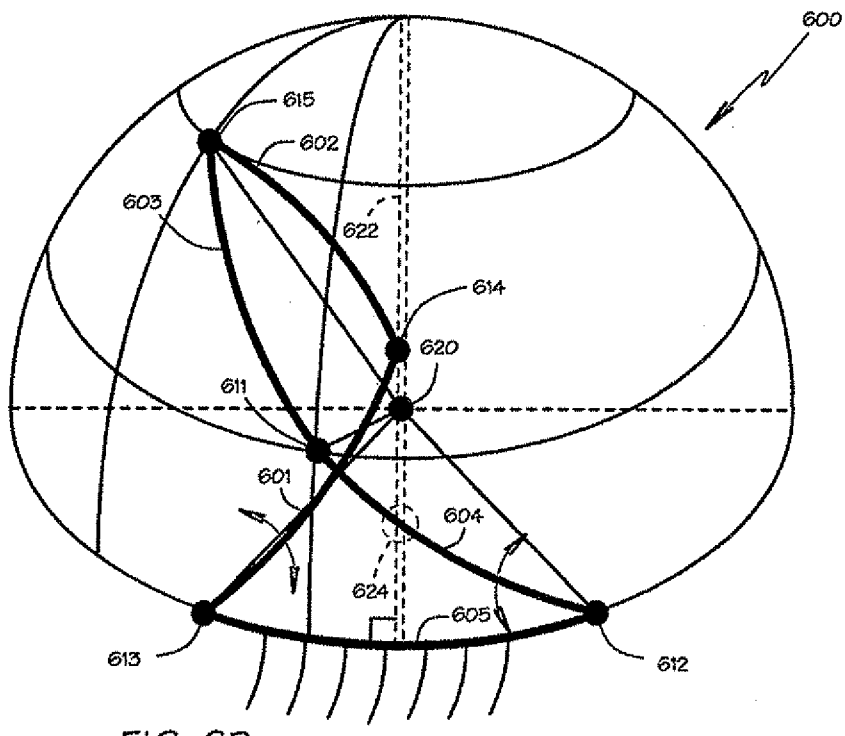

600
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FIG. 6B

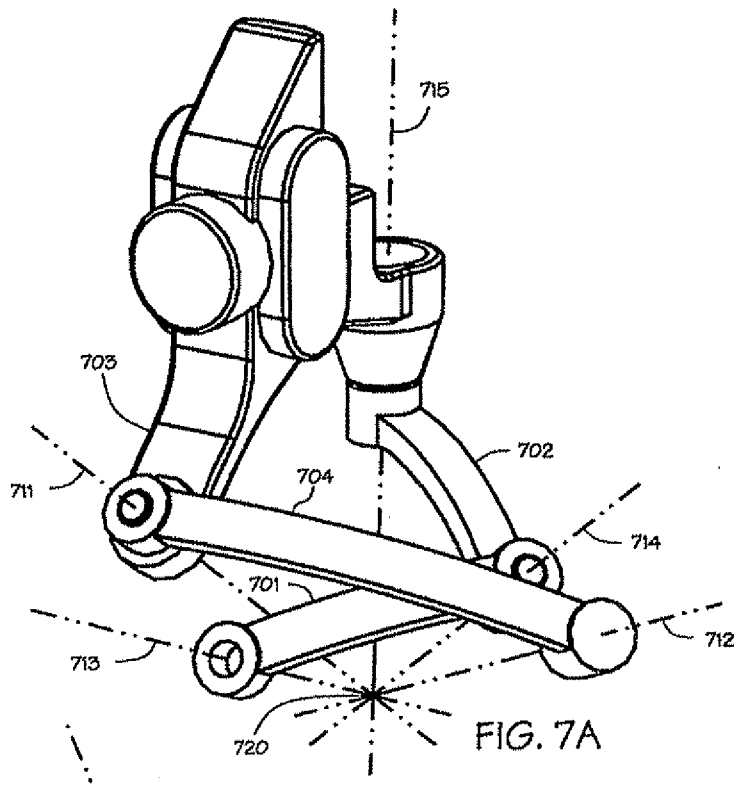

715
703
702
711
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701
712
713
720

FIG. 7A

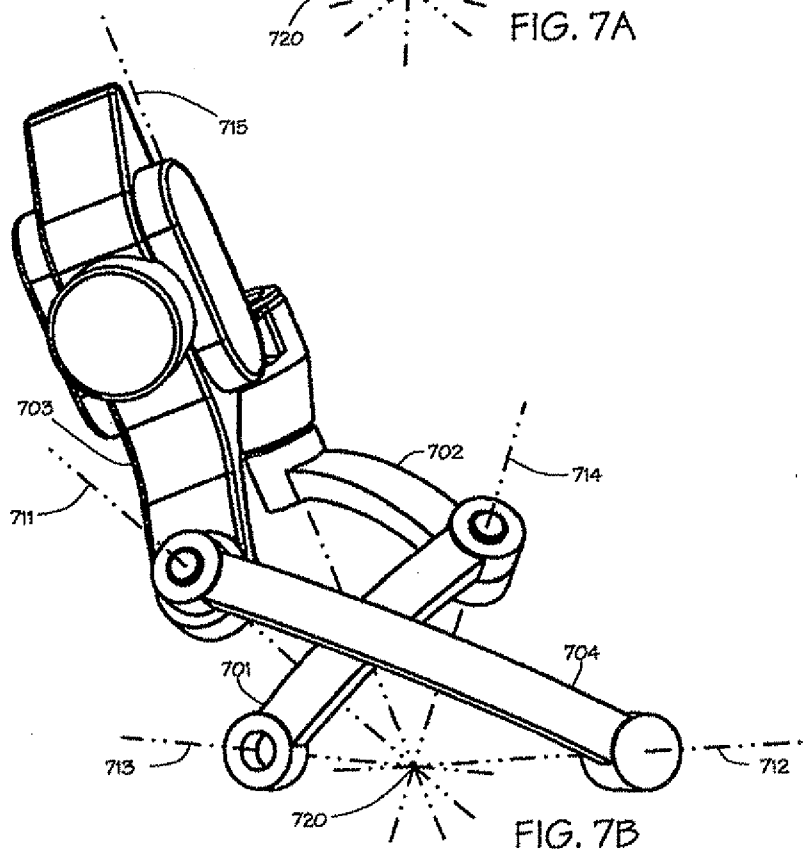

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FIG. 7B

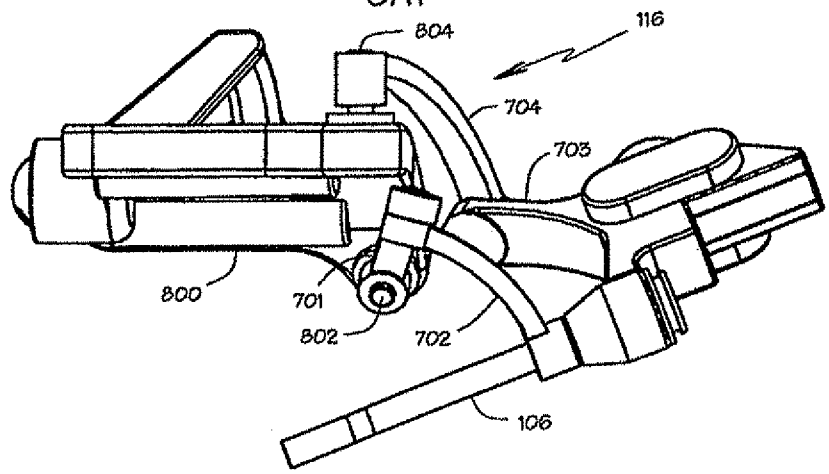


FIG. 8

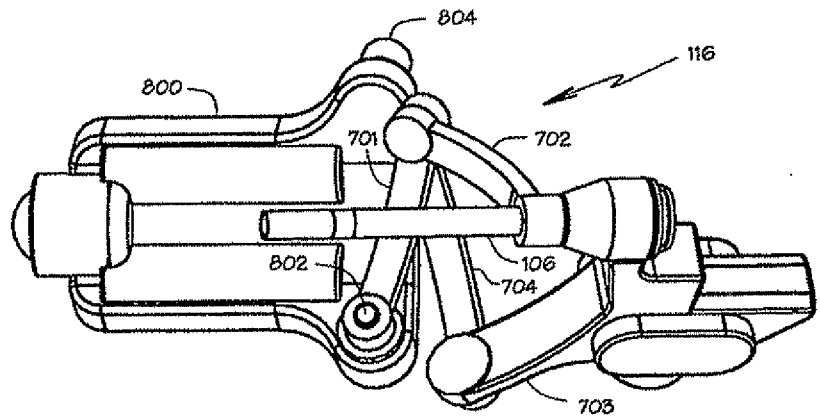


FIG. 9

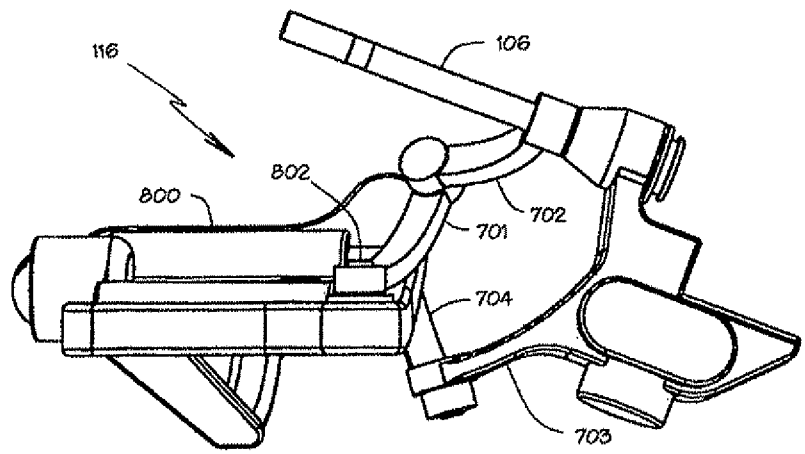


FIG. 10

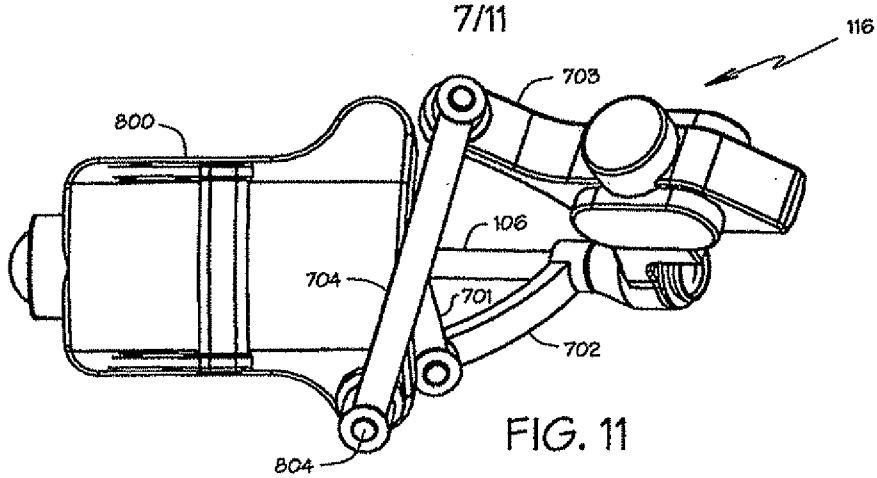


FIG. 11

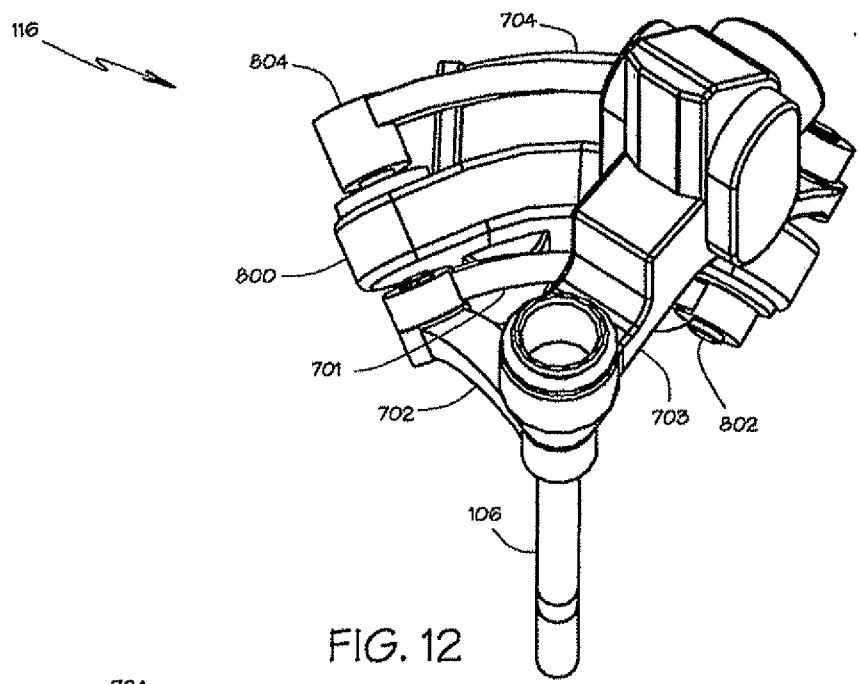


FIG. 12

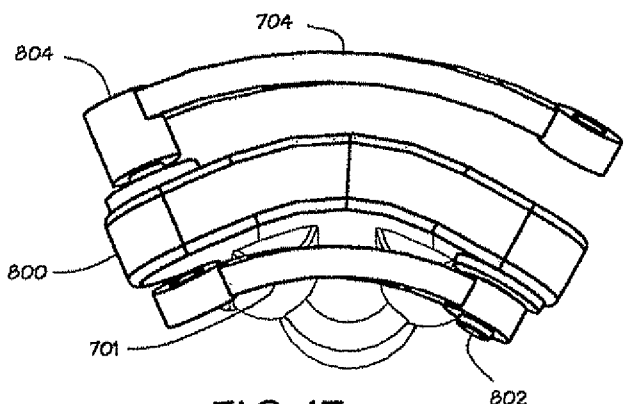


FIG. 13

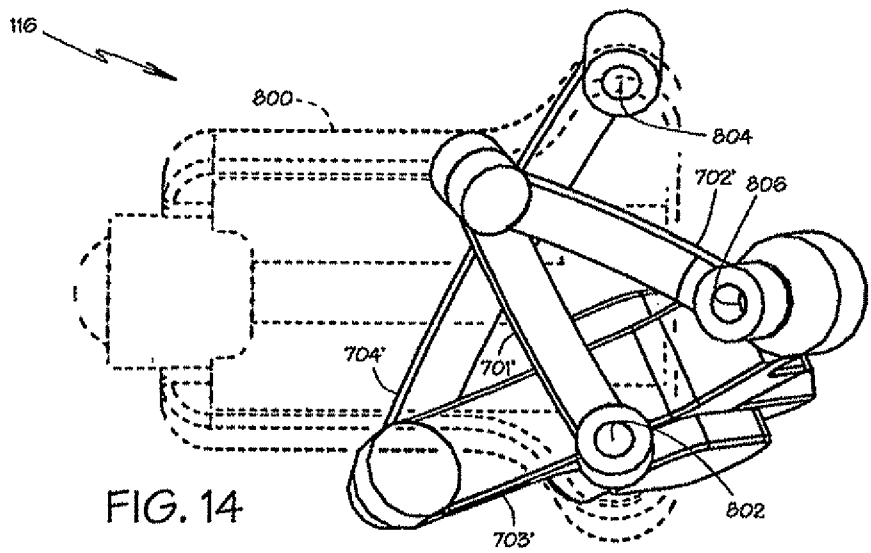


FIG. 14

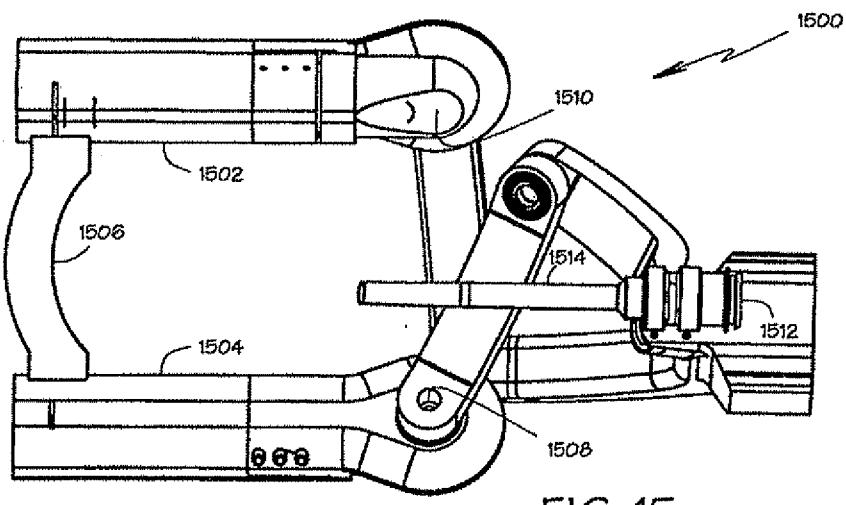


FIG. 15

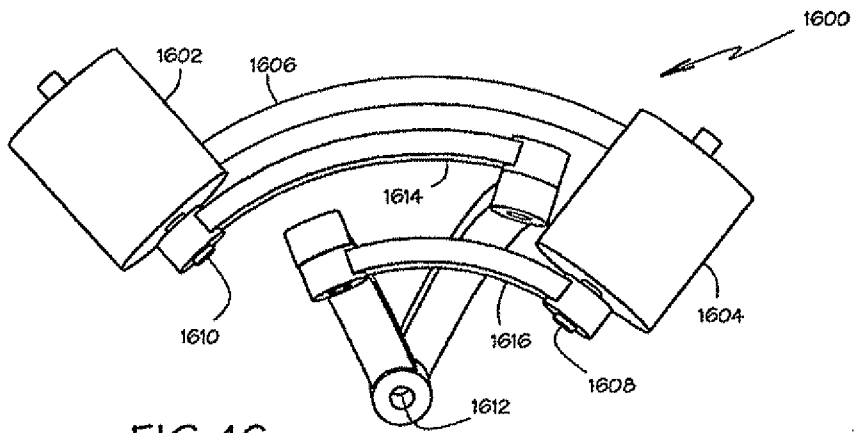


FIG. 16

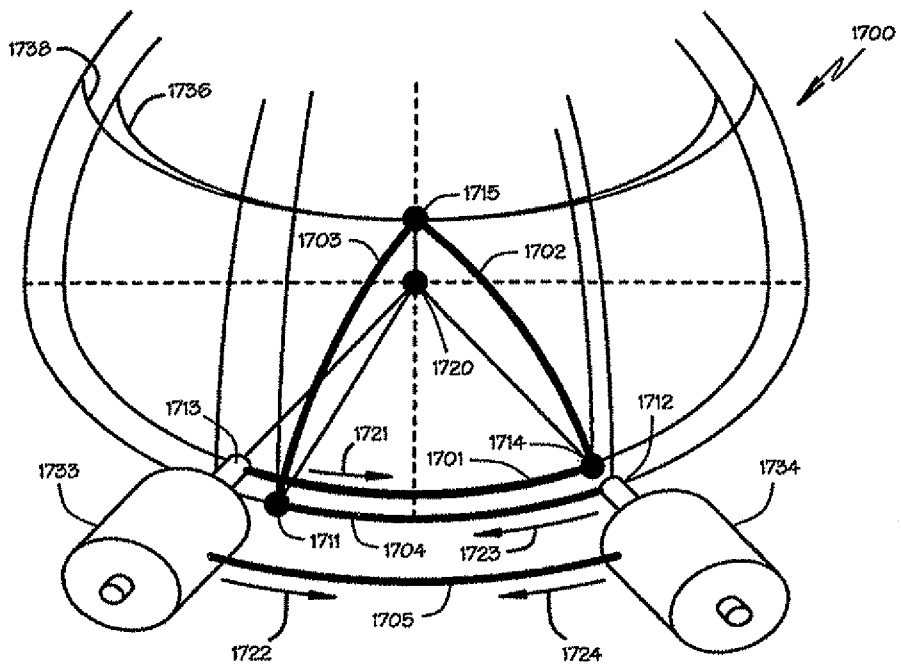

1700
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FIG. 17

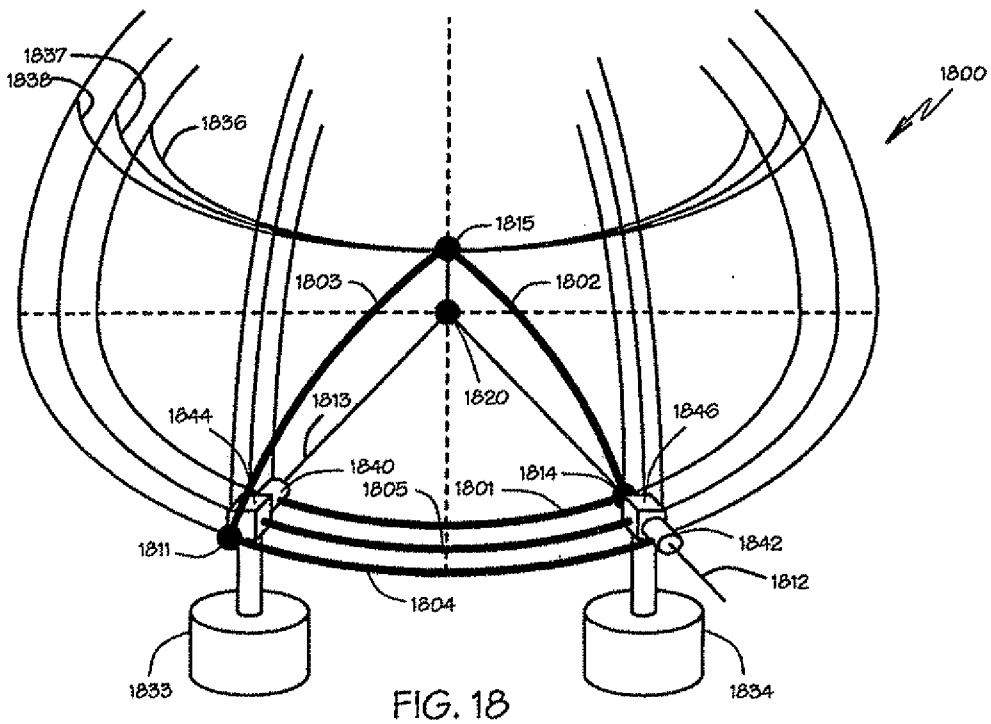

1800
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FIG. 18

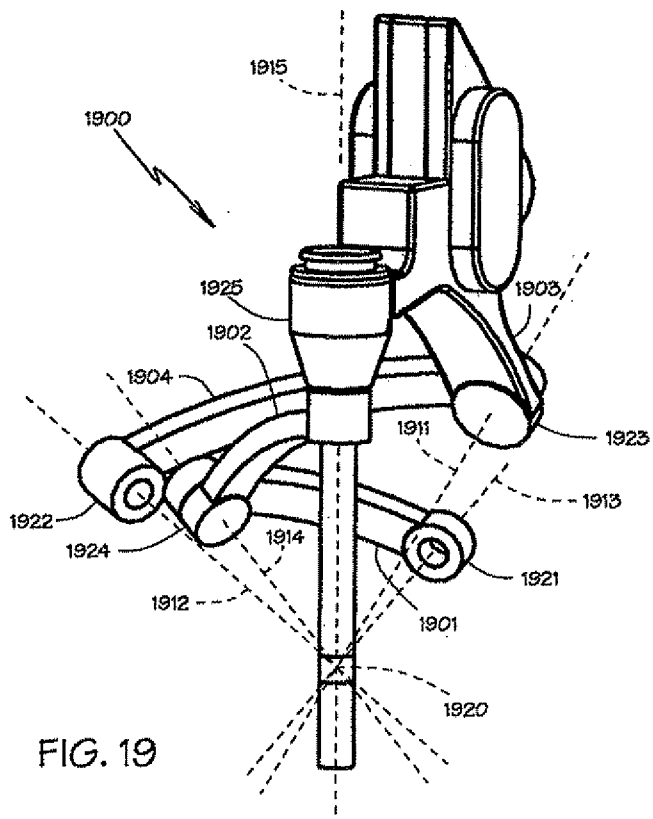

1915
1900
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1901
1920

FIG. 19

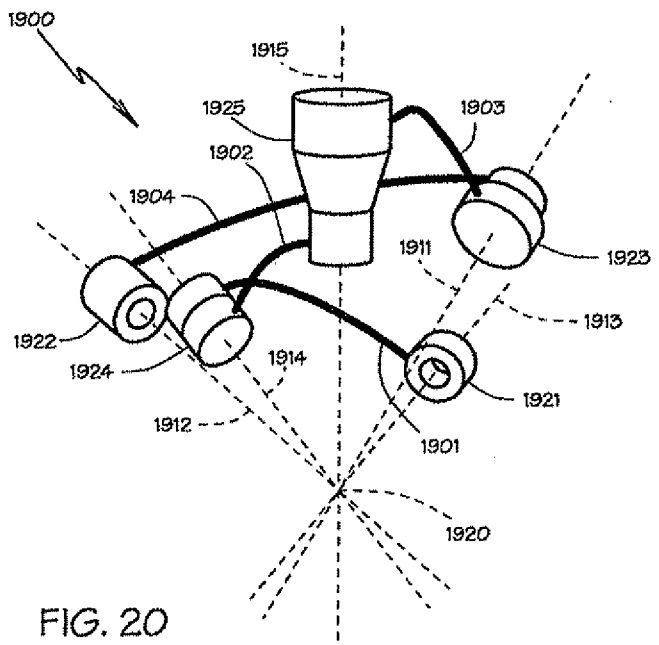

1900
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FIG. 20

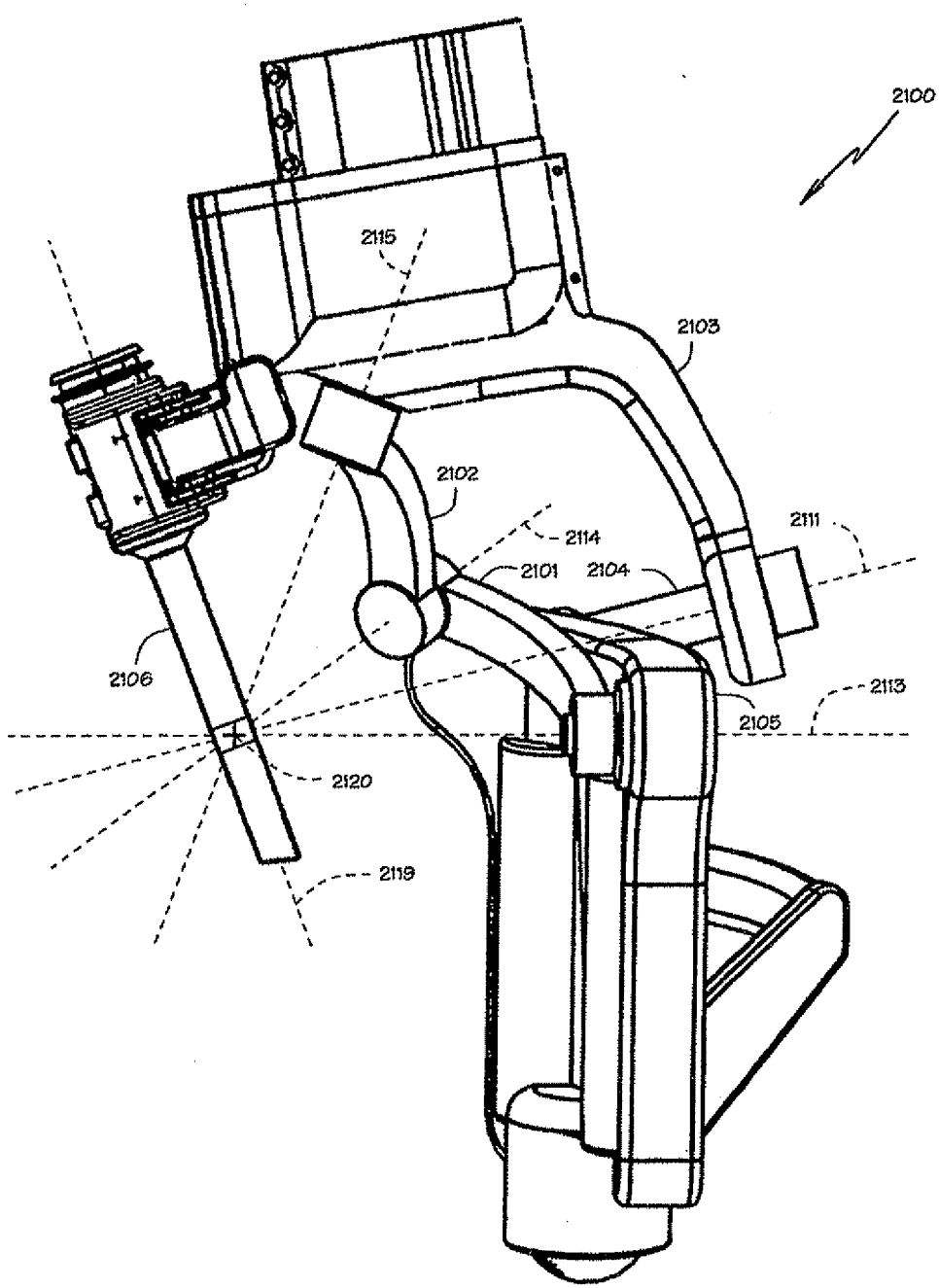

2100
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FIG. 21