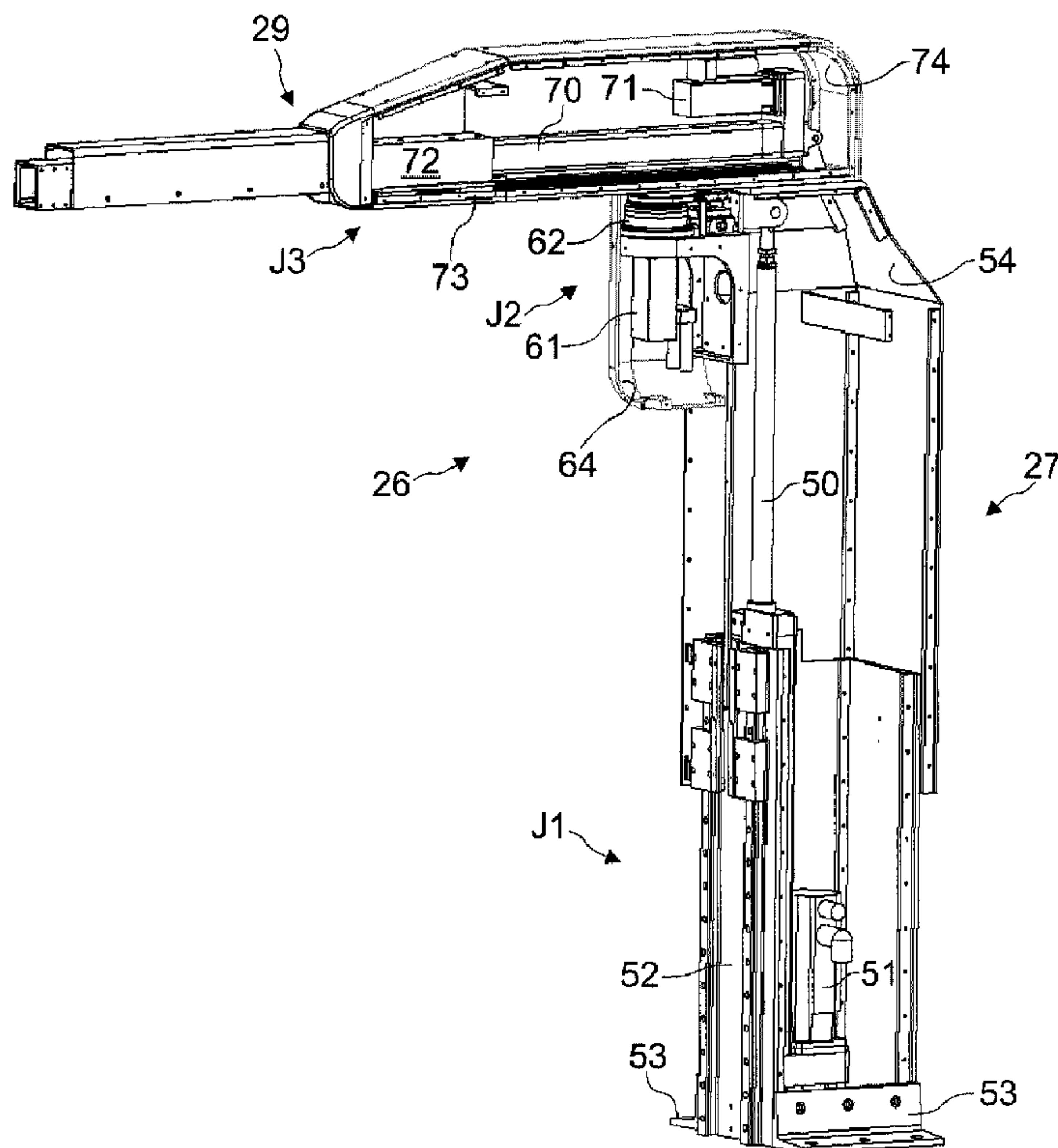




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(57) **Abrégé/Abstract:**

A medical robotic system (10) for performing medical procedures comprises a robot manipulator (14) for robotically assisted handling of a medical instrument, in particular a laparoscopic surgery instrument (18). The robot manipulator (14) comprises a



(57) Abrégé(suite)/Abstract(continued):

base (24); a manipulator arm (26) with an essentially vertical part (27) supported by the base and with an essentially horizontal part (29) supported by the vertical part (27); a manipulator wrist (28) supported by the manipulator arm (26); and an effector unit (30) supported by the manipulator wrist and configured for holding a medical instrument. The manipulator arm (26) has a cylindrical PRP kinematic configuration for positioning the manipulator wrist. More particularly, the PRP kinematic configuration has the following joint sequence: a prismatic (P) first joint (J1) for varying the height of the vertical part (27) by providing a translational degree of freedom along an essentially vertical axis, a revolute (R) second joint (J2) for varying the rotational angle between the vertical part (27) and the horizontal part (29) by providing a rotational degree of freedom about an essentially vertical axis, and a prismatic (P) third joint (J3) for varying the reach of the horizontal part by providing a translational degree of freedom along an essentially horizontal axis.

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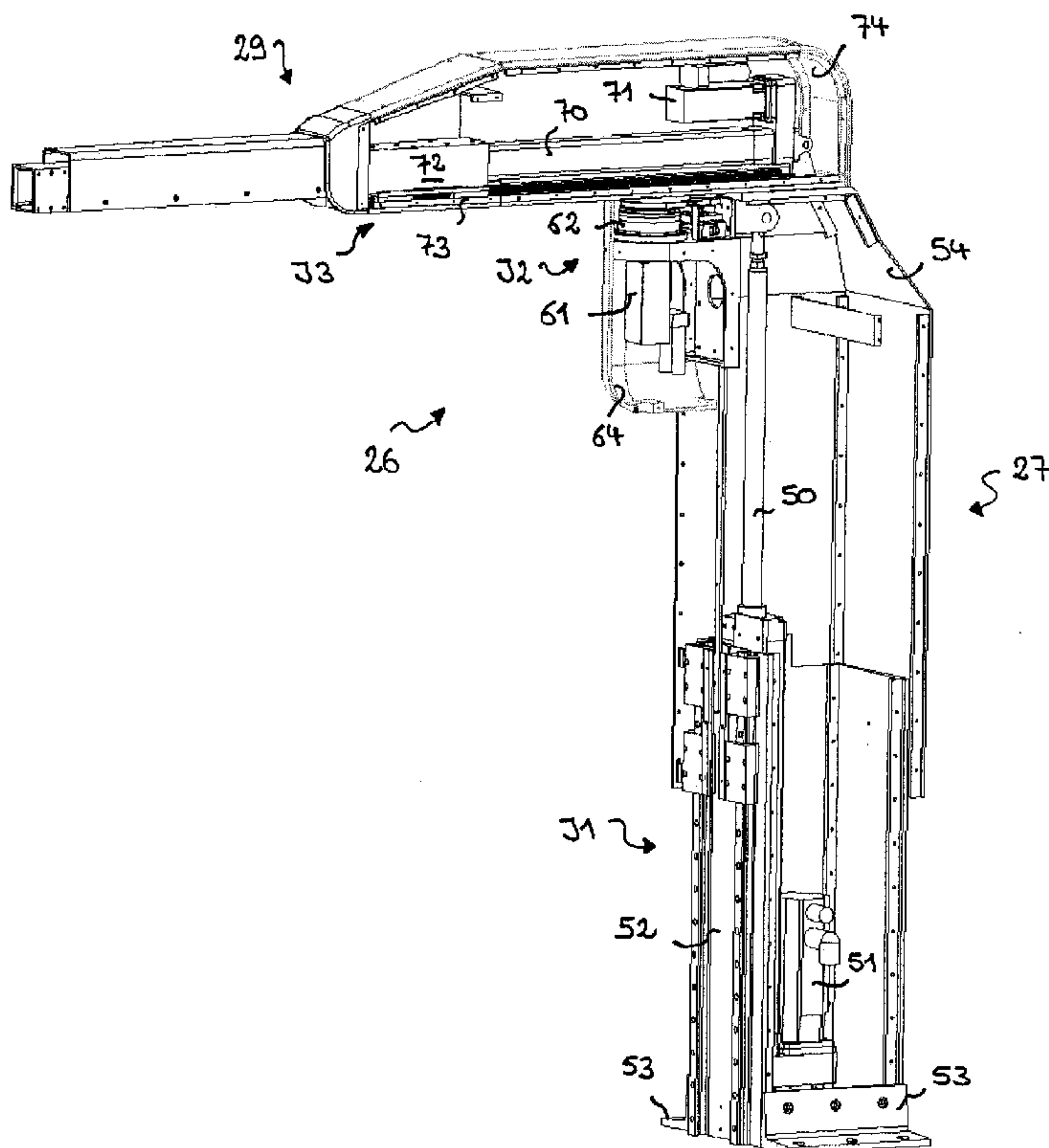
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(54) Title: MEDICAL ROBOTIC SYSTEM WITH MANIPULATOR ARM OF THE CYLINDRICAL COORDINATE TYPE



(57) Abstract: A medical robotic system (10) for performing medical procedures comprises a robot manipulator (14) for robotically assisted handling of a medical instrument, in particular a laparoscopic surgery instrument (18). The robot manipulator (14) comprises a base (24); a manipulator arm (26) with an essentially vertical part (27) supported by the base and with an essentially horizontal part (29) supported by the vertical part (27); a manipulator wrist (28) supported by the manipulator arm (26); and an effector unit (30) supported by the manipulator wrist and configured for holding a medical instrument. The manipulator arm (26) has a cylindrical PRP kinematic configuration for positioning the manipulator wrist. More particularly, the PRP kinematic configuration has the following joint sequence: a prismatic (P) first joint (J1) for varying the height of the vertical part (27) by providing a translational degree of freedom along an essentially vertical axis, a revolute (R) second joint (J2) for varying the rotational angle between the vertical part (27) and the horizontal part (29) by providing a rotational degree of freedom about an essentially vertical axis, and a prismatic (P) third joint (J3) for varying the reach of the horizontal part by providing a translational degree of freedom along an essentially horizontal axis.

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Medical robotic system

Field of the Invention

The claimed invention relates to the field of medical equipment and more particularly to a medical robotic system for performing medical procedures, in particular surgical procedures such as minimally invasive procedures.

Background of the Invention

It is well known that, as opposed to laparotomy, minimally invasive medical procedures
5 have the benefit of reducing the amount of extraneous tissue that is damaged during diagnostic or surgical procedures. This results in shorter patient recovery time, less discomfort and deleterious side effects, and lower costs of the hospital stay. Nowadays, in general surgery, urology, gynaecology and cardiology specialties, there is an increase of the amount of surgical operations carried out by minimally invasive
10 techniques, such as laparoscopic techniques.

Minimally invasive techniques in general and laparoscopy in particular do however put more stringent requirements on the surgeon carrying out the operation. The surgeon operates in an uncomfortable and tiring posture, with a limited field of view, reduced freedom of motion and poor tactile perception. To these problems adds the fact that
15 surgeons often have to carry out several consecutive interventions per day, each intervention lasting e.g. from 30 minutes to several hours. In spite of these difficulties, the trend towards minimally invasive procedures is probably going to increase sharply in the coming years due to the ageing population and the pressure of costs in the medical field.

20 In laparoscopy the surgeon is obviously required to be as precise in his moves as in laparotomy. Manipulating long-shaft instruments with motion dexterity reduced to four degrees of freedom about a fulcrum at the instrument access port, i.e. at the incision in the patient body, is not alleviating this task. Complications arise inter alia by the fact that the required posture is quite tiresome and reduces the already limited perception
25 of interacting forces between instrument and tissues. For example, when the surgeon stands aside the patient, he must lift and maintain stretched one of his arms to hold the instrument inserted at the opposite side of the patient. As a result, motorial capabilities

of the surgeon decay normally after 20-30 minutes, such that among others trembling, loss of accuracy and loss of tactile sensitivity occur with the resulting risks for the patient. Therefore, new technologies, such as robotically assisted laparoscopy, are emerging which aim at improving efficiency, quality and safety of interventions.

- 5 In view of the above, robotically assisted laparoscopy has known significant development since the early nineties. Two representative commercially available robotic surgery systems are the surgery system known by the trademark '*DA VINCI*' developed by Intuitive Surgical Inc., Sunnyvale, California and the surgery system known by the trademark '*ZEUS*' originally developed by Computer Motion Inc., Goleta, California.
- 10 The surgery system known by the name '*DA VINCI*' is described among others by Moll et al. in US 6,659,939; US 6,837,883 and other patent documents of the same assignee. The surgery system known by the name '*ZEUS*' is described among others by Wang et al. in US 6,102,850; US 5,855,583; US 5,762,458; US 5,515,478 and other patent documents assigned to Computer Motion Inc., Goleta, California.
- 15 These tele-operated robotic systems permit to control surgical interventions either directly from the operation theatre or from a remote site, using visual feed-back on a console. In either case, the tiring posture of the surgeon is eliminated.

Apart from the high purchase and maintenance costs of these robotics systems, their diffusion and acceptance in the medical community is limited among others because of

20 a lack of versatility. Both systems were designed specifically for cardiologic surgery where the topological anatomy is constant, the workspace is small and therefore accurate instrument motion and dexterity are required in a limited space only. Accordingly, the mechanical design of these systems is not readily suitable for use in other types of surgery (including gynaecology, urology and general surgery) where the

25 operating workspace is larger than in cardiology, the anatomical topology is variable (even sometimes unpredictable), and the mechanical properties of tissues and organs are diverse.

Irrespective of these two specific systems, the mechanical design of manipulators in robotic surgery systems currently leaves significant room for improvement in various

30 aspects among which versatility of the system is but one of many.

Object of the invention

Accordingly, one object of the invention claimed herein is to provide a medical robotic system for performing medical procedures comprising a robot manipulator having an improved kinematic configuration.

General description of the invention

In order to achieve this object, a medical robotic system for performing medical procedures, in particular laparoscopic procedures, comprising a robot manipulator for robotically assisted handling of a medical instrument, in particular a laparoscopic surgical instrument, as disclosed hereinafter is proposed. According to one aspect of the invention, the robot manipulator comprises a base; a manipulator arm having an essentially vertical part supported by the base and an essentially horizontal part supported by the vertical part; a manipulator wrist supported by the manipulator arm; and an effector unit supported by the manipulator wrist and configured for holding a medical instrument. According to another aspect of the invention, the manipulator arm has a cylindrical PRP kinematic configuration for positioning the manipulator wrist. More particularly, the proposed PRP kinematic configuration includes in sequence the following three joints: a prismatic (P) first joint for varying the height of the vertical part by providing a translational degree of freedom along an essentially vertical axis, a revolute (R) second joint for varying the rotational angle between the vertical part and the horizontal part by providing a rotational degree of freedom about an essentially vertical axis, and a prismatic (P) third joint for varying the reach of the horizontal part by providing a translational degree of freedom along an essentially horizontal axis.

Among other advantages described herein below, this specific kinematic configuration of the manipulator arm enables:

- reducing the space required above the patient by one single manipulator arm which enables among others the use of an increased number of separate manipulator arms in a given intervention;
- positioning the manipulator base at a certain distance from the patient such that putting the robot manipulator in a clearance position in case of an emergency merely requires turning the horizontal part of the arm into an unobstructive position;

- facilitating access of personnel to the patient and also to the region of the surgical instrument, e.g. for exchanging instruments;
- facilitating inter-arm collision avoidance;
- use of a minimum of joints in the manipulator arm itself, i.e. only 3 joints for providing 3 DOF for positioning the wrist, whereby any redundant joints in particular passive joints are eliminated.

It will be understood that different axis arrangements of a PRP configuration are possible. The axis arrangement indicated above is considered to be the most suitable kinematic configuration for the presently disclosed application. It will further be understood that, among others in terms of kinematics, actuator requirements and robot control, a PRP cylindrical robot configuration is fundamentally different from e.g. a PRR configuration as disclosed e.g. in US 5'351'676 or an RPP configuration as disclosed in US 6'120'433.

The skilled person will further appreciate that the kinematic configuration proposed herein challenges the established belief that SCARA, i.e. a certain type of PRR configuration, is considered most appropriate for laparoscopic applications. This long established belief is confirmed in patent and scientific literature e.g. in the paper "A Robotic Case Study: Optimal Design For Laparoscopic Positioning Stands"; A. Faraz and Sh. Payandeh; Proceedings of the 1997 IEEE Int. Conf. on Robotics and Automation; April 1997; (see paragraph 2.2. in particular).

Furthermore, the proposed kinematic configuration contributes to increased versatility of the system. In other words, this design of the robot manipulator renders the system suitable for a variety of applications, especially for minimally invasive surgery, but also for orthopaedic or biopsy interventions, for percutaneous therapy, for skin harvesting, for ultra-sound diagnostics, etc.

As will be appreciated, the disclosed robotic system breaks with the paradigm according to which SCARA kinematic configurations represent the most appropriate choice in the specific case of a robotic surgical system. A representative example of a medical robot system using manipulators with SCARA configuration is the aforementioned system known by the trademark "ZEUS", described e.g. US 6,102,850; US 5,855,583; US 5,762,458 and US 5,515,478.

As regards versatility of the medical robotic system, existing medical robotic systems are generally designed for a specific type of intervention. The "DA VINCI" and "ZEUS"

systems, for example, were designed especially for cardiologic surgery. Therefore, as mentioned above, these systems are designed for special articulated instruments. Furthermore, because of the limited workspace in cardiologic interventions, instrument motion is normally downscaled from the surgeon's commands at haptic interface in these systems. In general laparoscopic surgery (including gynaecology, urology and general surgery) the operating workspace is larger than in cardiology, the anatomical topology is variable (even sometimes unpredictable), and the mechanical properties of tissues and organs are diverse. Larger workspace implies a larger instrument motion envelope and the need of 1:1 motion scale. As a result, in general laparoscopy, increased motion dynamics are needed in order to accurately follow the surgeon hand motion. From experimental trials it has been found that the surgeon hand produces high speeds in a small workspace, and therefore very high acceleration. Speed can reach up to 100°/s along pivot pitch and yaw axes, and 200mm/s in the penetration direction. At 1:1 motion scale and in the mentioned conditions, the above systems display vibrations, oscillations and loss of accuracy. The robot manipulator, described in more detail herein below, is designed to reduce such problems and hence to be suitable for a variety of interventions of general laparoscopic surgery.

Furthermore, many existing systems have, besides a manipulator for the endoscope, only two manipulators for surgical instruments per se. This results in increased intervention time due to frequent and complex instrument exchange procedures. In a typical intervention, the surgeon uses five to seven different types of instruments and often needs to exchange them several tenths of times. Usually, instrument exchange takes from 5 to 10 seconds, depending on the surgeon assistant's skill, and these exchange operations substantially contributes to the total intervention time (by approximately 10-20%). Many existing robotics systems are not readily suitable for typical interventions requiring three or four instrument access ports. Other systems are restricted to diagnostics interventions which are normally short in time (about 20 minutes) and often do not justify the cost of a robotics system. Ideally, a robotic surgery system should be modular and have the capability to manage up to four instrument access ports and one endoscope access port. A significant constraint related to the design of suitable manipulators, is that some access ports can be distant by a few centimetres only and the respective instruments may need to be positioned nearly parallel or one above the other. In addition, it is desirable that manipulators do not excessively limit the surgeon's view on the patient body and access ports. The medical robotic system, especially by virtue of the kinematic configuration of the manipulator

arm, but also due to various other features described herein below and considered inventive per se, among others addresses the above issues and facilitates the simultaneous use of a plurality of robot manipulators.

5 Another relevant limitation of existing systems concerns the lack of reliable and safe means for collision avoidance between different manipulators, between manipulators and staff in the operation theatre, and between instruments and the endoscope. Any potential collision does however represent a severe risk to the patients health and possibly that of the operating staff and hence efficiently avoiding collisions in robotic surgery systems is of great importance. This problem obviously becomes even more
10 critical with a increasing number of robot manipulators used during a given intervention. By virtue of the PRP kinematic configuration, on the one hand, potential collision risks are reduced because of reduced obstruction by the manipulator arm itself and, on the other hand, methods for collision detection and avoidance are simplified.

It will be appreciated that the system provides the required manoeuvrability with a
15 minimum number of joints, i.e. with 6 DOF with only 6 joints. No further redundant joints are provided. In particular, special instruments with articulated instrument distal ends are not required. Furthermore, all joints are actuated that is to say no passive or free-rotating joints are present in the robot manipulator, whereby robotic control is significantly improved. Elimination of redundant passive joints, which are commonly used in
20 known systems for avoiding trocar stress, is achieved among others by providing the sensor assembly at the interface between the sixth joint and the laparoscopic instrument actuator. This arrangement of the sensor assembly enables force measurement and constraint restriction not only at the instrument tip level but also at the level of the trocar. Another particularity is to be seen in the fact that the wrist and effector unit joints
25 are all rotary, i.e. no prismatic joints are provided on these parts.

In an advantageous embodiment, which among others increases the manipulator stiffness, the first (P) joint has a vertical linear guide and a first linear actuator, preferably a linear ball screw axis, for actuating the first (P) joint. Similarly, the third (P) joint advantageously has a horizontal linear guide and a second linear actuator,
30 preferably a linear ball screw axis, for actuating the third (P) joint. Furthermore, both the first and third joints preferably have a brake and an absolute position sensor respectively associated thereto.

In order to protect the components of the vertical part and in order to minimize the dimensions of the foremost portion of the vertical part above the patient, it is preferred

that the horizontal part comprises an elongated covering which encloses the horizontal linear guide and the second linear actuator, the horizontal part comprising a beam which telescopes with respect to the covering on one side and supports the wrist on the other side.

- 5 Advantageously, the second (R) joint has a gear, preferably a harmonic drive gear, a motor, preferably a brushless servo-motor, coupled to the input stage of the gear, and an absolute position sensor coupled to the output stage of the gear. A compact construction is thereby achieved which additionally enables detection of a failure of the actuation mechanism on the second (R) joint.
- 10 In a further preferred embodiment, the manipulator wrist comprises a revolute (R) fourth joint and a revolute (R) fifth joint for orienting the effector unit. Consequently, the manipulator arm and the manipulator wrist together provide exactly five controllable degrees of freedom.

In order to warrant a certain distance from the patient which facilitates access for
15 personnel, e.g. in case of an emergency, the horizontal part of the arm preferably has a minimum link offset of 800mm, i.e. a certain minimum distance between the axes of rotation of the second and the fourth (R) joints. It may be noted that the space occupied by the base should be taken into account when calculating the offset required for unimpeded passing of personnel.

- 20 Preferably, the axes of rotation of the fourth (R) joint and the second (R) joint are parallel. It is furthermore preferred that the axis of rotation of the fourth (R) joint is coplanar with the plane formed by the axis of rotation of the second (R) joint and by the axis of translation of the third (P) joint.

More particularly, in a preferred configuration, the fourth (R) joint provides a rotational
25 degree of freedom along an essentially vertical axis for setting the yaw angle of the effector unit, and wherein the fifth (R) joint provides a rotational degree of freedom along an essentially horizontal axis for setting the pitch angle of the effector unit. Of course, the yaw angle depends also on the actual configuration of the second (R) joint. The latter is therefore taken into account for setting the yaw angle by means of the
30 fourth (R) joint. In combination with the kinematic configuration of the manipulator arm, this configuration avoids manipulator singularities as will become more apparent herein below. Simplified inverse kinematics and improved manoeuvrability are achieved in a preferred embodiment wherein the wrist comprises a support plate connected to the horizontal part of the arm, and a substantially L-shaped support member, the fourth (R)

joint jointing a first horizontal portion of the support member to the support plate, and the fifth (R) joint jointing a second vertical portion of the support member to a connecting means for the effector unit, the wrist being configured such that the axes of rotation of the fourth (R) joint and the fifth (R) joint have a point of intersection.

- 5 For robotically assisted manipulation of laparoscopic instruments, the effector unit preferably comprises a laparoscopic instrument actuator having means for mounting a surgical instrument to the manipulator and a linear actuation mechanism for actuating a mounted surgical instrument. In the later configuration for laparoscopic instruments it is preferred that the effector unit comprises a main support frame for connecting the
- 10 effector unit to the wrist and a revolute (R) sixth joint which joints the laparoscopic instrument actuator to the main support frame, the sixth (R) joint providing a rotational degree of freedom along an axis which coincides with the longitudinal axis of a surgical instrument mounted to the laparoscopic instrument actuator for setting the roll angle of the mounted surgical instrument. In the latter embodiment, it is preferred that the axes
- 15 of rotation of the sixth (R) joint and the fifth (R) joint are perpendicular. It is nevertheless also conceivable, e.g. in applications of the robotic system other than minimally invasive surgery, that these axes may be oblique, for example to avoid singularities due to possible alignment of the sixth and the fourth (R) joint.

Preferably, the manipulator wrist is configured such that the axes of rotation of the sixth

20 (R) joint and the fourth (R) joint are offset by a distance corresponding approximately to the diameter of the laparoscopic instrument actuator at its largest cross-section. This embodiment allows two robot manipulators to operate at closely located incisions with a reduced collision risk.

In order to enable force feedback at a haptic interface of a surgeon, the effector unit

25 advantageously comprises a sensor assembly comprising a 6 degrees-of-freedom (DOF) force/torque sensor and a 6 DOF accelerometer, the assembly connecting the laparoscopic instrument actuator to the sixth (R) joint. This sensor assembly allows to measure the linear and angular acceleration and inclination of the laparoscopic instrument actuator and any forces or torques exerted by a mounted instrument onto

30 the patient's body. The linear and angular accelerometer is used for compensating gravitational and acceleration influence on the force-torque sensor.

Many existing medical robotic systems lack force feedback and thereby preclude the surgeon from perception of forces exerted on the patient tissues. Hence, the surgeon can only rely on the visual feedback of his moves to limit the interaction of the instru-

ment with the tissues. In fact, force feed-back significantly contributes to safety in the use of robotics for surgical laparoscopy. In addition, tactile sensing is relevant for palpating organs, for holding viscous organs with an instrument which is not in the field of view of the endoscope, for applying adequate tension to sutures and avoiding wire rupture, for detecting excessive forces applied to organs and consequently stopping or limiting motion, for limiting the forces applied on the trocar incision, etc. In "Development of actuated and sensor integrated forceps for minimally invasive robotic surgery" by B. Kübler, U. Seibold, and G. Hirzinger - Jahrestagung der Deutschen Gesellschaft für Computer- und Roboterassistierte Chirurgie (CURAC), October 8-9, 2004, Munich, Germany; a miniaturized 6 DOF force/torque sensor installed at the tip of the instrument has been presented. This concept has several drawbacks, among which increased instrument expenses, the lack of robustness regarding sterilization, and EMI shielding problems when used with electrically powered instruments.

Regarding actuator construction, the fourth (R) joint, the fifth (R) joint and/or the sixth (R) joint advantageously has a motor, preferably a brushless servo-motor, a gear having an input stage coupled to the shaft of the motor, a belt transmission coupled to the output stage of the gear for transmitting motion to the associated joint, and an absolute position sensor coupled to the belt transmission. This design enables detection of joint failures at the end of the transmission chain.

For detecting intrusion of personnel into the workspace of the manipulator, the base of each robot manipulator preferably comprises a laser range scanner.

Brief description of the figures

The above aspects as well as other inventive aspects and objects of the present disclosure will be more apparent from the following description of a not limiting embodiment with reference to the attached drawings, wherein:

- 25 Fig.1: is a perspective view of a medical robotic system for generic surgical laparoscopy in an operation theatre with three robot manipulators placed around an operation table on which lays a patient;
- Fig.2: is a perspective view of a medical robotic system for generic surgical laparoscopy with five robot manipulators;
- 30 Fig.3: is a perspective view of a robot manipulator of the medical robotic system of Fig.1 and Fig.2 showing main coordinate systems;

- Fig.4: is a perspective view of the robot manipulator of Fig.3 partially disassembled into its main parts;
- Fig.5 is a schematic diagram of the kinematic configuration of the robot manipulator of Fig.3 including joints J1 to J6;
- 5 Fig.6 is a top view of a robotic surgery system with five robot manipulators, illustrating 2D collision detection boxes enveloping manipulator components;
- Fig.7: is a perspective view of the base of the robot manipulator of Fig.3;
- Fig.8 is a top view of a medical robotic system showing a 2D laser based detection to detect proximity of a surgeon assistant with respect to a robot manipulator;
- 10 Fig.9: is a perspective view of the internal components of joints J1, J2 and J3 of the robot manipulator of Fig.3;
- Fig.10: is a perspective of the internal components of joint J2 of the robot manipulator of Fig.3;
- Fig.11: is a first perspective view of internal components of the manipulator wrist including joints J4 and J5;
- 15 Fig.12: is a second perspective view of internal components of the manipulator wrist including joints J4 and J5;
- Fig.13: is a third perspective view of internal components of the manipulator wrist including joints J4 and J5
- 20 Fig.14: is a perspective view showing an effector unit of the robot manipulator of Fig.3 and an adapted instrument to be connected to the effector unit;
- Fig.15: is a perspective view of main internal components of the effector unit of Fig.14;
- Fig.16: is a perspective view of a fulcrum reference frame;
- 25 Fig.17: is a perspective view of an instrument stem adaptor (ISA) and a corresponding instrument stem;
- Fig.18: is an enlarged perspective view of a laparoscopic instrument actuator (LIA) as shown in Fig.14;
- Fig.19: is a perspective view of a drive assembly in the LIA of Fig.18;
- 30 Fig.20: is a perspective view from underneath showing further internal components of the LIA shown in Fig.18;
- Fig.21: is a perspective view from above showing further internal components of the LIA shown in Fig.18;
- Fig.22: is a perspective view showing a coupling mechanism used in the LIA shown in
- 35 Fig.18;

- Fig.23: is a perspective view of a robot manipulator according to Fig.3 having a modified manipulator wrist;
- Fig.24: is a perspective view of a medical robotic system for generic surgical laparoscopy with four robot manipulators according to Fig.23 and one robot manipulator according to Fig.3 ;
- 5 Fig.25: is a perspective view of an alternative embodiment of a laparoscopic instrument actuator (LIA) for use in the effector unit shown in Fig.14;
- Fig.26: is a perspective view of the LIA of Fig.24 with an alternative embodiment of an instrument stem adaptor (ISA) connected to the LIA;
- 10 Fig.27: is a perspective view of an alternative drive assembly used in the LIA of Fig.24;
- Fig.28: is another perspective view of the ISA shown in Fig.26;
- Fig.29: is a partially broken perspective view of the ISA shown in Fig.26 and Fig.28;
- Fig.30: is another partially broken perspective view of the ISA shown in Fig.26 and
- 15 Fig.28 with different instrument connected to the adaptor.

In these drawings identical reference numerals are used to identify identical parts throughout.

Detailed description with respect to the figures

Fig.1 shows a medical robotic system for generic surgical laparoscopy, generally identified by reference numeral 10. A patient P covered by a sterile sheet is lying on an operation table 12 around which a plurality of robot manipulators 14 are disposed. In the example of Fig.1, the medical robotic system 10 is set up for an intervention on the pelvic area. A surgeon S operates a surgical master console 15 and a surgeon assistant A stands near the operation table 12 and near a tray 16 with a set of adapted laparoscopic instruments 18. The robot manipulators 14 are designed for positioning and orienting an effector unit which supports and possibly actuates various kinds of laparoscopic instruments 18. During operation, the robot manipulators 14 are tele-operated by one or more surgeons S via one or more surgical master consoles 15 which are connected to a control unit (not shown). As will be appreciated, the medical robotic system 10 is modular and configurable according to the type of the surgical intervention, generally with up to 5 manipulators and normally a minimum configuration of 2 manipulators. A configuration of a medical robotic system 10' with 5 manipulators 14 is shown for example in Fig.2. The system 10 shown in Fig.1 is equipped with laser

range scanners 22 located at the base of each robot manipulator 14. The laser range scanners 22 are used for surgical assistant personnel safety in the operation theatre.

Fig.3 is a three-dimensional view of a robot manipulator 14 which forms one mechanical unit of the robotic surgery system 10. The robot manipulator 14 is mounted on a base 24, which is attachable to the floor of the operation theatre and mobile when not attached. Three coordinate systems are also shown in Fig.3, i.e. the Base, Tool Flange (TF) and Laparoscopic Instrument Tip (LIT) coordinate system. As seen in Fig.3, the robot manipulator 14 comprises a manipulator arm 26 and a manipulator wrist 28.

In Fig.4, the main parts of the robot manipulator 14 are shown. The arm 26 has an essentially vertical part 27 and an essentially horizontal part 29. The first end of the arm 26 on the vertical part 27 is to be attached to the base 24 whereas the wrist 28 is to be attached to the second end of the arm 26, i.e. the extremity of the horizontal part 29. An effector unit 30 for adapted laparoscopic instruments 18 is to be connected to a tool flange 32 of the wrist 28. As indicated by arrows in Fig.3, the arm 26 has three degrees of freedom (DOF) and the wrist 28 has two DOF. Accordingly, the robot manipulator 14 is basically a 5 DOF robot manipulator. An auxiliary DOF for rotating the laparoscopic instrument 18 mounted to the effector unit 30 about its longitudinal axis is provided by the effector unit 30. The arrangement of the DOF of the robot manipulator 14 and the effector unit 30 will become more apparent from the following description of Fig.5.

As best seen in the geometrical model of Fig.5, the arm 26 is jointed to the base 24 by means of a first joint J1 which is a prismatic sliding (P) joint (or rectilinear translation joint). The first joint J1 is connected to the base 24 by means of a base link L0 and provides a translational DOF along an essentially vertical axis. The first joint J1 hence allows vertical positioning of the first essentially vertical link L1 and the subsequent components attached to the latter with respect to the base 24 and the link L0. In other words, joint J1 defines the height of the vertical part 27. A second joint J2, which is a revolute (R) joint, connects the first link L1 to a second essentially horizontal link L2 of the arm 26. The rotation axis of the revolute joint J2 is essentially vertical. The joint J2 allows to set the relative angle between the link L2 and its initial angular position in a horizontal plane. A third prismatic sliding (P) joint J3 connects link L2 to a third essentially horizontal link L3. The joint (P) J3 provides a translational degree of freedom along an essentially horizontal axis and allows to set the reach or extension of the arm 26, more precisely the horizontal part 29, by horizontal displacement of the link

L3 with respect to the link L2. The links L2 and L3 together with the (P) joint J3 form an essentially horizontal extensible jib or boom of the robot manipulator 14.

With two (P) joints and one (R) joint arranged as seen in Fig.5, the arm 26 has one rotational DOF about an essentially vertical axis, and associated thereto two translational DOF along two perpendicular axes. Accordingly, the arm 26 of the robot manipulator 14 has cylindrical configuration, i.e. the kinematic configuration of the manipulator 14 belongs to the class of cylindrical robots of PRP (Prismatic-Revolute-Prismatic) type. More precisely, each joint among the first three J1, J2, J3 respectively corresponds to a cylindrical coordinate (z, θ, r) : z being the elevation (or height) coordinate, θ being the rotational (or azimuth) coordinate and r being the radial elongation (or radius) coordinate.

As further seen in Fig.5, the wrist 28 comprises two revolute joints J4, J5 and the effector unit 30 includes one revolute joint J6. The revolute joints J2, J4, J5, J6 respectively define the orientation of an adapted laparoscopic instrument 18 attached to the effector unit 30. The revolute joint J4 connects the link L3 to a link L4 and allows to rotate link L4 with the subsequent parts, about an essentially vertical axis that is parallel to the rotation axis of joint J2. Hence, the revolute joint J4 allows to set the yaw angle of the effector unit 30, in combination with the actual setting of joint J2. It should be noted that the axis of rotation the revolute joint J4 is coplanar with the plane formed by the axis of rotation of the revolute joint J2 and by the axis of translation of the prismatic joint J3. The revolute joint J5 connects link L4 to the tool flange 32 and allows to rotate the tool flange 32 with the subsequent parts along an essentially horizontal axis perpendicular to the rotation axis of joint J4. Hence, the revolute joint J5 allows to set the pitch angle of the effector unit 30. The effector unit 30 is connected to the tool flange 32 through a link L5. The rotation axis of the revolute joint J6 is substantially perpendicular to the rotation axis of joint J5 and connects link L5 to a link L6. The rotation axis of revolute joint J6 is aligned with link L6 and defines the relative angle of link L6 with respect to its initial angular position. An adapted laparoscopic instrument 18 is connected to link L6. The instrument 18, represented by link L7, is aligned with link L6. The end point of link L7 represents the instrument tip 17.

The cylindrical PRP kinematic configuration of the manipulator 26 has various advantages among which:

- a relatively small contained room occupied by the manipulator structure above the operation table;

- the fact that the manipulator base is at sufficient distance (due to a minimum link offset of the horizontal part 29 of 800m) from the operation table to facilitate surgeon access to the operation table and patient transfer from/to the operation table;
- 5 ▪ easy and fast inter-manipulators collision detection computation.

These and other aspects will become more apparent from the following paragraphs.

An advantage resulting from the chosen PRP kinematic configuration of the robot manipulator arm 26 is the simplification of collision detection computation between a plurality of manipulators 14 arranged with intersecting workspaces around the operation table 12 (Figs.1 and 2). Due to the cylindrical configuration, the robot manipulator 14 can be approximated with simple planar geometrical features in a two-dimensional (2-D) horizontal plane. As best seen in Fig.6, the mechanical links of the arm 26 can be enveloped by a rectangle of variable length and orientation respectively corresponding to $(J3 + L2 + L3)$ and to $J2$; the width of the rectangle envelop is given by the mechanical link geometry plus a margin depending, for instance, on the space required to brake the robot from maximum speed to stop plus a safety threshold. The margin of each side of the rectangle envelops can be dynamically sized according to the direction and speed of motion, e.g. the higher is the velocity in the direction of an envelop side, the higher is the margin for this envelop side. The wrist 28 is approximated by a rectangle enveloping the body of link L4 and part of link L5 and with a variable planar orientation given by the current angular position of joint J4. Similarly, the effector unit 30 can be approximated by a rectangle enveloping its projection on the 2-D horizontal plane where the projection angle corresponds to the current angular position of joint J5. The same principle applies to the stem of the instrument 18 connected to the effector unit 30. Such simple geometrical two-dimensional features permit to establish simple and efficient algorithms for collision detection based on the intersection of their lines. In a first stage, the collision detection method consists of checking a collision in the 2-D horizontal projection. Only if any of these 2-D figures collides with a figure from a different robot manipulator 14, an effective risk of real collision is subsequently verified by including the third dimension. As will be appreciated, 3-D calculations therefore need to be carried out only for the intersecting sides of the concerned parts of the robot manipulators 14. In this simplified 3-D calculation, the concerned parts are enveloped, for example, with a triangular-based model. As a result fast intersection-detection algorithms can be easily implemented, e.g. those proposed in "A Fast Triangle-Triangle Intersection Test" by Moller, Journal of Graphics Tools, 2(2), 1997. In practice, collision

detection between stems of instruments 18 is relevant especially to protect the endoscope from powered instruments.

For an accurate result of the collision detection between robot manipulators 14, the position and orientation of all the robot manipulators 14 with respect to a common reference coordinate system is determined through a calibration procedure after the
5 positioning of the manipulators 14 in the operation theatre. From the functional point of view, after the detection of a collision risk, the control system must halt the concerned manipulators 14 and warn the surgeon S through appropriate display information and/or a repulsive force feed-back on the master console 15. The surgeon S can then
10 simply achieve recovery by tele-operating one of the manipulators in a safe direction. In a further improvement, several collision-safety levels are implemented using at least two envelopes with different margins for each of the sets of parts, e.g. arm 26, wrist 28, effector unit 30 and/or instrument 18. After detecting a risk of collision with the more protuberant envelope, motion commanded by the surgeon S in the collision direction is
15 sharply scaled down in function of the penetration in the margin area.

Another advantage regarding the configuration of the arm 26 is related to improved controllability of the actuators associated to the joints J1, J2, J3. When compared to other classes of robots (e.g. spherical or articulated robots), and as a result of the arm configuration, control of these actuators is improved because J1, J2, J3 and J4 are not
20 subject to varying gravitational loads, and because J1, J3 and J5 do not have varying inertial loads. This enables simplified optimisation of control loops (e.g. PID with feed-forward) and to achieve very low position dynamics tracking errors, e.g. of a few motor encoder counts only. Besides the presented advantages, the mechanical design shall consider a stiff but lightweight structure for links L2 and L3 to limit their deflection and
25 oscillations in case joint J1 and/or joint J2 executes abrupt motion.

Two further advantages resulting from the geometry of the robot manipulator 14 should be noted. Firstly, with the manipulator base 24 located at sufficient distance from the operation table 12 (e.g. at least 600mm away) and the arm 26 designed such that it can be turned by hand about joint J2 (with brakes released) to a parking position, the
30 surgeon S can readily and rapidly access the operation table 12 for manual tasks such as insufflation, anatomic organ removal, final suturing, etc. Furthermore, transfer of the patient P on to or away from the operation table 12 is rapidly possible. Secondly, compared to a SCARA geometry, used e.g. in the manipulator arm known by the commercial name *ZEUS*, having an elbow rotation joint connecting two co-planar links
35 of similar length to reach a certain horizontal location, the cylindrical configuration of

manipulator 14 has a single radial elongation joint J3 that considerably reduces the space taken to position the wrist 28 above the body of patient P. As shown in Fig.2, this feature enables five manipulators 14 and more to be positioned at the operation table 12 providing that the dimensions of the wrist and of the effector unit be sufficiently small, i.e. occupy a sufficiently contained space in the available workspace above the patient body.

In the following paragraphs a more detailed description of the construction of the robot manipulator 14 will be given by reference to Figs.7 to 15.

Fig.7 shows several features of the base 24. The base 24 includes a main base plate 40 and is arranged as moveable structure by means of four wheels 42 installed in openings at the corners of the main plate 40. Each wheel 42 is enclosed in a cover 43 with an opening for access to a handle for extracting or retracting the wheels 42. When the wheels 42 are retracted, the base 24 rests stable on the floor of the operation theatre by means of cushion supports (not shown) of the wheels 42. After extracting the wheels 42, the base 24 including the robot manipulator 14 can be moved by hand. In a different design, the base 24 can be mounted on a moveable or fixed linear rail axis or on a cart designed to support several bases 24 and associated manipulators 14. The main base plate 40 is designed such that it can be fixed to the floor if necessary, e.g. by screwing using holes 44, in order to give additional stability to the robot manipulator 14. The robot manipulator 14 is attached to the base 24 through bolts in threaded holes 45. In the base plate 40, several high precision bores 46 are machined. The bores 46 serve to support optical calibration reflectors which are used to determine the position and orientation of the base 24 by means of an optical measurement system, as described in *"Robot calibration"* by R. Bernhardt and S. Albright, ed. Chapman & Hall, 1993. It may be noted that the robot manipulator 14 is calibrated during the factory set-up procedures in order to accurately determine its geometrical model. Furthermore the base comprises an enclosure 48 for power supply and servo-drives of brushless motors, signal conditioning devices, means for local processing of arm-mounted sensors, and communication channels to a remote system control unit. As shown in Fig.1 and best seen in Fig.8, a 2D laser range scanner 22 is installed on the base 24, more precisely on the enclosure 48, to enable detection of intrusion, e.g. by assistant A, inside a safety perimeter around the links L2 and L3.

It should be noted that generally two different types of robot manipulators 14 are used in the medical robotic system 10. Although the two types of robot manipulators 14 essentially have the same geometry and kinematic PRP configuration of the arm 26,

the first type is preferably specifically arranged to handle an endoscope used for visualization whereas the second type is arranged to handle any of various kinds of adapted laparoscopic instruments 18 used for operation per se. For laparoscopy, normally one robot manipulator 14 of the first type is used whereas several robot manipulators 14 of the second type are used. In the medical robotic system 10, the major differences between these two types of robot manipulators 14 are:

- travel of joint J3 is longer for an endoscope manipulator (about 750mm) because it requires 360° rotation around its access port (usually for exploration purposes).
- travel of joint J4 is infinite for an endoscope manipulator because it requires 360° of rotation around the access port. This is enabled by use of a signal collector on the J4 axis.
- joint J6 is not needed for the endoscope manipulator, i.e. the endoscope can be attached directly to the joint J5.
- the effector unit 30 of an endoscope manipulator normally consists of the endoscope and of a force/torque sensor to detect extra-forces
- speed/acceleration requirements for all joints are lower by min. 60% for an endoscope manipulator because it requires positioning capability for the endoscope only.

Taking into account these differences, the present description is focused on the second type of robot manipulator 14, since the latter has the more stringent design requirements.

Referring to Fig.9, details regarding the configuration of joints J1 to J3 of the manipulator arm 26, including their respective actuators, are given below.

As associated linear actuator, the (P) joint J1 for arm elevation comprises a ball screw linear axis 50 (for example a suitable model of the ET series produced by Parker Hannifin, Electromechanical Division, Offenburg, Germany & Poole, UK). The ball screw linear axis 50 is driven by a brushless servo-motor 51 equipped with an incremental motor position encoder and a brake. The linear axis 50 is additionally provided with an additional absolute linear position sensor (not shown) at the output stage, with limit switches and with a mechanical end-of-travel bumper (not shown). A vertical linear guide 52 is operatively associated to the linear axis 50 in order to ensure axis linearity and torsion stiffness. The linear axis 50 is attached to brackets 53 for mounting the arm 26 to the base 24. Signal and power wires are guided in a vertical cable channel (not shown) inside the cover of the joint J1. An external cover 54 encloses the components

of the prismatic (P) joint J1 as best seen in Fig.3. Regarding the actuator assembly of joint J1 it may be noted that the motor/load reduction ratio is set such as to prevent undesired falling of the horizontal part 29 also when the motor brake is disengaged or when the servo-motor 51 is not powered. In addition, an emergency stop button (not shown) is placed on the external cover 54, which serves to stop motion of all robot joints in case of an emergency. As seen in Fig.9, the aforementioned components of the manipulator arm 26 constitute its essentially vertical part 27.

Fig.9 also shows the (R) joint J2 forming the shoulder joint of arm 26. As best seen in Fig.10, joint J2 comprises an assembly of a brushless servo-motor 61 in-line with a gear 62 of the Harmonic Drive® type to drive the load. The brushless motor 61 is equipped with a position encoder and a fail-safe brake. In addition, the actuator assembly comprises a further absolute rotary position sensor 65, which is driven by a belt 66 connected to the output stage of the gear 62, and mechanical end-of-travel bumper and limit switches (not shown). A key switch (not shown) is provided on cover 64, which allows to release brakes of the joints J2, J3, J4, J5 and J6 when their respective motors are not powered. This allows to move the arm 26 and the effector unit 30 by hand into a parking position. Signals and power cables from downstream joints J3 to J6 and from the effector unit 30 are routed from J3 to J1 through a flexible cable duct (not shown) which passes inside the cover 64. Alternatively, such cables could be guided for instance through the hollow-shaft of an adapted gear and motor assembly.

Fig.9 also shows the design of the horizontal part 29 of the arm 26 including (P) joint J3 for setting the radial extension, i.e. reach of the horizontal part 29. Joint J3 comprises a linear cylinder axis 70, e.g. a ball screw linear axis, as associated linear actuator. For example, an ET model actuator produced by the aforementioned company, driven by a brushless servo-motor 71 equipped with a motor position encoder and a fail-safe brake is used. The rod of the linear cylinder 70 axis moves a beam 72 which is configured as rectangular tube and mounted on trolleys of a linear guide 73. This construction allows reducing linear deflection. The linear cylinder axis 70 is additionally provided with an additional absolute linear position sensor at the output stage, with limit switches and with end-of-run mechanical bumpers (not shown). Signal and power lines are guided in a horizontally placed cable chain. A covering 74 is fixed to the parts forming the second link L2 and encloses the components of the (P) joint J3, in particular the linear actuator 70 and the linear guide 73. As seen in Fig.9, the beam 72, which forms part of link L3, is configured for telescoping into respectively out of the covering 74. The arm 26 is

thereby provided with a horizontal part 29 narrowing into an extremity which requires only a limited amount of space above patient P. Furthermore, lamps are preferably provided on the rear-top of the covering 74 to visually indicate the power and activation status.

5 By reference to Figs.11-13, the construction of wrist 28 and more particularly the joints J4 and J5 will be detailed below.

The mechanical and actuation design of (R) joint J4 shown in Figs.11-13 comprises a support plate 80 to which a brushless servo-motor 81 is mounted vertically. The servo-motor 81 is provided with a position encoder 82 and a hall sensor on the motor shaft.

10 As servo-motor 81, a suitable model of the EC motor series from MAXON MOTOR A.G., Sachseln, Switzerland is used for example. The (R) joint J4 further comprises a transmission mechanism through a gear 83 coupled to the servo-motor 81 and through a transmission belt 84 and pulley 85 system to drive a load axis pulley 86 which is coupled to a connection flange 87. An additional absolute single-turn sensor 88 is
15 connected to a pulley 89, which is also driven by the transmission belt 84, and attached to the bottom side of the support plate 80. In order to easily route cables from joint J5 to joint J4, the assembly comprising the load axis pulley 86 and the connection flange 87, has a hollow shaft and a lateral window on the connection flange 87. The support plate 80 is stiffly attached to the beam 72 by means of two mounting plates 90. As seen
20 in Fig.14, a cover 92 serves to protect to parts of joint J4. Inside the cover the cables from the effector unit 30, from joints J5 and J4 are provided with connectors to make the wrist 28 detachable for maintenance purpose. An emergency stop button is provided on the cover 92 of joint J4. A fail-safe brake is preferably mounted on the shaft of the servo-motor 81. In order to reduce the lateral offset O1, which could
25 constitute a limiting factor in a multi-robot configuration, the motor can also be aligned with the axes of the load axis pulley 86 and the sensor 88. In this case, the support plate 80 preferably has a rounded border around the load axis pulley 86.

The mechanical and actuation design of (R) joint J5 is also shown in more detail in Figs.11-13. An essentially L-shaped support member 100 links the joint J5 to the joint
30 J4, with a horizontal portion connected to joint J4 and a vertical portion as fixed frame for joint J5. It comprises a brushless servo-motor 101, for example a suitable EC model of MAXON MOTOR A.G., with a position encoder 102 and a hall sensor on the motor shaft. As seen in Fig.13, the servo-motor 101 is mounted transversely on the support member 100. As seen in Figs.12 and 13, the (R) joint J5 further comprises a transmis-
35 sion mechanism through a gear 103 coupled to the motor 101 and a transmission belt

104 and pulley 105 system to drive a load axis pulley 106. An additional absolute single-turn sensor 108 is connected to a pulley 109 which is also driven by the transmission belt 104, and attached to the inner side of the support member 100. In order to easily route cables from the effector unit 30 to joint J4, a number of features are included. These are two holes 110 and 112 provided in the support member 100, a hollow central passage 114 in the pulley 106 and the tool flange 32, and a cable routing support 116 for the pulley 106. The L-shaped support member 100 has lateral reinforcements to provide a rigid structure for supporting the effector unit 30 through the tool flange 32. If required, the (R) joint J5 preferably includes limit switches and a fail-safe brake (not shown). When provided, the latter are preferably mounted on a pulley driven by transmission belt 104 in order to reduce lateral offset O2, which may constitute a limiting factor in a multi-robot configuration.

Fig.14 and 15 show the effector unit 30, designed to be connected to the tool flange 32 of joint J5, with its three main parts: a laparoscopic instrument actuator 120, a sensor assembly 122 including a 6 DOF force/torque sensor and a 6 DOF linear/angular accelerometer, and a cover 124 for joint J6. Joint J6 is connected to the sensor assembly 122. The laparoscopic instrument actuator 120 is provided with a seat 130 for mounting an adapted laparoscopic instrument 18 to the robot manipulator 14.

For alleviation, the laparoscopic instrument actuator 120 and the sensor assembly 122 including force, torque and acceleration measurement sensors shall be referred to by the acronym LIA and FTAS respectively. The components of the effector unit 30 are aligned in such a way that joint J6 rotates the adapted laparoscopic instrument 18 about the latter's longitudinal axis of symmetry, and such that this axis coincides with the normal Z axis of the FTAS 122. The position of the effector unit 30 with respect to the rotation axis of (R) joint J5 is selected at the equilibrium point of the effector unit 30 such as to avoid tilting when joint J5 is stopped and not powered. Hence, a main support frame 140 of the effector unit 30, which connects to the wrist 28, is configured such that the assembled effector unit 30 is balanced on the rotation axis of (R) joint J5. The motor/load reduction ratio for joint J5 also contributes to the tilting resistance.

Fig.15 shows the construction of the joint J6. To the main support frame 140 (to be connected to the tool flange 32) is mounted a brushless motor 141 with an incremental encoder 142 and a gear assembly 143. A motor pulley 145 connected to the motor 141 is coupled to a load pulley 146 by means of a belt 144. The load pulley 146 provides the rotational DOF of joint J6. An additional absolute position sensor 148 is mounted on the axis of the load pulley 146 coinciding with the axis of (R) joint J6. The position

encoder 148 has a hollow shaft for passing signal and power lines of the LIA 120 and FTAS 122 to a rotating collector 150 of the "slip-ring" or sliding contact type. The slip-ring 150 enables infinite axis rotation for joint J6. The load pulley 146 is connected to the FTAS 122 through a connection flange 152. Cables for power and signal lines for the LIA 120 and FTAS 122 are guided inside the cover 124 through a hollow passage in the connection flange 152. As will be appreciated, the robot manipulator 14 as a whole is provided with internal channels to ensure protected guiding of all signal and power lines e.g. of joints J1-J6 and effector unit 30 components such as LIA 120 and FTAS 122. In a further improvement (not shown) the configuration of joint J6 implements the following two modifications: Firstly, reduction of the offset O3 by locating the motor-gear-pulley assembly 141, 143, 144, 145 at -90 degrees with respect to the orientation shown in Fig.15. Secondly, the offset O4 is reduced by configuring the motor-gear assembly 141, 143 to be located closer to the LIA 120.

As will be appreciated, the rotation axes of joints J4, J5 and J6 intersect at the same point in space in the presented embodiment. Thereby a potential offset caused by link L5 is eliminated.

As shown in Fig. 23 and Fig.24, an alternative design could however present an offset O5 due to link L5 e.g. in order to improve manoeuvrability in case two adapted laparoscopic instruments 18 are to be inserted in nearly located trocars (access ports 20). For instance, the specific design shown in Figs. 23 and 24 provides a modified manipulator wrist 28' having a negative offset O5 due to link L5. This negative offset O5 allows to place the effector unit 30 of a first robot manipulator 14 above the effector unit 30 of a second robot manipulator 14 without collision between the wrists 28'. This modified configuration requires however an increased reach for joint J3 and higher speed and acceleration capabilities for joints J2, J3 and J4. As will be appreciated from Fig.24, the configuration of the wrist 28' is advantageous for operating at multiple closely located access ports 20 (trocars 200). It will be understood that a preferred value of the offset O5 between the axis of rotation of J6 and J4 as shown in Fig.23 is approximately the diameter of the LIA 120 at its largest cross-section.

Some further aspects and advantages regarding the design of the robot manipulator 14 and its components will be detailed below.

As regards the described configuration of transmissions and motors used for the wrist 28 and the effector unit 30, other configurations are also possible using, for instance, cables and pulleys as transmission means or compact gear-motor-brake assemblies with torque motors. Cables and pulleys as transmissions are however more difficult in

implementation and to maintenance, whilst assemblies based on torque motors are generally less compact. For the safety of the described system, servo-drives were selected which have a 'dynamic brake' function to allow stopping the motors 51, 61, 71, 81, 101, 141 in case of an emergency stop. The external cover of the robot manipulator 14 is made of a suitable cleanable plastic material and possibly in part of aluminium but all external conductive parts are connected to electrical ground. All internal components are shielded against EMI regarding reception and emission. Regarding sterilization in the operation theatre, a sterile plastic bag is normally used to cover the robot manipulator 14 completely, i.e. from the effector unit 30 to the base 24.

Regarding actuation, the design of the robot manipulator 14 as described above presents two further advantages: Firstly, the joints of the robot manipulator 14 can be actuated manually, except for joint J1 because it presents high static friction and reversed inertia. In other words, when all brakes are disengaged, the effector unit 30 mounted to the wrist 28 at flange 32 can be moved by hand through manual actuation of joints J2, J3, J4, J5 and J6 requiring a pushing force less than 5kg only (in horizontal direction). Secondly, system safety is increased by sensorial redundancy. As described above, each one of the joints J1 to J6 has both a position encoder on the motor shaft and an additional position sensor (e.g. 65, 88, 108, 148) measuring the effective motion output of the respective joint. In practice, this sensorial redundancy is used to detect failures (e.g. of a motor wire, of a belt or of a servo-drive).

Furthermore, the design avoids end-of-run conditions at each of the joints J1 to J6. End-of-run occurs when a joint runs out of its motion limit and is a critical condition particularly in tele-operated robotic surgery, because it is difficult and cumbersome for the surgeon S to achieve recovery with an instrument 18 inserted in the body of patient P. In order to avoid end-of-run conditions, the prismatic joints J1, J3 of the arm 26 are designed with sufficient travel and the roll joint J6 of the effector unit 30 is designed for unlimited rotation. As a result, avoidance of end-of-run conditions requires only certain predetermined initial configuration and set-up conditions to be respected.

Fig.16 schematically shows a trocar 200 and its workspace 202 external to the body of the patient P. A fulcrum reference frame FRF is also shown in Fig.16, by means of a Cartesian coordinate system (x,y,z) with the z axis oriented upwards approximately parallel to the direction of gravity. The trocar 200 is normally introduced through a small incision in the abdomen of patient P, indicated at 204, into the peritoneal cavity. The trocar 200 together with the incision forms one access port 20 as shown in Fig.1 and 2.

In order to reach the organ or region in which an operation is to be carried out, the

longitudinal axis of the trocar 200 indicated by z' is pivoted in the workspace 202 about the origin of the FRF, named pivot point 206. In other words, this origin defines a fulcrum for the trocar 200. The fulcrum is preferably determined in between the abdominal wall and the skin of the patient P, at the minor tilting resistance location, in order to reduce the risk of pulling out the trocar 200.

The following maximum force and torque ranges were experimentally registered at a 6DOF force/torque sensor placed at the handle of a modified laparoscopic instrument (see *"Surgeon-Tool Force/Torque Signatures – Evaluation of Surgical Skills in Minimally Invasive Surgery."* by J.Rosen et al - Proceedings of Medicine Meets Virtual Reality, MMVR-7, IOS Press, San Francisco, CA, January 1999):

- Forces: $F_x, F_y = \pm 10 \text{ N}; F_z = \pm 30 \text{ N};$
- Moments: $M_x, M_y = \pm 1 \text{ Nm}; M_z = \pm 0.1 \text{ Nm}.$

Herein F_i represents the force along the corresponding axis $i=x,y$ or z and M_i represents the moment about the corresponding axis $i=x,y$ or z of the FRF in Fig.16. The operational ranges of the force-torque sensor in the FTAS 122 shall take into account these values plus the weight of the LIA 120, the motion dynamics loads and pivoting and penetration resistance exerted onto the trocar 200. In practice, the force-torque sensor in the FTAS 122 is used for force/torque reflection, i.e. force/torque feedback to a haptic interface operated by the surgeon S, for manually driving the effector unit 30 using the FTAS 122 as a joystick, and for monitoring force/torques interacting with an instrument 18 connected to the effector unit 30, e.g. the forces/torques at the tip of the instrument 18 or at the pivot point 206 in Fig.4. The linear and radial accelerometer in the FTAS 122 are used for compensating gravity and acceleration influence on the force-torque sensor information. The measurement axes of the accelerometer and force-torque sensor in the FTAS 122 are geometrically coincident.

During operation, a laparoscopic instrument 18 is inserted through the trocar 200. For most surgical procedures, the surgeon S operates the instrument 18 within the following maximum ranges of angular workspace and speed about the FRF of Fig.16:

Fulcrum axis	Max Travel	Max Speed
Yaw Pivot	+/-70 °	100 %/s
Pitch Pivot	[+10° -80°]	60 %/s
Penetration	[0 200mm]	200mm/s

Roll	[-360° +360°]	300°/s
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Table 1

In the design and configuration of some prior art robot manipulators, the pivot point of the trocar 200 remains fixed after the wrist installation thanks to the mechanical arrangement of the wrist structure that pivots around a fixed point (see for example: 5 *“Remote center of motion robot”* by Taylor et al. - US patent No. 5667323 – May 1995). Other prior art designs implement a mechanical compliance along pivot axes in order to limit forces applied to the trocar (see for example: *“Medical robotic system”* by Wang et al.- US patent No. 6102850, August 2000). As opposed thereto, the robot manipulator 14 proposed herein is designed neither with mechanical compliance nor with centre of motion, but relies on accurate resolved motion about a pivot point 206 determined by a 10 specific procedure, and on real-time control of forces and torques applied to the effector unit 30 in order to optimise the location of the pivot point 206. Moreover, this feature gives the flexibility to translate the pivot point 206, if required by the surgeon S, in order to improve the intra-abdominal workspace. Another advantage is the capability 15 to adapt to variations of the absolute location of the pivot point 206 due, for instance, to the loss of abdominal pressure.

As is apparent, the robot manipulator 14 should have certain motion capabilities in order to provide the effector unit 30 with a dexterity comparable to manual handling of laparoscopic instruments by surgeons. Based on the motion conditions given in 20 Table 1, the preferred kinematic capabilities which have been found for the joints J1 to J6 in this specific example are summarized in Table 2. . Roll, pitch and yaw angles can be defined relative to an absolute reference system, e.g. on the fulcrum.

Joint	Max Travel	Max Speed	Max Acceleration
J1 – Elevation	700 mm	600 mm/s	4 m/s ²
J2 – Shoulder	+/- 90 °	60 °/s	400 °/s ²
J3 – Radial	600mm	600 mm/s	4 m/s ²
J4 – Yaw	[-360° +360°]	260 °/s	1900 °/s ²
J5 – Pitch	[-60° +180°]	75 °/s	500 °/s ²
J6 – Roll	Infinite	250 °/s	2400 °/s ²

Table 2

In terms of speed and acceleration capabilities for the respective joint, the values given in Table 1 are relatively high and therefore require strong actuators, a rigid structure of arm 26 and wrist 28 and an appropriated floor fixation by means of base 24. Obviously, lower values can be chosen which lead to reduced requirements, but this comes at the cost of reduced dynamics at the pivot point 206.

Another relevant aspect, especially in tele-operated robotic surgery with force reflection, is the accuracy requirement for the manipulator 14. Sufficient accuracy contributes to reducing stresses at the trocar incision, and allows to carry out precise force/torque compensation.

In the chosen design, the static accuracy of the manipulator 14 at the connection to effector unit 30, i.e. at the tool flange 32 (see Fig.4) shall be better than $\pm 2\text{mm}$ for position and better than $\pm 0.1^\circ$ for orientation at the FRF (see Fig.16). Herein an external load of 1.5kg is assumed at the tip of a connected laparoscopic instrument 18 and the FRF is assumed at 280mm from the axis of (R) joint J5. The dynamic accuracy shall be better than $\pm 4\text{mm}$ for position and $\pm 0.5^\circ$ for orientation at the FRF. These features are obtained, among others, through accurate mechanical machining of structural parts, stiffness of links L1-L6 and joints J1-J6, sufficient resolution of position sensors, proper tuning of PID motor control loops, kinematics calibration of the manipulator, etc.

In this context, the aforementioned absolute position sensors (e.g. 65, 88, 108, 148) provided at the output of each joint J1 to J6 provide the following advantages:

- Homing the joints J1 to J6 of the robot manipulator 14 without actuating the joints; this means that the initial value of the incremental sensors used to control the motors, is provided by the absolute sensors. If absolute sensors were not available, a homing procedure could be implemented moving every joint in a giving direction to find a reference signal. No automated moves for homing at start-up ensures a fast set-up procedure and improved safety.
- Real-time determination of position and orientation of the effector unit 30 avoiding joint elasticity errors caused by transmission mechanisms;
- Monitoring deviations of the robot manipulator 14 from the FRF;
- Detecting a joint transmission failure (e.g. belt rupture) or other hardware failure by monitoring data consistency using the positions indicated by the respective motor encoder provided at each joint J1-J6.

Another aspect in robotics is the mathematical model used to control the robot manipulator 14. Departing from a theoretical model of the robot manipulator 14, the

effective and accurate "concrete" model, including parameters such as offsets to the kinematics arrangement, elasticity of joints J1 to J6, elasticity of links L1 to L7, actuators backlash and other linearity errors is necessarily determined during a calibration process. The identified "concrete" manipulator model is used for three purposes: firstly, to improve accuracy of the robot manipulator 14 using the theoretical model in the motion controller (which simplifies the inverse kinematics calculation) with real joints offsets and links lengths; secondly, to accurately compute, in real time through forwards formulation, the position and orientation of the 6-DOF FTAS 122 and the loads attached, (these values are required for compensating gravitational and acceleration loads); thirdly, to determine, in real time through forwards formulation, the position and orientation of the instrument tip and deduce parameters required for force-reflection (e.g. the penetration of the instrument 18).

The following paragraphs give a more detailed description of the laparoscopic instrument actuator (LIA) 120.

As seen in Figs.14 and 15, the LIA 120 forms part of the effector unit 30. The LIA 120 provides a generic actuation interface for using standard laparoscopic instruments such as grasping/dissecting forceps, scissors, suction/irrigation tools, etc. with the robot manipulator 14. Hence, the LIA 120 forms the extremity the manipulator 14 and represents its hand part since it reproduces the actions of a surgeon hand. The LIA 120 comprises a housing 154 the rear end of which forms an interface flange 156 for connection to the FTAS 122 whereas its front end forms the extremity of the robot manipulator 14. In a different configuration of an effector unit, a LIA could include joint J6. This configuration requires however a more complex mechanical design of the instrument adaptor that shall include a rotation mechanism together with the open-close mechanism and power-transmission. In addition, the sterile field should be maintained even with the rotation mechanism.

The LIA 120 shown in Figs.14-15 and Figs.18-22 is adapted for use with any standard laparoscopic instrument that can be divided into a handle on one side, and a stem on the other side. Herein the stem is defined as comparatively thin elongated tube having at its tip, for example, forceps/scissor jaws inserts, suction/irrigation means, basic tools like a knife or an electric cautery/cutting device. The end opposed to the tip comprises a socket which is designed to connect the stem to the handle for the surgeon.

Compatibility of the robot manipulator 14 with standard instruments is achieved by the design of the LIA 120 and the design of corresponding instrument stem adaptors, in the

following referred to by the acronym ISA, of which an example is shown in partial sectional view in Fig.17.

Fig.17 shows the ISA (instrument stem adaptor) 300 to which an instrument stem 302 can be connected. The ISA 300 is connectable to the LIA 120 by mounting it into the seat 130 shown in Fig.15. To this effect, the ISA 300 comprises a case 303 with an essentially cylindrical outer surface. As seen in Fig.17, the ISA 300 is designed as a coupling element between the instrument stem 302 of a conventional (laparoscopic) instrument, and the LIA 120. To this effect, the ISA 300 comprises a stem connector 304 at its front end. The stem connector 304 is designed for connection to a specific type socket 306 of the stem 302, which depends on the actual instrument. Originally, the socket 306 is designed for connection to a laparoscopic instrument handle (not shown). As seen in Fig.17, the stem connector 304 reproduces the connector of the original handle for which the stem 302 was designed. The ISA 300 further comprises a coupling member 308 for secure connection to the LIA 120. The coupling member 308 is arranged laterally on the case 303 and protrudes radially therefrom so as to block rotation of the ISA 300 when it is mounted to the LIA 120. A small metallic block 309 is included in the coupling member 308 in order to provide a metallic detection surface for an inductive presence switch (cf. part 404 described below) of the LIA 120. A linearly slideable piston 310 is arranged in a cylindrical guide 312 internal to the ISA 300. A cylindrical slider pin 314 is attached transversely to the piston 310 and protrudes out of the case 303 for operating the piston 310. Sliding operation of the piston 310 actuates a rod inside the instrument stem 302 for operating the tool at the tip of the instrument stem 302. As will be appreciated, the ISA 300 reproduces the functionality of the handle originally connected to the stem 302 as regard operating the instrument stem 302, while providing together with the LIA 120 a connection interface to the robot manipulator 14.

It will be understood that the specific embodiment of the ISA 300 shown in Fig.17 is designed for an instrument requiring mechanical actuation such as an open/close function for the instrument tip, for example, scissors and graspers with or without unipolar or bipolar electric power transmission. A variety of other types of analogous adaptors are also encompassed by the present disclosure, each adaptor being adapted to a specific type of laparoscopic instrument, i.e. a specific type of stem (e.g. 302), which is to be connected to the LIA 120. Accordingly, the ISA comprises, depending on the requirements of the instrument, a linear slider pin 314 e.g. for actuation of the jaws of the instrument, one or more electrical connectors 318, e.g. for unipolar or bipolar

cautery power, etc, and/or one or more conduit connection(s), e.g. for irrigation or suction instruments. Although shown in Fig.17 with electrical connectors 318, it will be understood that for a purely mechanical instrument 18, the parts of the ISA 300 forming the electrical connectors 18 (drawn in thin line width in Fig.17) need not be provided. It may be noted that the constituent material of any type of ISA shall be chosen such that it can be sterilized e.g. through a steam autoclave. In fact, by virtue of the design of the LIA 120, the ISA is the only part of the medical robotic system 10 that needs to be sterilized (besides the instrument stem of course). During operation, the housing 154 of the LIA 120 and the other parts of the effector unit 30 are enclosed in a sterile plastic bag. Although not shown, it is apparent that, for mechanically non-actuated but electrically powered instruments such as electro-bistouries or knives, the ISA does not need to have the slider pin 314 and an associated mechanical transmission. For instruments such as an irrigation or suction canula, the ISA is equipped with two tubes that are remotely commanded through electro-valves electrically actuated by the robot control system.

The LIA 120 shown in Fig.18 is designed lightweight (e.g. less than 800g of total weight) and so as to fit into a relatively small cylindrical envelope of about 90mm or preferably 75mm of diameter to increase the available workspace of two adjacent tools with nearby access ports 20. The total length of the LIA 120 (about 130mm in a specific example) is mainly determined by the length of the ISA 300. The length of the LIA 120 is minimised in order to limit the distance between the rotation axis of the joint J5 and the pivot point 206 of the FRF (see Fig.17). In fact, this distance offset is determining for the travel range and speed/acceleration capabilities of all manipulator joints J1 to J5. It is however recommended that the length of the LIA 120 be at least 6 cm in order to allow gripping the LIA 120 by hand in manual mode (i.e. using the housing 154 connected to the FTAS 122 as a "joystick").

As seen in Fig.18, the outer surface of the housing 154 has smoothed edges. It is made of an easily cleanable, lightweight and non-conductive material. Moreover, the LIA 120 has a partially rotationally symmetric design with respect to the stem 302 of an adapted instrument 18 mounted using an ISA 300. When the ISA 300 is properly connected to the LIA 120, the axis of the stem 302 coincides with the roll axis of joint J6 and with the normal axis of the FTAS 122.

As further seen in Fig.18, the housing 154 of the LIA 120 comprises a linear actuation mechanism 400 for actuating a mounted instrument 18 by means of the ISA 300 as will be detailed below. The seat 130 is formed as a concave elongated semi-cylindrical

recess in an access surface 401 of the LIA 120 to facilitate insertion and extraction of the ISA 300. The seat 130 for receiving the ISA 300 is approximately coaxial to the rotation axis of the joint J6 and extends along the central axis of the housing 154. As will be appreciated, the mounting and removing direction of the ISA 300 with respect to the LIA 120 is radial relative to the rotation axis of the joint J6. The LIA 120 is configured such that the seat 130 is accessible from the entire half plane above the access surface 401. As seen in Fig.18, the seat 130 comprises a longitudinal groove 402 which deepens the seat 130 radially into the body of the LIA 120. The additional groove 402 is configured for receiving the coupling member 308 of the ISA 300. The engaging part of a locking mechanism 406 associated to the seat 130 is arranged in the groove 402 and cooperates with the coupling member 308. The seat 130 is formed as a semi-cylindrical recess with a rounded end portion conformed to the outer cylindrical shape of the case 303 of the ISA 300. A presence detector 404, e.g. an inductive presence switch, is arranged in the seat 130 for presence detection of the ISA 300 by sensing the metallic block 309 (see Fig.17). A dead-man switch button 408 allows switching the control system of the robot manipulator 14 to manual mode. In manual mode, the LIA 120 (and, if connected, the instrument 18) is positioned and oriented by the robot manipulator 14 using the information produced by the assistant handling the housing 154 of the LIA 120 and read by the FTAS 122. Manual mode is particularly useful for inserting or extracting an instrument through a trocar.

Details of the linear actuation mechanism 400 are best seen in Fig.20. The actuation mechanism 400 comprises a miniature brushless motor 411 connected via a gearbox 412 and pulleys 414 and 416, which are coupled by a belt 418, to a ball-screw 420. The ball screw 420 cooperates with a nut 422 arranged thereon so as to transform rotation into linear motion as seen in Fig.19. The nut 422 is guided by a linear guide 424 in order to reduce transversal efforts on the ball-screw 420. Inductive limit switches 426 and 428 are placed at the end-of-travel locations of the nut 422 and connected to a control unit for limiting travel of the actuation mechanism 400.

As seen in Fig.19, the actuation mechanism 400 communicates linear motion to a slider carriage 430 of the LIA 120, as will be detailed below. In a preferred embodiment, the following parameters were chosen for the actuation mechanism 400:

- maximum mechanical travel of the slider carriage 430: 7mm (normally 5mm are sufficient for standard instruments, but it has been found that several stems of the same type may have travel lengths varying by up to 2mm);
- travel speed range: from 1mm/sec to 20mm/sec;

- maximum actuation force: 200N;

Stepper motors are preferably avoided in the LIA 120 because they produce vibrations that would be a considerable source of noise for the FTAS 122. Therefore, a miniature brushless motor 411 equipped with a shaft position encoder is used. Such motors are available e.g. from Faulhaber GmbH, Schoenaich, Germany. Other non-vibrating linear motion mechanisms such as cable-driven transmission are however not excluded.

Fig.20 shows a power and control unit 440 for the motor 411 which is embedded in the housing 154 of the LIA 120 and supplied e.g. with 24VDC power. In order to further reduce the diameter of the housing 154, the power and control unit 440 may be placed in an additional housing either between the flange 156 and the FTAS 122, or between the FTAS 122 and a connection flange to the joint J6 (not shown), or inside the cover 124 of the joint J6, e.g. behind the slip-ring collector 80 close to the motor 141. The power and control unit 440 is designed inter alia for actuating the slider carriage 430 with a given speed profile according to received position commands, for limiting motor current on user demand, for managing motion based on signals from limit switches 426, 428, for homing the motor 411 using a limit switch, and for monitoring the presence detector 404 on the housing 154. Other safety functions, e.g. emergency-stop functions, are also implemented using a servo error of the motor 411, i.e. target position minus effective position, and thermal protection of the motor 411. In order to reduce required space for the LIA 120, the linear actuation mechanism 400 is not equipped with an absolute position sensor. Nevertheless, an automated homing procedure is ensured by using limit switches 426 and 428 as home sensors. During operation, the absolute position of the slider carriage 430 can be periodically recorded, e.g. in a suitable memory of the robot control system, for fast recovery of the system after a power shutdown or failure. Presence of the ISA 300, i.e. whether it is correctly mounted to the LIA 120, is sensed through the inductive presence switch 404 (see Fig.18) arranged in the seat 130. The output of the inductive presence switch 404 is fed to an available input of the control unit 440.

As best seen in Figs.17 and 19, the slider carriage 430 of the actuation mechanism 400 is adapted to receive the slider pin 314 of the ISA 300. By action of the motor 411, the slider carriage 430 is repositioned so as to drive the slider pin 314 of a connected ISA 300. The slider pin 314 in turn actuates the piston 310 to operate a working element or tool at the tip of the stem 302 (not shown), e.g. a jaw open/close mechanism. In other words, the combination of linear actuation mechanism 400 and ISA 300 simulates action of the handle which has been removed from the stem 302 and replaced by the

ISA 300. Insertion of the slider pin 314 into the slider carriage 430 is facilitated by bevelled guiding surfaces 434.

Fig.21 and Fig.22 show in more detail the configuration of the locking mechanism 406 of the LIA 120 only partially shown in Fig.18. The locking mechanism 406 is configured as latch and comprises a slideable catch 450 arranged in the groove 402 (shown in Fig.18) of the seat 130. It will be understood that the catch 450 is guided by suitable means in the groove 402. The groove 402, together with the slideable catch 450, are configured for engagingly receiving the coupling member 308 of the ISA 300 shown in Fig.17. The catch 450 comprises two noses 452 for engaging two protrusions 316 formed by slots in the coupling member 308 (see Fig.17). The edges of the coupling member 308 are rounded to ease insertion and removal in/from the groove 402.

The design of the catch 450 is best seen in Fig.22. A spring 454 resiliently urges the catch 405 towards the FTAS 122. A linearly guided knob 456 allows to rotate a pivot 458 which is coupled to the linearly guided catch 450 in order to manually disengage the catch 450 from the coupling member 308 when the ISA 300 is to be removed. The noses 452 of the catch 450 are bevelled so as to allow insertion of the ISA 300 simply by pushing. The engaging portions of the noses 452 and the protrusions 316 are rounded according to a conjugated profile in order to limit damages to a sterile plastic sheet used for covering the LIA 120. As will be understood, other equivalent coupling or locking mechanisms could also be used, for example using permanent magnets installed in the LIA with metallic plates and a cam-based lever mounted on the ISA to replace the latch mechanism. It is preferred that the fixation mechanism, e.g. the locking mechanism 406 and coupling member 308, is designed to ensure that the ISA 300, when mounted to the LIA 120, can resist to the following forces and moments without disconnecting from the LIA 120:

- traction and compression forces of 100N;
- torsion moments corresponding to radial forces of 15N at the instrument tip;
- bending moments of up to 5Nm.

It will be appreciated that the LIA 120 and each cooperating ISA (e.g. 300) are designed for fast and easy manual installation and removal of an adapted laparoscopic instrument 18, i.e. a stem (e.g. 302) assembled with an ISA (e.g. 300), by the surgeon assistant A. The essentially cylindrical outer shape of the ISA 300, its coupling member 308, the seat 130, the groove 402 and the locking mechanism 406 as described above provide guided insertion and a simple connecting procedure of the ISA 300 to the LIA 120. The design ensures the required stiffness when the ISA is inserted and a simple

extraction procedure by means of a few manual moves. By means of this design, insertion and extraction of the adapted instrument 18 (i.e. stem and ISA) can be carried out essentially as fast as in manual surgical operations, where the assistant replaces a conventional instrument for the surgeon in about 6-9 seconds.

- 5 It should be noted that insertion or removal of an adapted instrument 18 comprising the ISA (e.g. 300) and the stem (e.g. 302) can be done safely in both cases, when the instrument is outside the body of patient P or when the instrument is inserted in the body of patient P. It is also possible to carry out removal while the slider pin 314 is driven.
- 10 Before mounting the adapted instrument to the LIA 120, a number of preliminary conditions should be met. Firstly, if the instrument is partially inserted in the trocar (without exceeding the trocar length), the LIA 120 should previously be positioned and oriented by the manipulator 14 into a taught position that aligns the rotation axis of the effector unit 30 (joint J6) with the trocar. Secondly, the slider carriage 430 should be
- 15 placed into the "insertion reference position" by the robot control system, e.g. a position closest to the interface flange 156. When an ISA (e.g. 300) is removed, the slider carriage 430 should be automatically moved into this "insertion reference position" by the robot control system. As mentioned above, presence, absence or abnormal release of an ISA can be detected by the presence detector 404. Thirdly and if present, the
- 20 slider pin (e.g. 314) of the ISA (e.g. 300) should be in an "insertion reference position" corresponding to that of the slider carriage 430. This position of the slider pin 314 is preferably defined such that instrument is in "closed" configuration, for example, the jaws of a forceps/scissor instrument are loosely but sufficiently closed in this position. As best illustrated by Fig.14, the insertion procedure of an adapted laparoscopic
- 25 instrument 18 including an ISA (e.g. 300) and a stem (e.g. 302) can be carried out by only one simple manual move according to arrow 460 consisting of placing the ISA (e.g. 300) on its seat 130 and of slightly pushing on the ISA along the same direction to engage the coupling member 308 with the locking mechanism 406. The presence detector 404 gives an affirmative output when the coupling member 308 is correctly
- 30 installed in the groove 402. During this insertion procedure, the slider carriage 430 engages the slider pin 314 without the need for further measures, if the aforementioned conditions have been met.

When the surgeon S requests an instrument change through his master console 15, four operations are normally carried out automatically by the robot control system.

- 35 Firstly, the robot control system controls the instrument 18 to release any tissue.

Secondly, it moves the instrument near the trocar port following the instrument axis direction. Thirdly, the tool tip, e.g. the instrument jaws, are brought into a configuration which avoids hooking of the tip at the trocar. Fourthly, it releases the motor of joint J6 such that the surgeon assistant A can freely rotate the LIA 120 to facilitate removal of the instrument from the LIA 120. After these operations, removal of an adapted laparoscopic instrument 18 can be carried out safely in two simple moves and at any time.

The first extraction move consists of pushing the knob 456 so as to unlock the locking mechanism 406. The second extraction move consists of pivoting the ISA (e.g. 300) and the stem (e.g. 302) about the tip of the stem by rotation about an axis perpendicular to the stem axis so as to remove both from the seat 130 and subsequently, if still inserted, so as to extract the stem (e.g. 302) from the body of patient P.

As is apparent from the above insertion and removal procedures, the design of the LIA 120 and ISA (e.g. 300), enables instrument insertion or extraction even when the stem (e.g. 302) of an adapted instrument 18 is still partially inserted in the body of patient P through the trocar 200 (see Fig.16). As will be appreciated, the moves required for extraction are not in the penetration direction with respect to the patient P since they consist of a pivoting move perpendicular to the longitudinal axis of the seat 130 and a subsequent extraction move. Moreover, in case a move in a given pivoting direction could harm the patient, this direction can be changed by rotating the LIA 120 by hand LIA through joint J6. In addition, in case of power failure, an ISA (e.g. 300) together with its stem (e.g. 302) can be released and extracted manually.

With respect to the LIA 120 as described above, it will be appreciated that a wide variety of existing standard laparoscopic instruments can be used in the robotic system 10 by means of simple instrument stem adaptors (ISA) (e.g. 300). The LIA 120 in combination with a corresponding ISA replaces the handle part of a given laparoscopic instrument without loss of actuation or power supply capability. The LIA 120 is generically designed i.e. independent from the type of instrument that is to be coupled to the robot manipulator 14. Hence, only the ISA (e.g. 300) needs to be designed specifically in accordance with the instrument requirements. As described above, the LIA 120 is capable of providing inter alia the following functions:

- “open/close” actuation of instrument tool tips, e.g. of instrument jaws, using the linear actuation mechanism 400;
- adapting the required “open/close” travel length for every type of instrument;

- handling non-actuated instruments like knives through action of the robot manipulator 14.

Furthermore, the LIA 120 permits beneficial cost-effectiveness in robotic laparoscopy because of several factors. Firstly, as opposed to prior art devices which require several actuators per manipulator because the instrument and the associated actuator are assembled as single unit in a single enclosure, only one LIA 120 is needed for each manipulator 14. This allows savings inter alia on actuator costs. Secondly, instrument costs are reduced by using the stems (e.g. 302) of standard laparoscopic instruments and a corresponding instrument stem adaptors (e.g. 300) of simple construction. Therefore, the cost of an adapted instrument 18 for use with the LIA 120 is almost identical to the cost of a standard manual laparoscopic instrument (i.e. including the handle). Thirdly, instrument maintenance costs are essentially equal to those for standard laparoscopic instruments because the ISA (e.g. 300) design is robust against sterilization cycles.

Turning to Fig.25, an alternative embodiment of a LIA 1120 will be described. Since many aspects and advantages of the LIA described herein above also apply to the LIA 1120, only the main features and differences will be detailed hereinafter.

The LIA 1120 shown in Fig.25 has a semi-cylindrical housing 1154 that has an upper substantially flat access surface 1401 for facilitating mounting and removing of an ISA to the LIA 1120. The opposite surface 1155 of housing 1154 is semi-cylindrical in conformity with a cylindrical envelope that is coaxial to the rotation axis of J6. The diameter of the semi-cylindrical surface 1155 is chosen ergonomically to allow handling by a human operator, e.g. in the range of 50-135mm, preferably of about 90mm, especially for commanding the robot manipulator 14 in the manual mode mentioned above. Since the semi-cylindrical housing has a substantially smaller cross-section than the interface flange 156 by means of which the LIA 1120 is attached to the FTAS 122, the housing 1154 further includes gradual reinforcing ribs 1157. The reinforcing ribs have a gradual i.e. smoothly growing shape starting from access surface 1401 up to the upper edge of the interface flange 156. The reinforcing ribs 1157 are further curved in conformity with the cylindrical envelope of the semi-cylindrical surface 1155. The reinforcing ribs 1157 connect the access surface 1401 to the interface flange 156 and thereby reinforce and increase the rigidity of attachment of the housing 1154 to the interface flange 156. Thereby the reinforcing ribs 1157 ensure a more accurate transmission of forces and torques from an ISA via the LIA 1120 to the FTAS 122. It may be noted that similar reinforcing ribs are also provided in the LIA 120 of Fig.14.

Fig.25 further shows an alternative coupling mechanism for mounting an instrument stem adaptor to the LIA 1120 and thereby to the effector unit 30. In the LIA 1120, as in the LIA 120, a seat 1130 is formed as a concave elongated semi-cylindrical recess in the access surface 1401 to provide self-centering of an adaptor on the rotation axis of J6. Furthermore, the coupling mechanism comprises a plurality of magnetic devices 1423, two on the side of the slider carriage 1430 and one on the other side of the seat 1130, the latter one being arranged on an elevation 1425 off the access surface 1401. The elevation 1425 provides an additional retaining constraint in axial direction to a mounted adaptor and permits self-adjusted positioning in axial direction of the adaptor by slopes towards the access surface 1401. As will be understood, the magnetic devices 1423, which can be electromagnets, permanent magnets or a combination of both, ensure fastening of a correspondingly designed ISA by means of magnetic attraction. Avoiding a mechanical snap-in attachment eliminates the risk of damage to a sterile plastic cover used to wrap up the manipulator 14 or at least the effector unit 30.

Fig.25 illustrates a plurality of inductive presence sensors 1431 for identifying an instrument mounted to the effector unit 30 by means of an inductively identifiable material pattern provided on an ISA. Four inductive presence sensors 1431 are arranged in a row and allow to distinguish and identify 16 instrument types when using a binary code (4 bit word) based on the presence or absence of conductive material in a row of corresponding locations on the ISA facing the inductive presence sensors 1431. Furthermore, the inductive presence sensors 1431 also allow for presence detection if the pattern code (4 bit word) corresponding to an absent instrument is used for this purpose, i.e. when no conductive material faces any inductive sensor 1431.

An engagement member 1433 is separately shown in Fig.25. The engagement member 1433 is part of the actuation mechanism which includes the slider carriage 1430 and has bevelled capture surfaces 1434 leading into a slit for engaging the slider pin 314 of an ISA. The bevelled surfaces 1434 facilitate insertion of the slider pin 314 of an ISA. As will be appreciated, the engagement member 1433 is detachable from the slider carriage 1430 and made of sterilization compatible material. The engagement member can thereby be installed on the carriage 1430 only after a sterile wrap covers the LIA 1120. Since the motion range of the carriage 1430 is limited, no damage to the sterile wrap can occur.

Fig.26 shows an alternative embodiment of an ISA 1300 mounted to the LIA 1120 of Fig.25. The ISA 1300 is designed to be compatible with the alternative design of LIA

1120 and will be detailed hereinafter. The ISA 1300 is dimensioned such that its base is confined to the access surface 1401. The function of the ISA 1300 is the same as that of the ISA 300 shown in Fig.17, namely to provide an interface allowing the use of stems 302 of standard manual laparoscopic instruments on the robot manipulator 14
5 without loss of any functionality available in manual interventions. Fig.26 also shows a switch button 408 provided on the LIA 1120 for switching the system to manual mode. The ISA 1300 is provided with a lever 1301 for easy manual demounting i.e. separating the ISA 1300 from the LIA 1120. The ISA 1300 also has an electrical connector 1308 for connecting powered instruments (e.g. coagulation or cutting instruments) directly to
10 an electrical power source without wires passing through the LIA 1120.

As is apparent from Fig.25 and 26, the design is such that all components of the LIA 1120, including the housing 1154, the flange 156, the reinforcing ribs 1157, the FTAS 122 sensor assembly and all parts of the mounted ISA 1300, including lever 1301 are located within the cylindrical envelope defined by the semi-cylindrical surface 1155.
15 This is to reduce the risk of collision and damage when the LIA 1120 is rotated by J6.

Fig.27 shows an alternative actuation mechanism 1400 for communicating linear motion to the slider carriage 1430, differing in design from the mechanism of Fig.19. It comprises a miniature brushless motor 1411 connected via gearbox 1412 and a ball screw or worm gear 1420 to a nut member 1422. The carriage 1430 is fixed to the nut member 1422 via the intermediate of a force sensor 1427. The force sensor 1427 allows to measure forces exerted by the carriage 1430 onto the slider pin 314 and vice-versa. It will also be appreciated that the by virtue of mounting the slider carriage 1430 to the side of the longitudinal seat 1130, the motor 1411 and connected gears can be arranged in parallel to the longitudinal axis of ISA 1300 and stem 302. This allows
20 minimizing the total length of the LIA 1120 whereby the requirements on actuator dynamics for certain joints (e.g. J4) are reduced. Furthermore, it will be appreciated that this actuation mechanism 1400 is optimized with respect to producing detrimental vibration. Other aspects and advantages of the drive mechanism 1400 are similar to those of the mechanism 400 described herein before.

30 Fig.28 shows the underneath side of the ISA 1300 of Fig.26 when detached from the LIA 1120. The ISA 1300 comprises an elongated case 1303 with a stem connector 1304 at its front end (see Fig.30). The stem connector 1304 enables removable connection to a type socket 306 fixed to the stem 302 (only partly shown) of a standard manual laparoscopic instrument as long as any type of detachable connection is
35 provided. Of course, connector and socket could respectively be located on stem and

ISA. Similar to the case 303, the case 1303 has a semi-cylindrical surface on its underneath side for cooperation with the seat 1130. As seen in Fig.28, lateral wings 1305 protrude from either side of the case 1303. The lateral wings 1305 have a flat lower surface that is conjugated to the access surface 1401 on the LIA 1120 (e.g. also to the elevation 1425). A cut out space 1307 is provided in one wing 1305 above the slider pin 314 for providing visibility and access, e.g. for manually moving the slider pin 314 when the ISA 1300 is coupled to the LIA 1120. Fig.28 also shows flat ferromagnetic elements 1311 arranged in each wing 1305 on either side of case 1303. The ferromagnetic elements 1311 form coupling means that cooperate respectively with a corresponding magnetic device 1423 on the LIA 1120 as shown in Fig.25. In the region 1313, an inductively identifiable pattern is provided on the ISA 1300 for identifying, by means of the inductive sensors 1431 shown in Fig.25, the instrument that is used. In this embodiment shown in Fig.25 a full metallic plate corresponds to a given 4 bit word (e.g. 1111 or 0000) whereas in other adapters voids can be provided, e.g. by drilling holes in one or more of the positions facing the inductive sensors 1431 to give a different bit word for identification.

Fig.29 shows the ISA 1300 of Fig.28 in partly dismantled view. As seen in Fig.29, the ISA 1300 has an internal hollow serving as a cylindrical guide 1312 for a piston 310 of a certain manual laparoscopic instrument. The piston 310 is typically used in the manual instrument for communicating motion from the instrument handle to the shaft guided in the stem 302. It will be appreciated that the existing piston of a manual instrument can be arranged to slide in the guide 1312. As seen in Fig.28, an oblong through hole 1315 is provided in the case 1303 allowing the slider pin 314 attached transversely to the piston 310 to protrude from the case 1303 and to be shifted forward and backward in axial direction of the case 1303 for operating the piston 310. The piston 310 shown in Fig.29 is an original part of a manual bipolar instrument, used to provide bipolar electric power to the instrument and to lock/unlock the instrument.

Fig.30 is to illustrate that the same type of adaptor can be used to accommodate different pistons of different types of commercially available laparoscopic instruments for manual intervention, e.g. the piston 1310 for a monopolar manual instrument as shown in Fig.30. It follows that the adaptors such as the ISA 1300 (or ISA 300) allow using the essential parts of any commercially available relatively inexpensive manual instrument on the robot manipulator 14. Fig.29 also shows one of the two tenons 1317 of the lever 1301 and the shaft 1319 on which it pivots. By pushing down the lever 1301, the tenons 1317 lift the lower surface, and in particular the ferromagnetic

elements 1311, of the ISA 1300 away from the access surface 1401 of the ISA 1120 such that the ISA 1300 can be manually removed in a direction perpendicular to the axis of rotation of J6 i.e. the instrument stem axis.

In addition to the aspects described herein above, the medical robotic system 10
5 further presents the following features:

- the robot manipulators 14, by virtue of their design, can be easily and quickly retracted to permit the surgeon S to access the operation table 12 or to permit installation of a radiological instrument;
- 10 - the robot manipulators 14, by virtue of their design and using information from an external sensor, can easily adapt with no significant increase of intervention time to angular variations of the operation table 12 during the intervention, for the (anti-) Trendelenburg (-/+20-35 deg.) or for sideways orientation of the patient;
- 15 - the robot manipulators 14, by virtue of their design and using information from an external sensor, can easily manage trocar position variations due to changes of the intra-abdominal pressure;
- 20 - the medical robotic system 10 enables short instrument change times in order to minimize total intervention time, the design of the LIA 120; 1120 and the robot manipulator 14 enable instrument change times essentially as short as in manual laparoscopy procedures (ranging from 6 to 9 seconds), when used with an endoscope, the design of the robot manipulator 14 also enables quick endoscope extraction and reinsertion, e.g. for cleaning the optics;
- 25 - the medical robotic system 10 enables rapid and simple set-up of the system, including the configuration of a plurality of robot manipulators 14 around the operation table 12;
- the robot manipulator 14 is designed versatile in order to be suitable for a variety of applications like minimally invasive surgery, orthopaedic, biopsy, percutaneous therapy, skin harvesting, ultra-sound diagnostics, etc.

30 While the present patent application as filed in principle concerns the invention as defined in the claims attached hereto, the person skilled in the art will readily understand that the present patent application contains support for the definition of other inventions, which could e.g. be claimed as subject matter of amended claims in the present application or as subject matter of claims in divisional and/or continuation

applications. Such subject matter could be defined by any feature or combination of features disclosed herein.

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(amended claims - 03/12/2007)

Claims

1. Medical robotic system for performing medical procedures comprising a robot manipulator (14) for robotically assisted handling of a medical instrument (18), wherein said robot manipulator comprises
a base (24);
5 a manipulator arm (26) having an essentially vertical part (27) supported by said base and an essentially horizontal part (29) supported by said vertical part;
a manipulator wrist (28) supported by said manipulator arm; and
an effector unit (30) supported by said manipulator wrist and configured for holding a medical instrument;
10 characterized in that
said manipulator arm (26) has a cylindrical PRP kinematic configuration, having, in sequence, a prismatic (P) first joint (J1) for varying the height of said vertical part by providing a translational degree of freedom along an essentially vertical axis, a revolute (R) second joint (J2) for varying the rotational angle between said vertical
15 part and said horizontal part by providing a rotational degree of freedom about an essentially vertical axis, and a prismatic (P) third joint (J3) for varying the reach of said horizontal part by providing a translational degree of freedom along an essentially horizontal axis.
2. Medical robotic system according to claim 1, wherein said first (P) joint (J1) has a
20 vertical linear guide (52) and a first linear actuator (50), preferably a linear ball screw axis, for actuating said first (P) joint (J1).
3. Medical robotic system according to claim 2, wherein said third (P) joint (J3) has a horizontal linear guide (73) and a second linear actuator (70), preferably a linear ball screw axis, for actuating said third (P) joint.
- 25 4. Medical robotic system according to claim 3 wherein said horizontal part comprises an elongated covering (74) which encloses said horizontal linear guide and said second linear actuator, said horizontal part comprising a beam (72) which telescopes with respect to said covering on one side and supports said wrist (28) on the other side.

5. Medical robotic system according to any one of claims 1 to 4, wherein said second (R) joint (J2) has a gear, preferably a harmonic drive gear (62), a motor (61), preferably a brushless servo-motor, coupled to the input stage of said gear, and an absolute position sensor (65) coupled to the output stage of said gear.
- 5 6. Medical robotic system according to any one of claims 1 to 5, wherein said horizontal part (29) of said arm has a minimum link offset of 800 mm.
7. Medical robotic system according to any one of claims 1 to 6, wherein said manipulator wrist (28) comprises a revolute (R) fourth joint (J4) and a revolute (R) fifth joint (J5) for orienting said effector unit (30).
- 10 8. Medical robotic system according to claim 7, wherein the axes of rotation of said fourth (R) joint (J4) and said second (R) joint (J2) are parallel.
9. Medical robotic system according to claim 8, wherein the axis of rotation of said fourth (R) joint (J4) is coplanar with the plane formed by the axis of rotation of said second (R) joint (J2) and by the axis of translation of said third (P) joint (J3).
- 15 10. Medical robotic system according to claim 9, wherein said fourth (R) joint (J4) provides a rotational degree of freedom along an essentially vertical axis for setting the yaw angle of said effector unit (30), and wherein said fifth (R) joint (J5) provides a rotational degree of freedom along an essentially horizontal axis for setting the pitch angle of said effector unit (30).
- 20 11. Medical robotic system according to claim 10, wherein said wrist (28) comprises a support plate (80) connected to said horizontal part (29) of said arm, and a substantially L-shaped support member (100), said fourth (R) joint (J4) jointing a first horizontal portion of said support member to said support plate (80), and said fifth (R) joint (J5) jointing a second vertical portion of said support member (100) to
25 a connecting means (32) for said effector unit (30), said wrist being configured such that the axes of rotation of said fourth (R) joint and said fifth (R) joint are perpendicular and have a point of intersection.
12. Medical robotic system according to any one of claims 1 to 11, wherein said effector unit (30) comprises a laparoscopic instrument actuator (120; 1120) having
30 means for mounting a surgical instrument (18) to said manipulator and a linear actuation mechanism (400; 1400) for actuating a mounted surgical instrument.
13. Medical robotic system according to claim 12, wherein said effector unit (30) comprises a main support frame (140) for connecting said effector unit (30) to said

wrist (28) and a revolute (R) sixth joint (J6) which joints said laparoscopic instrument actuator (120; 1120) to said main support frame, said sixth (R) joint providing a rotational degree of freedom along an axis which coincides with the longitudinal axis of a surgical instrument mounted to said laparoscopic instrument actuator, for setting the roll angle of said mounted surgical instrument.

- 5 14. Medical robotic system according to claim 13, wherein the axes of rotation of said sixth (R) joint (J6) and said fifth (R) joint (J5) are perpendicular.
- 10 15. Medical robotic system according to claim 13 or 14, wherein said manipulator wrist (28) is configured such that the axes of rotation of said sixth (R) joint (J6) and said fourth (R) joint (J4) are offset by a distance (O5) corresponding approximately to the diameter of the laparoscopic instrument actuator (120; 1120) at its largest cross-section.
- 15 16. Medical robotic system according to claim 13 or 14, wherein said effector unit (30) comprises a sensor assembly (122) comprising a 6-DOF force/torque sensor and a coincident 6-DOF linear and angular accelerometer, said assembly connecting said laparoscopic instrument actuator to said sixth (R) joint (J6).
- 20 17. Medical robotic system according to claim 7 or 13, wherein said fourth (R) joint (J4), said fifth (R) joint (J5) and/or said sixth (R) joint (J6) has a motor (81; 101; (141), preferably a brushless servo-motor, a gear (83; 103; 143) having an input stage coupled to the shaft of said motor, a belt transmission (84; 104; 144) coupled to the output stage of said gear for transmitting motion to the associated joint, and an absolute position sensor (88; 108; 25 148) coupled to said belt transmission.
18. Medical robotic system according to any one of claims 1 to 17, wherein said base (24) comprises a laser range scanner (22) for detecting intrusion of personnel into the workspace of said manipulator.
- 30 19. Medical robotic system according to any one of claims 1 to 18, wherein said prismatic (P) first joint (J1) and said prismatic (P) third joint (J3) respectively have an associated brake and an associated absolute position sensor.

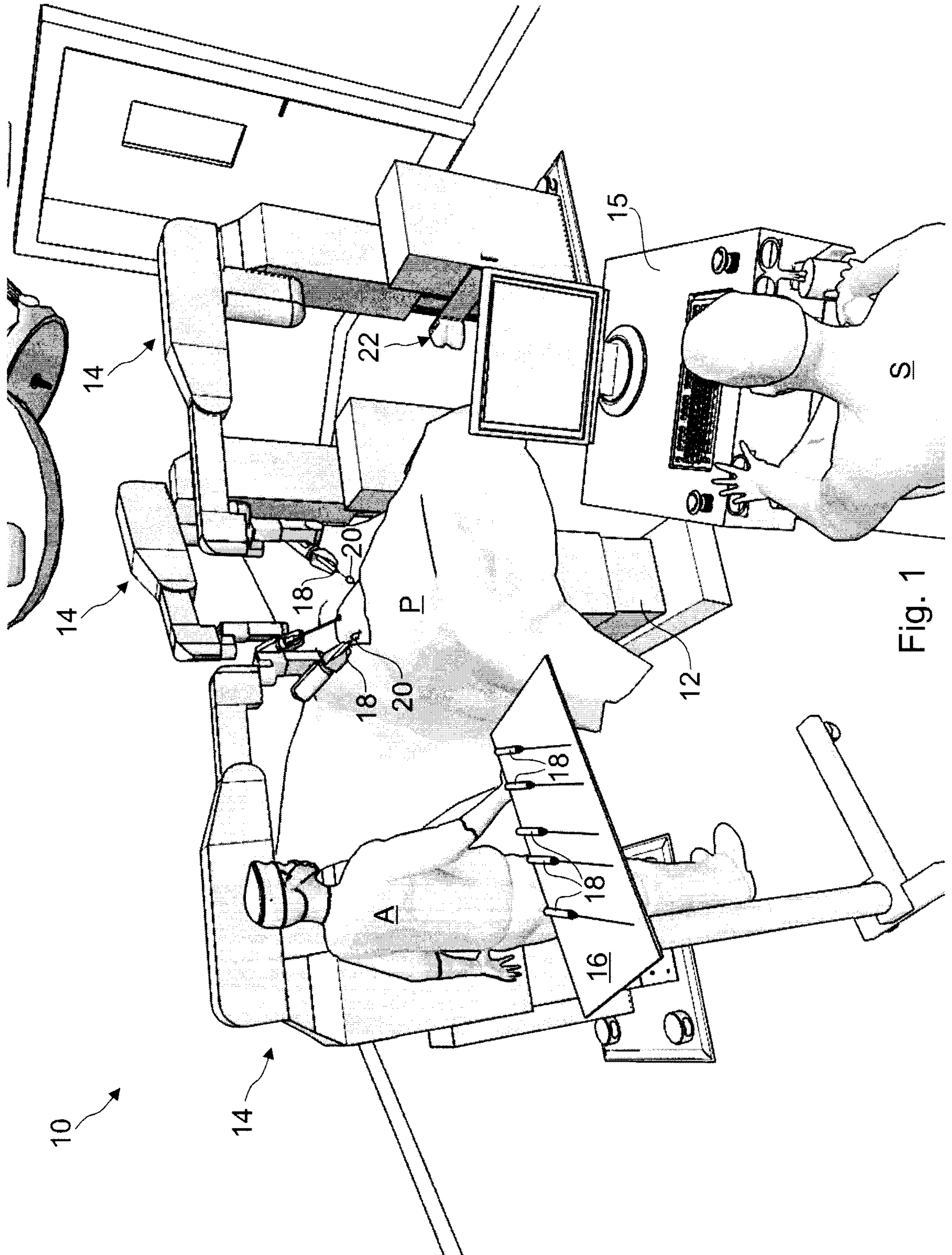


Fig. 1

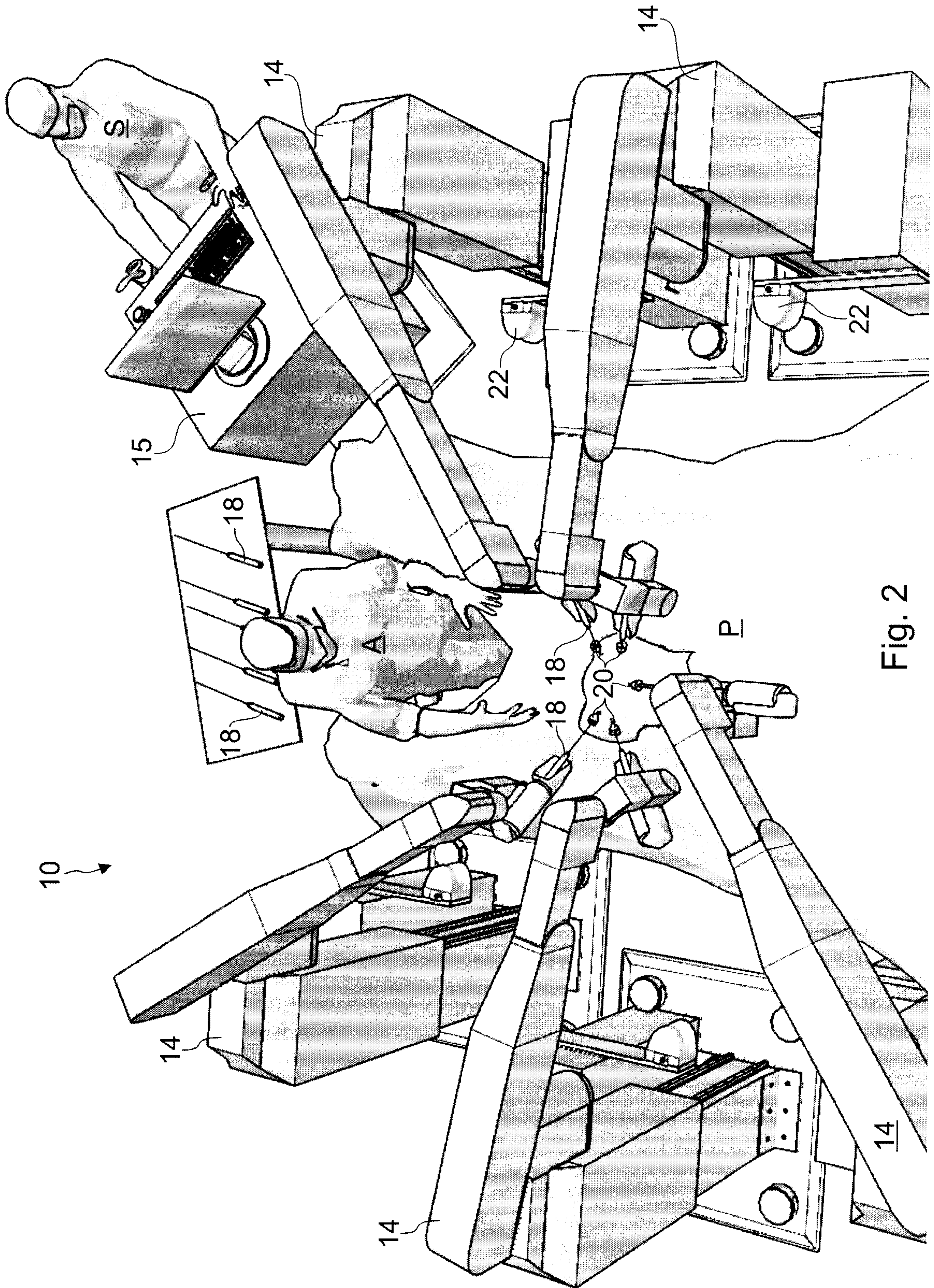


Fig. 2

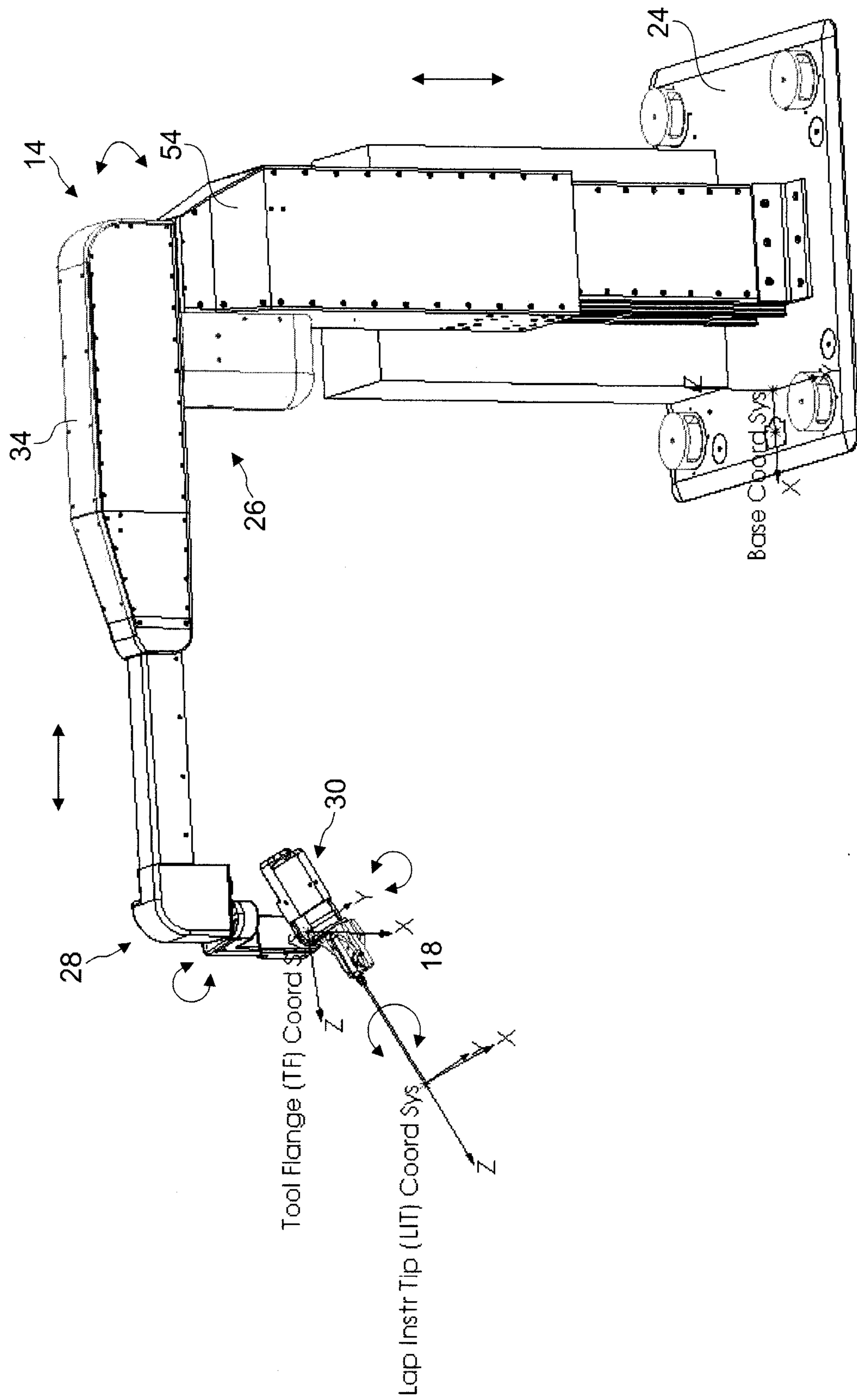


Fig. 3

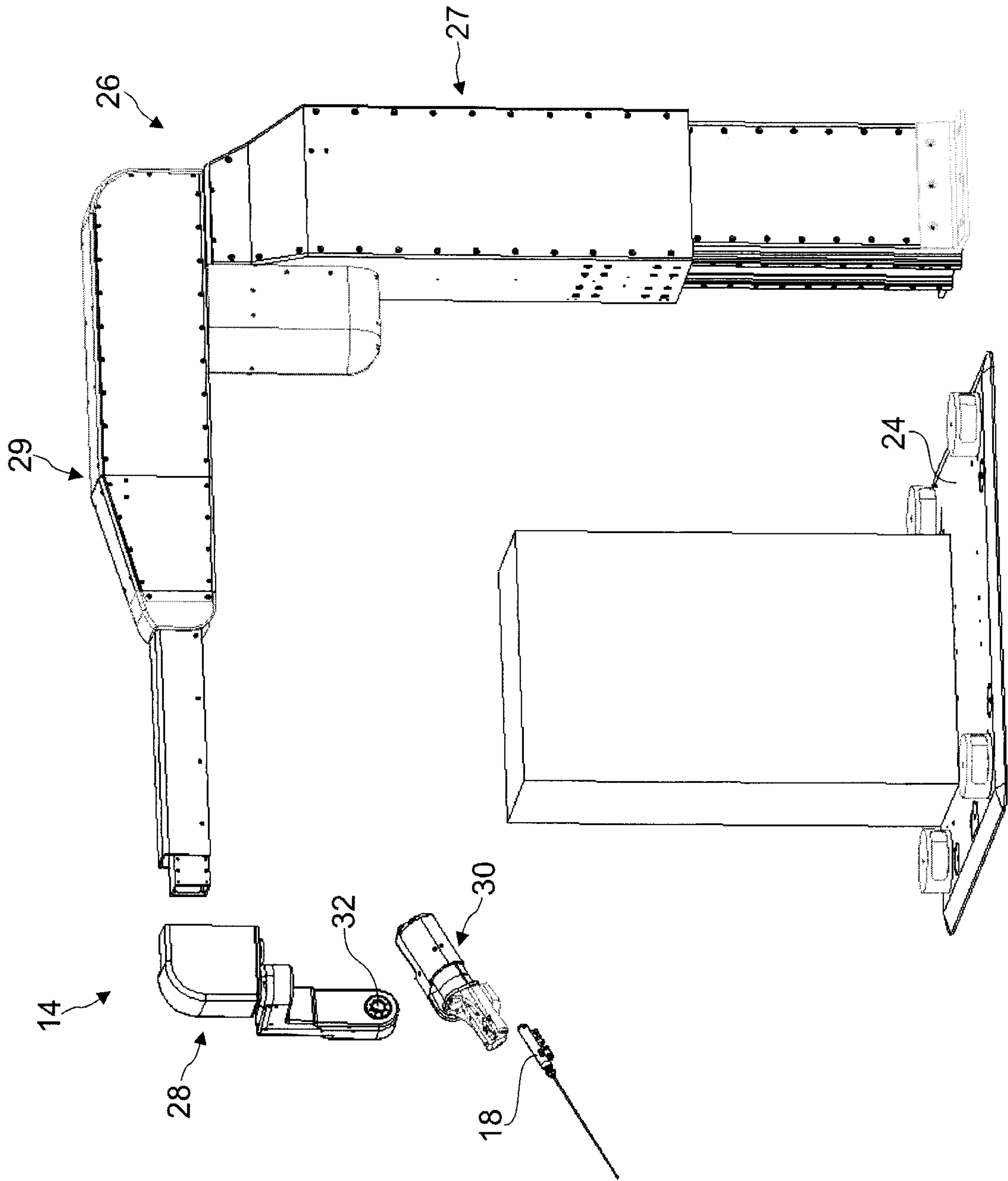


Fig. 4

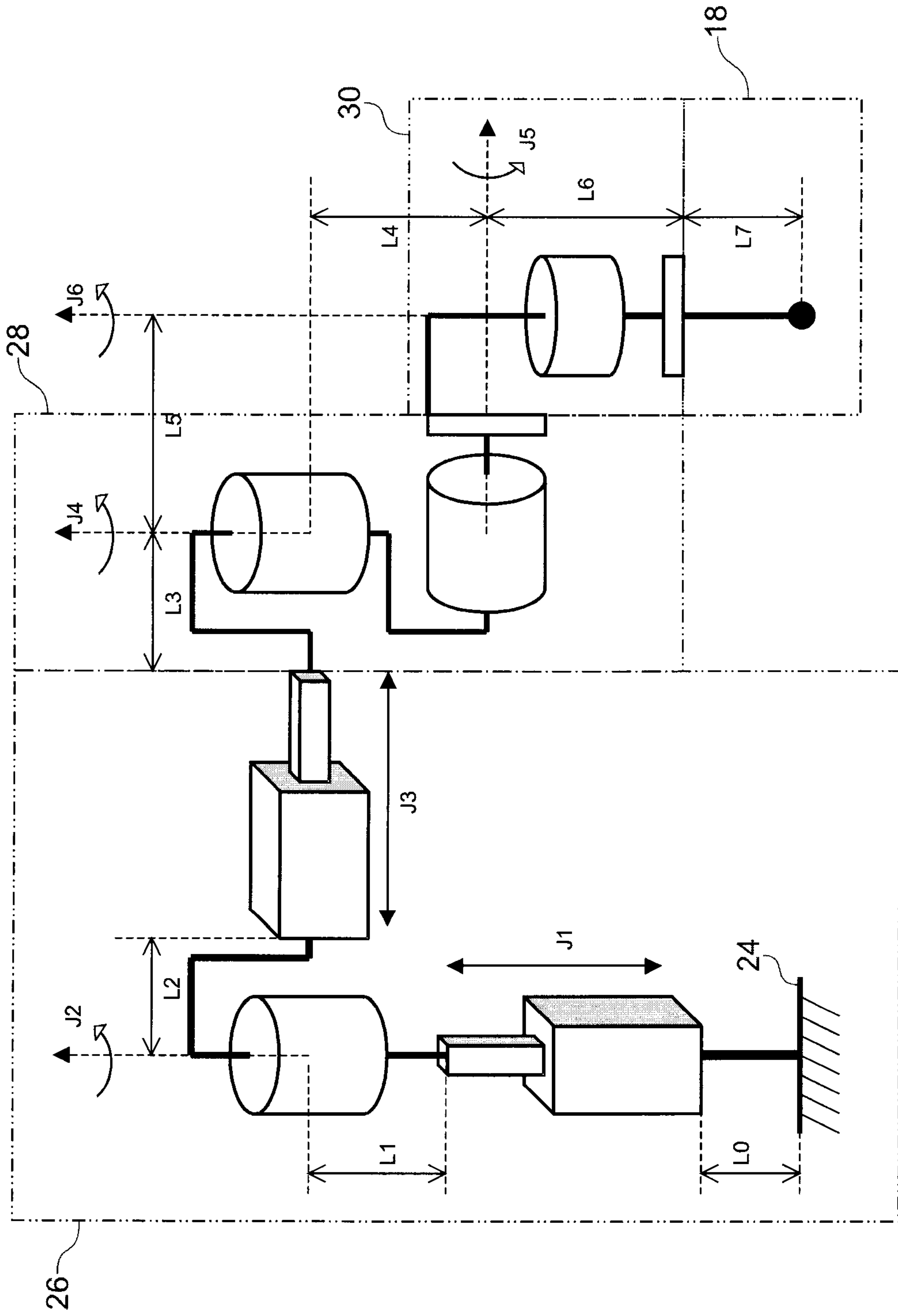
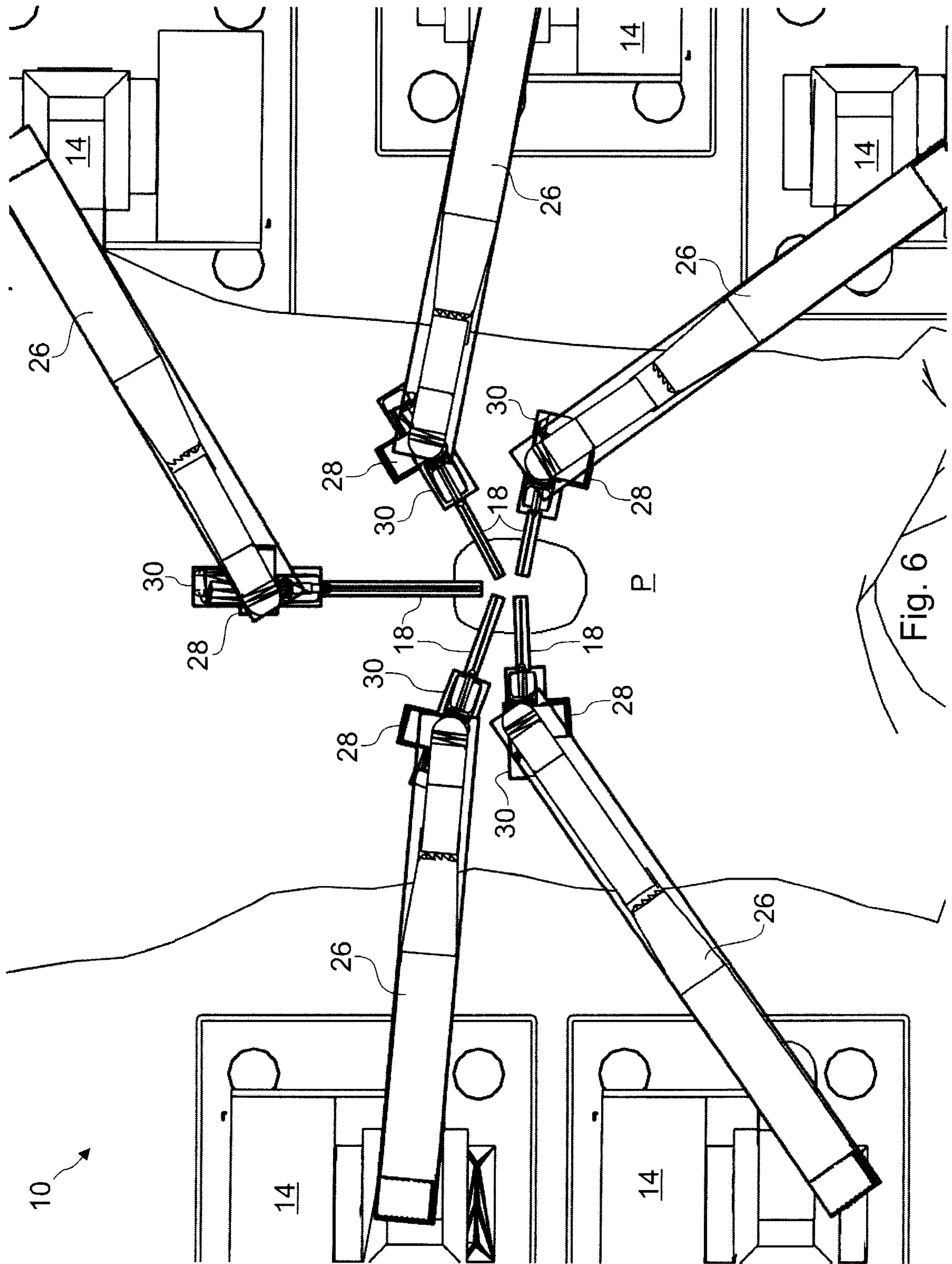


Fig. 5

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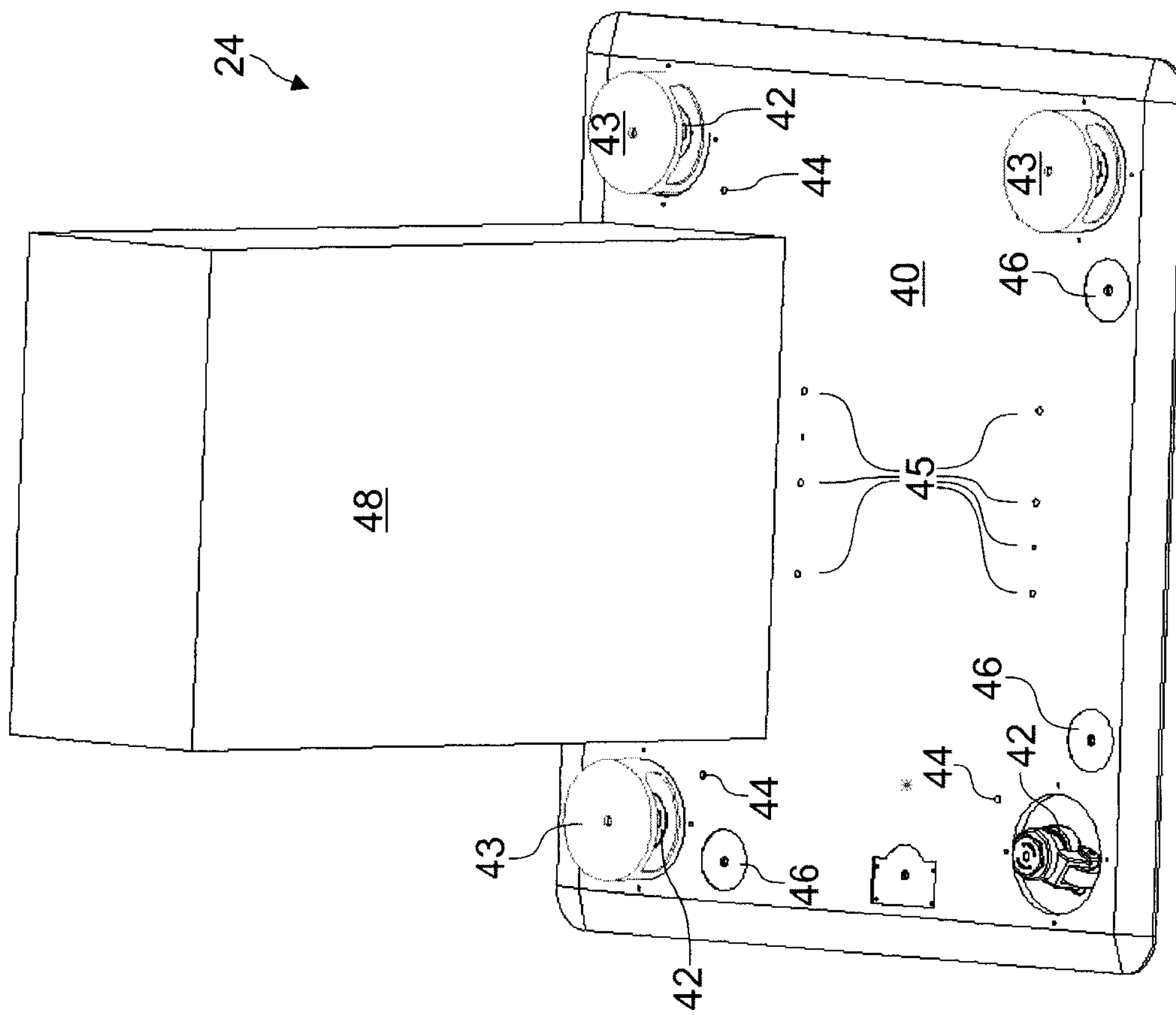


Fig. 7

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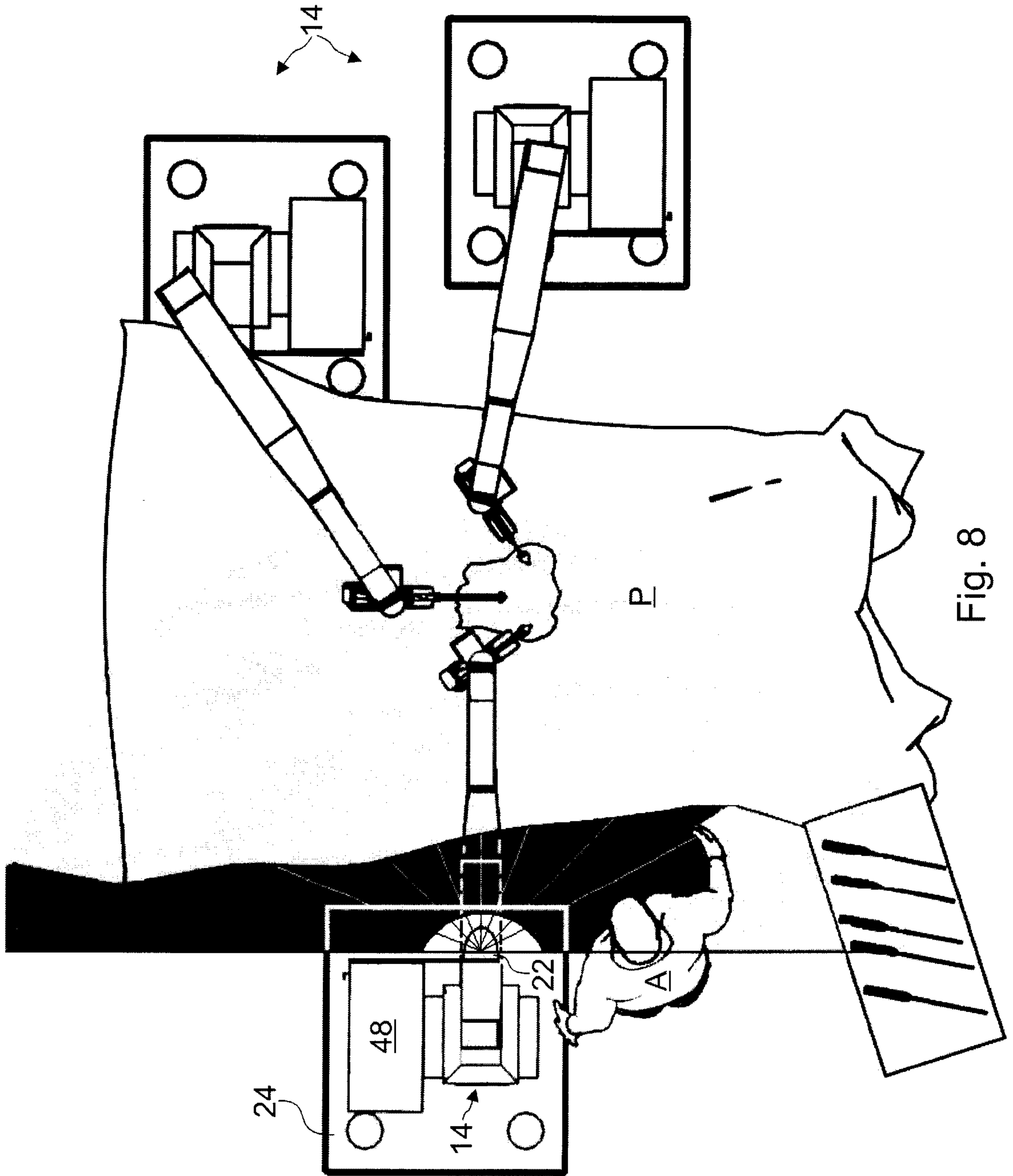


Fig. 8

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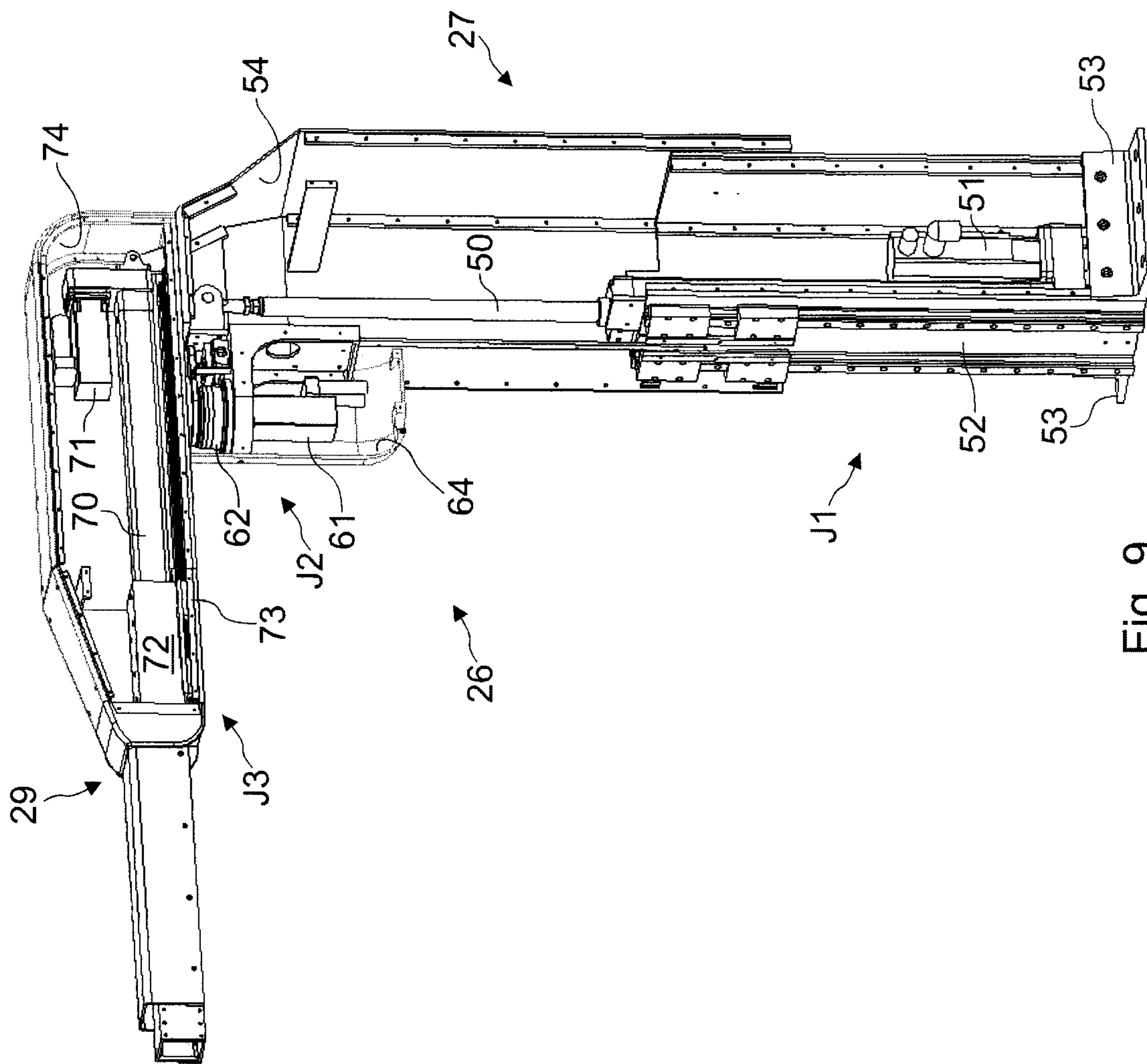


Fig. 9

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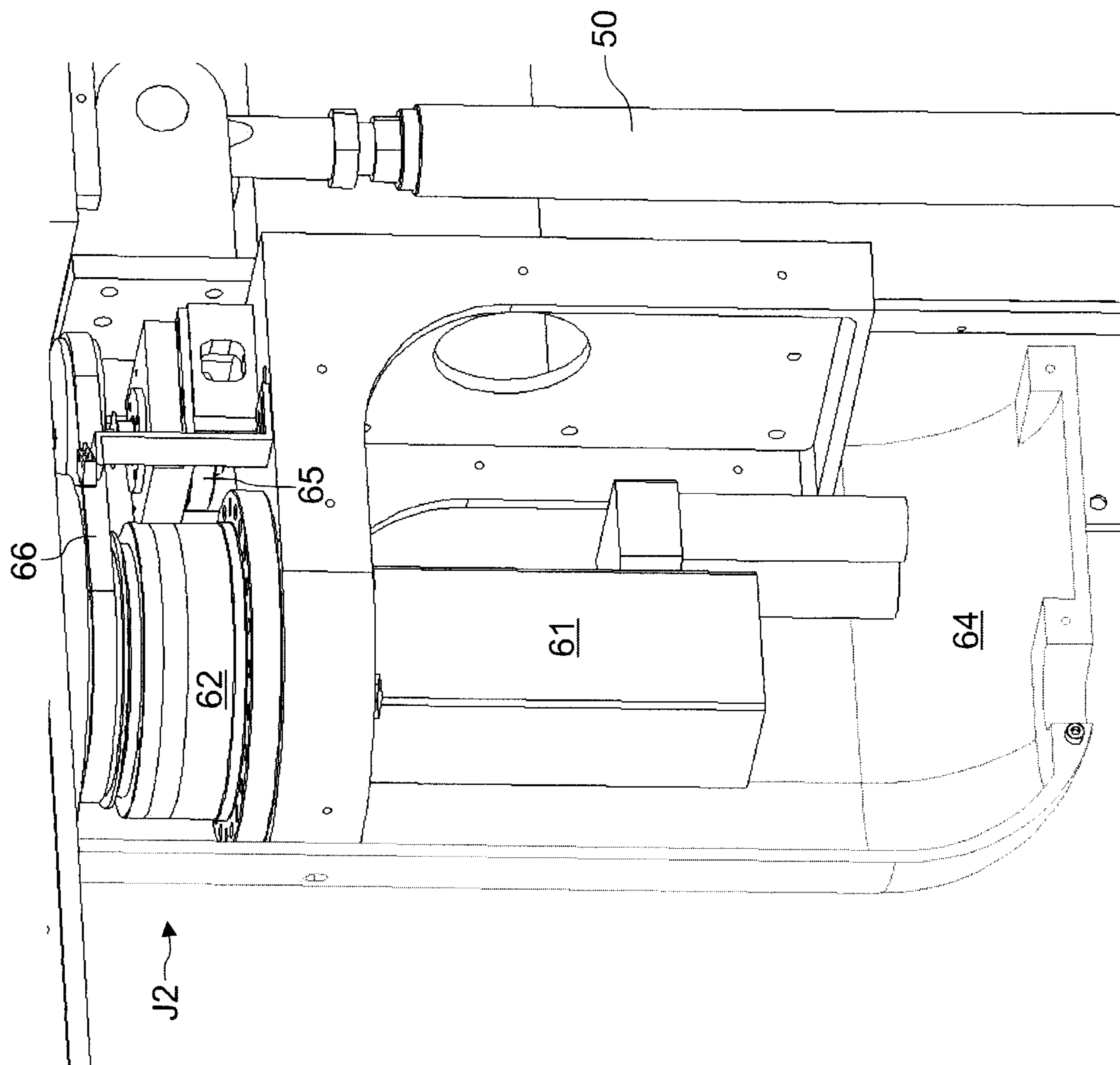


Fig. 10

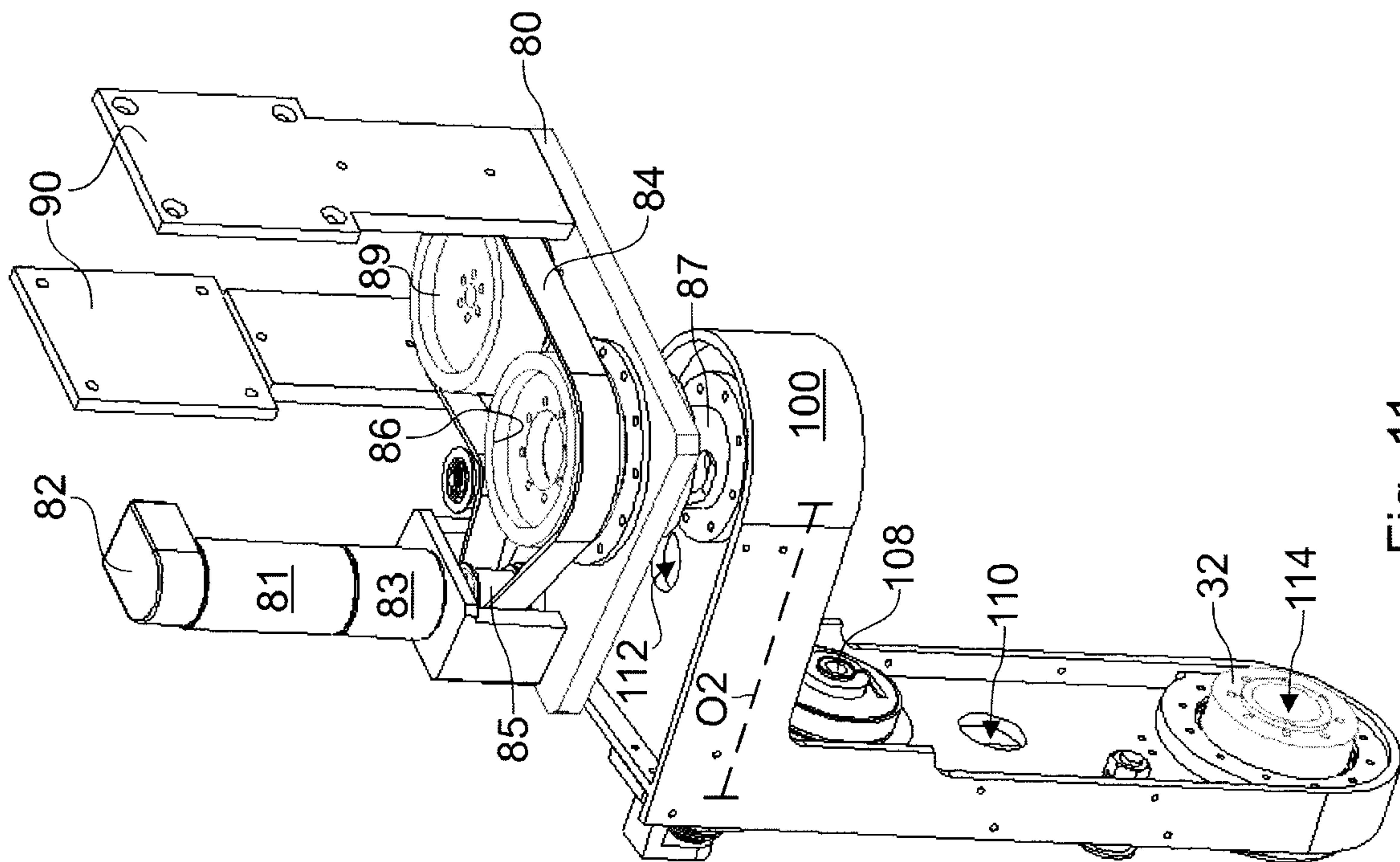


Fig. 11

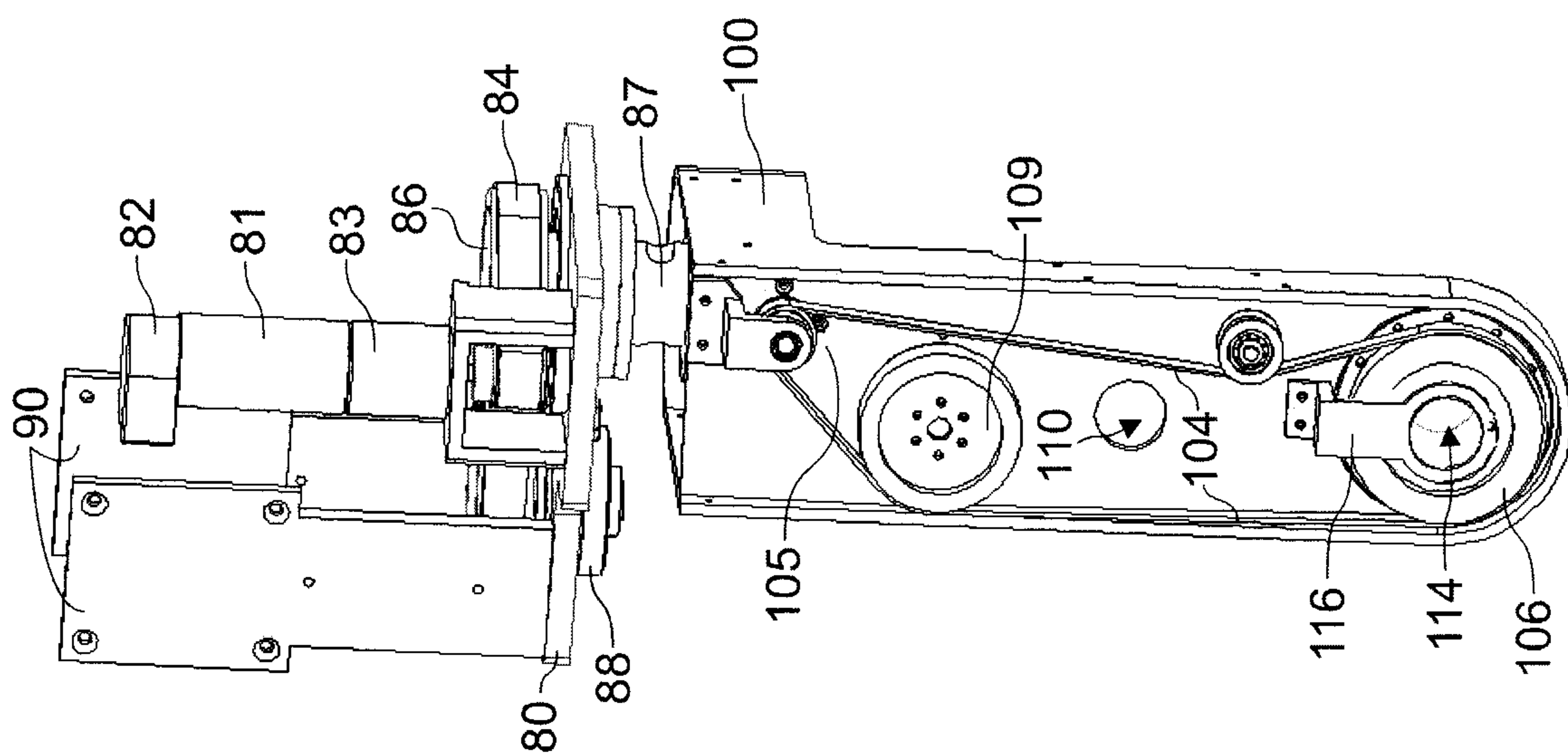


Fig. 12

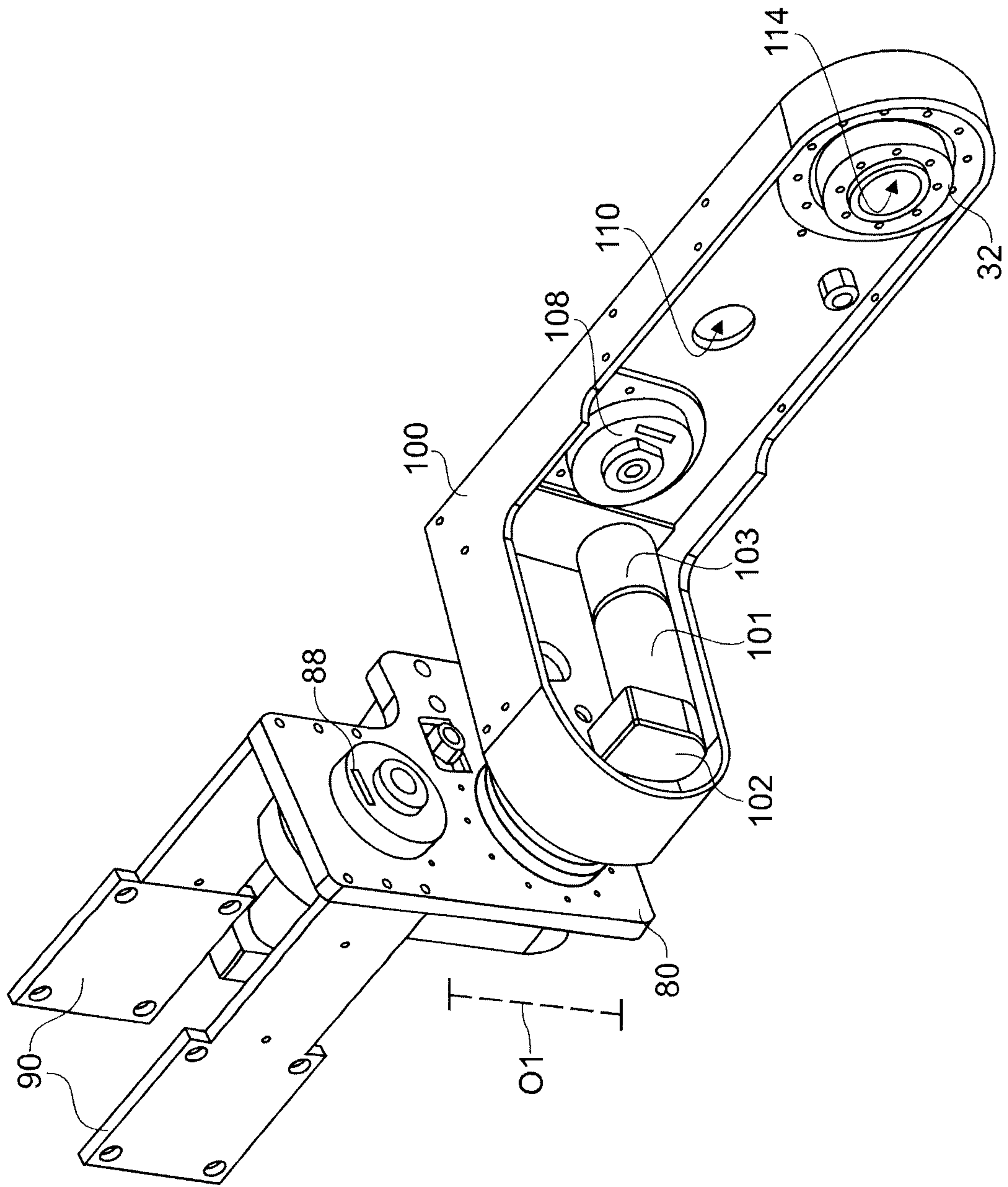


Fig. 13

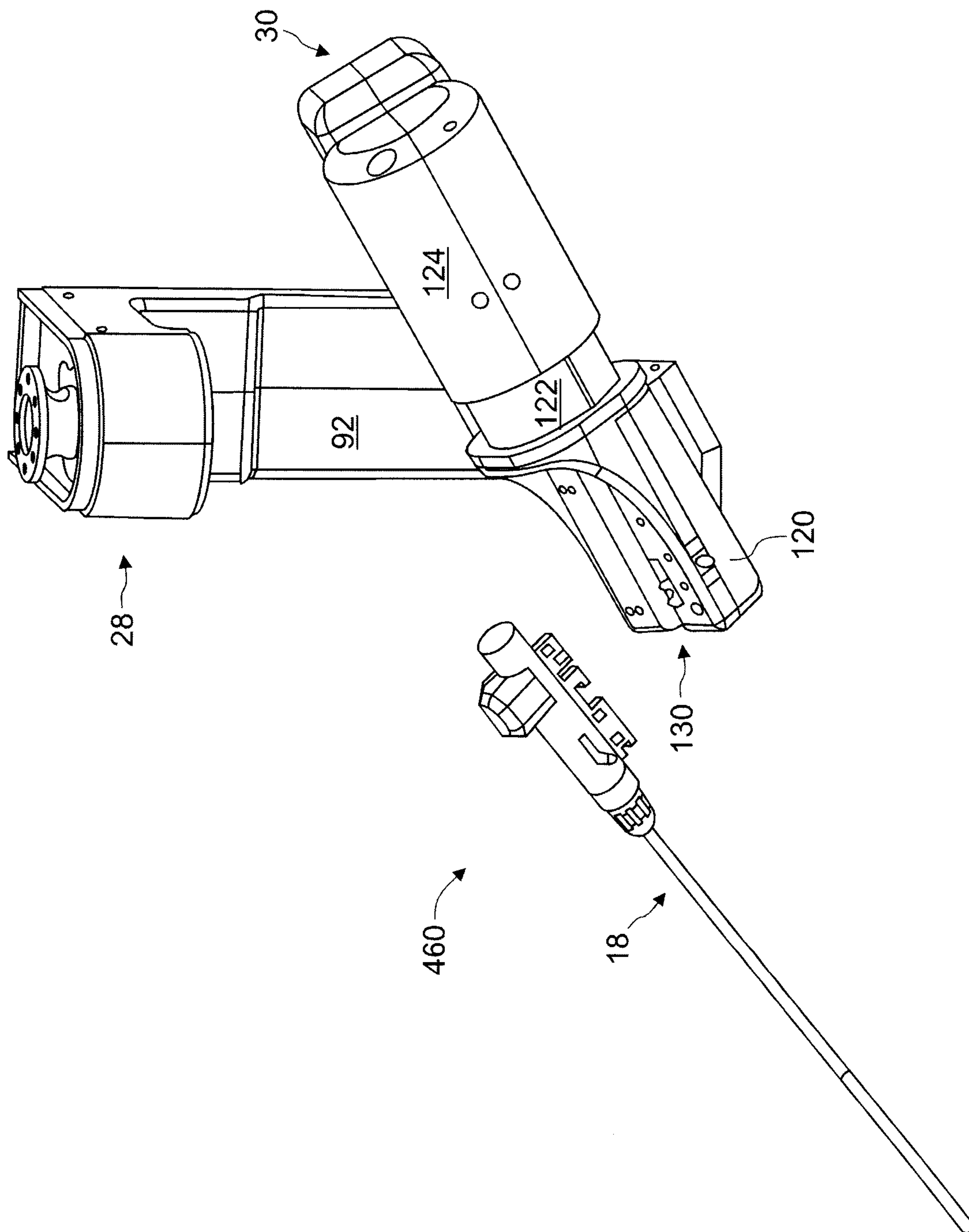


Fig. 14

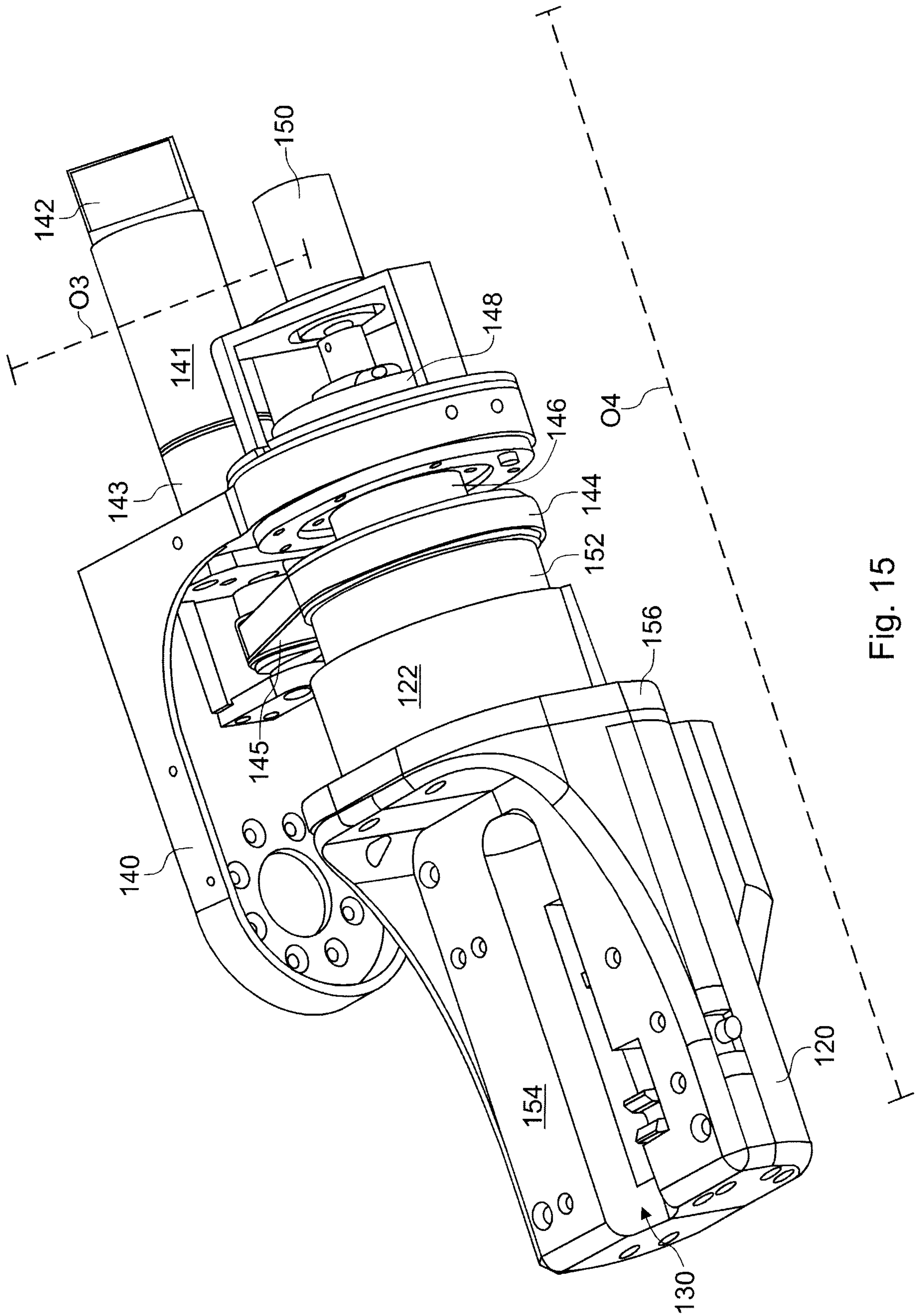


Fig. 15

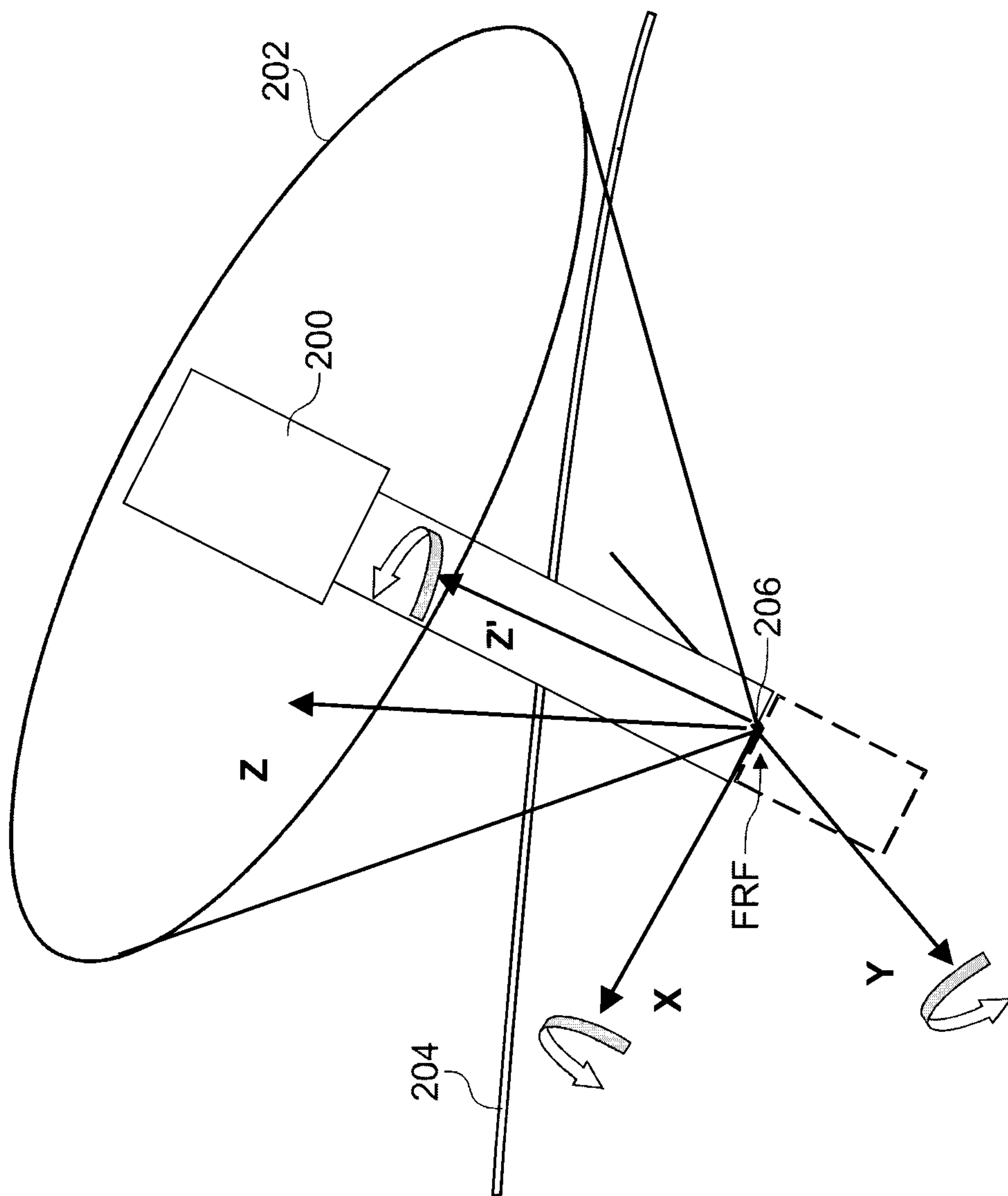


Fig. 16

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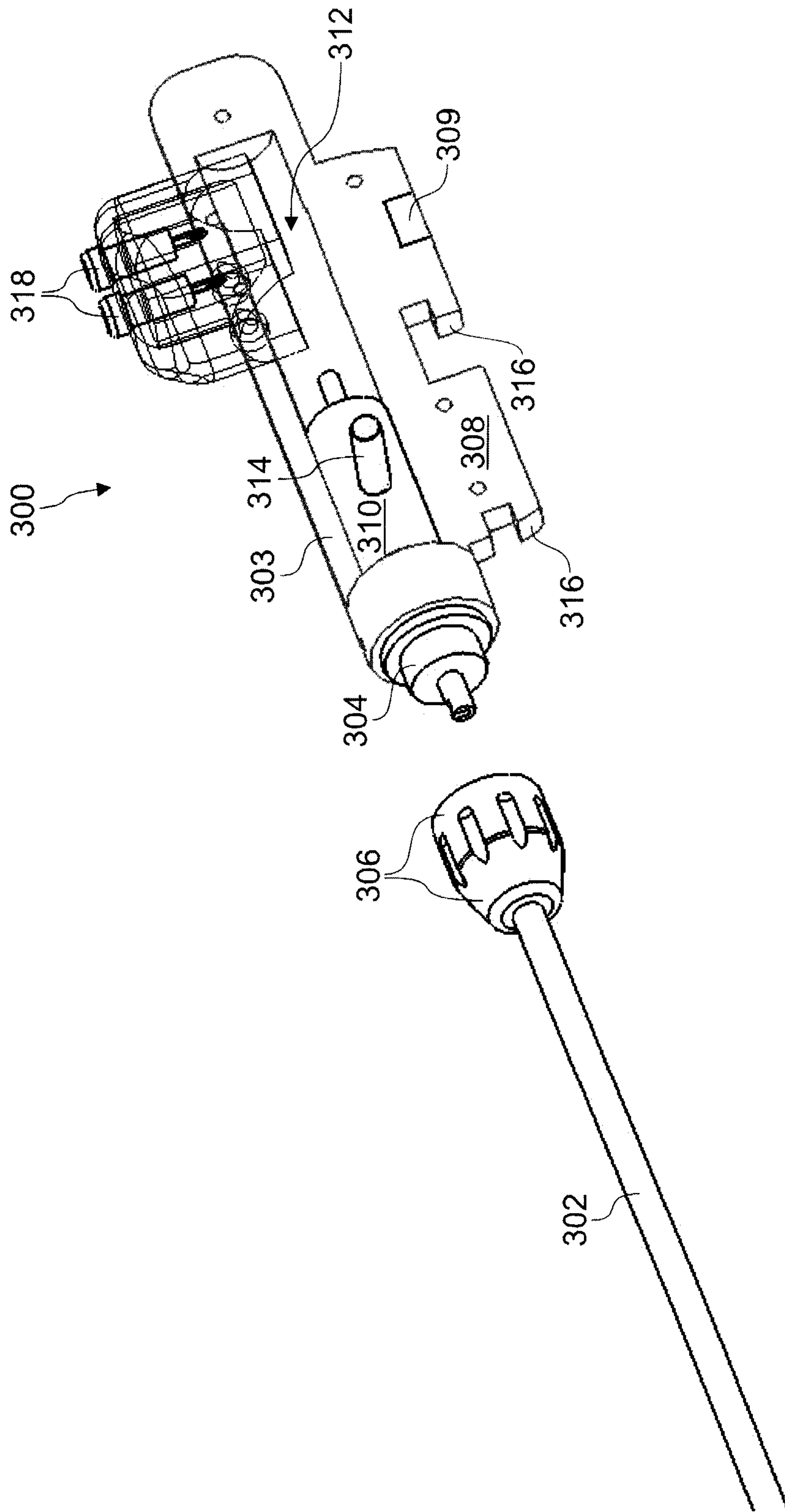


Fig. 17

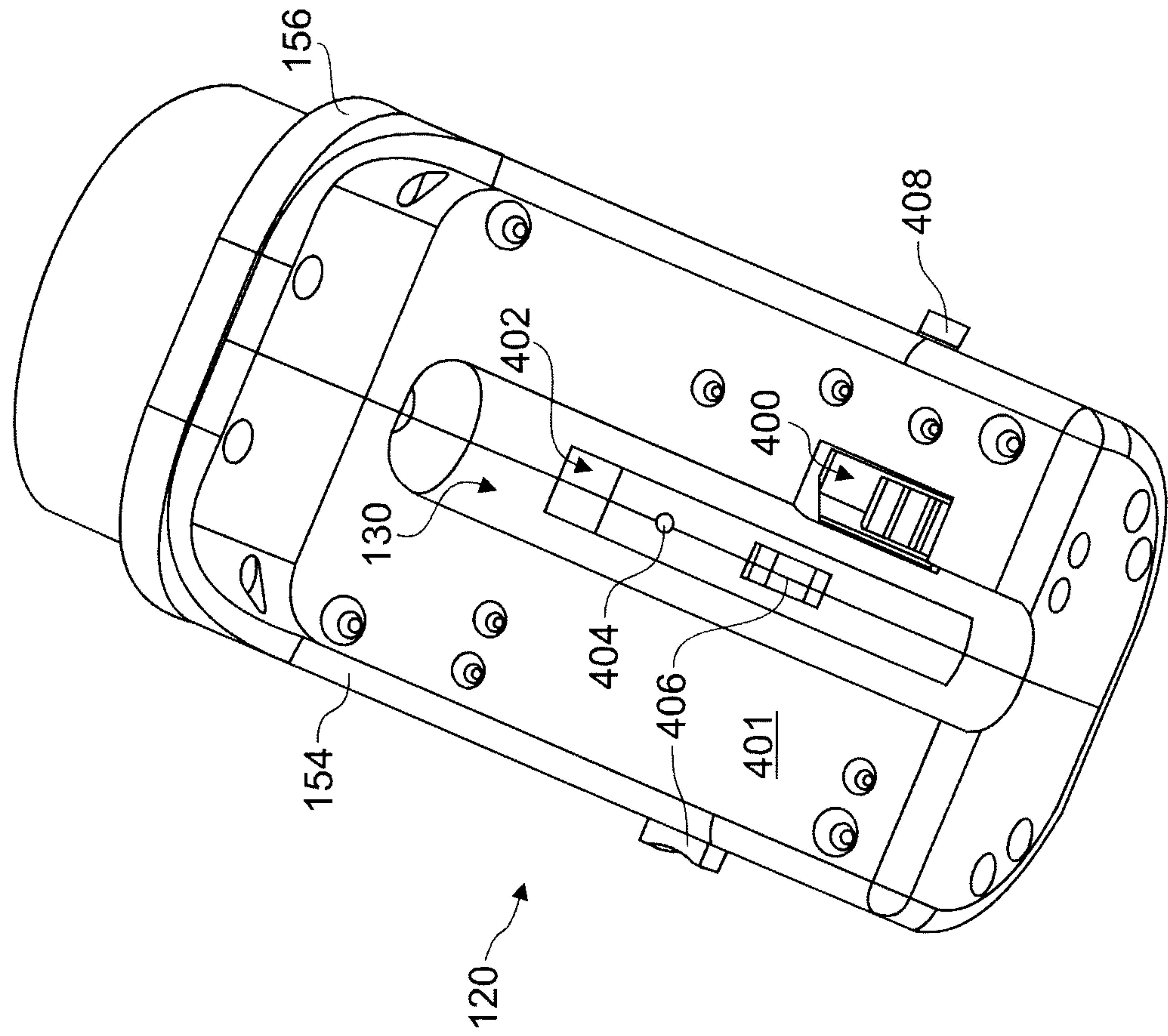


Fig. 18

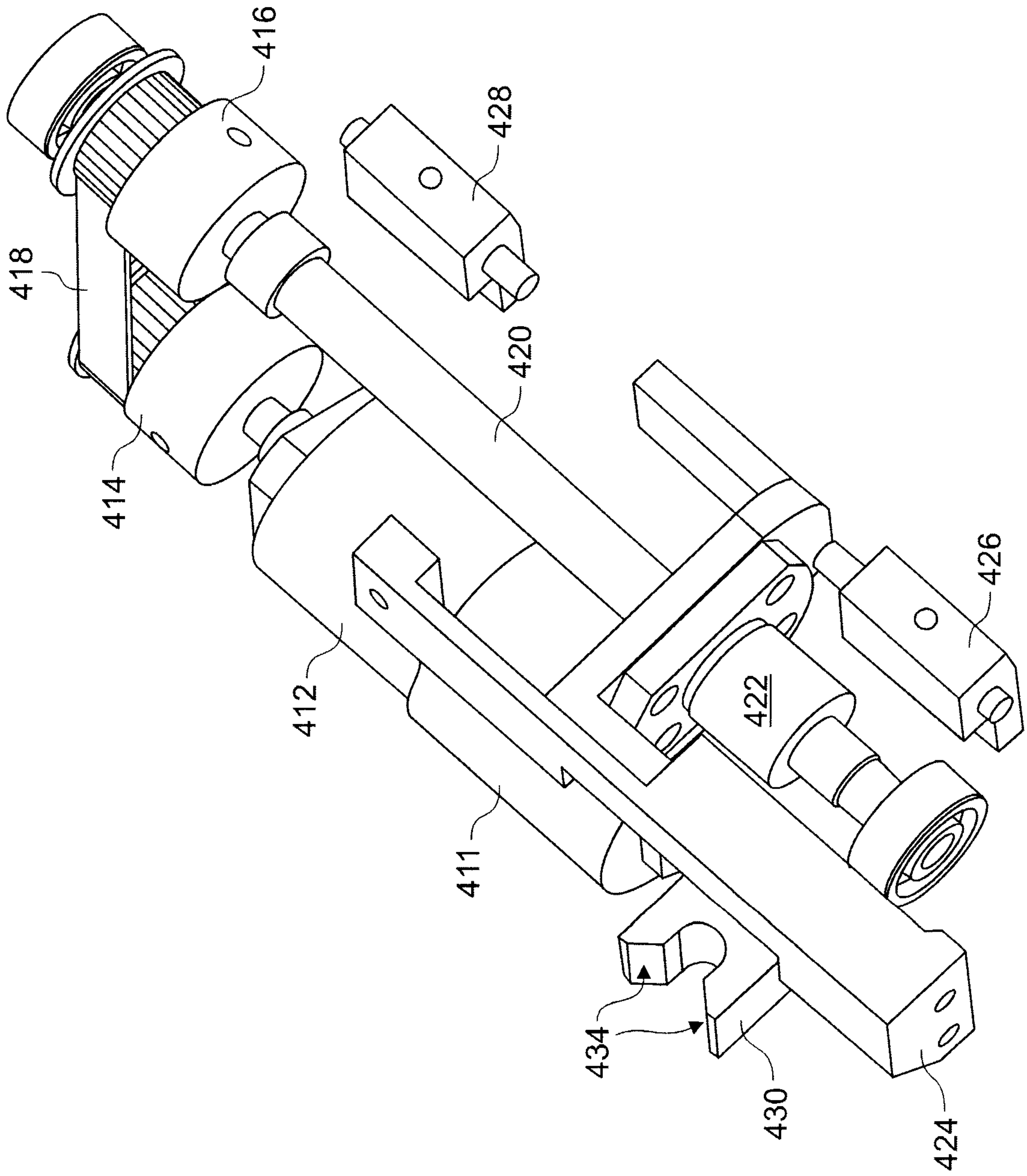


Fig. 19

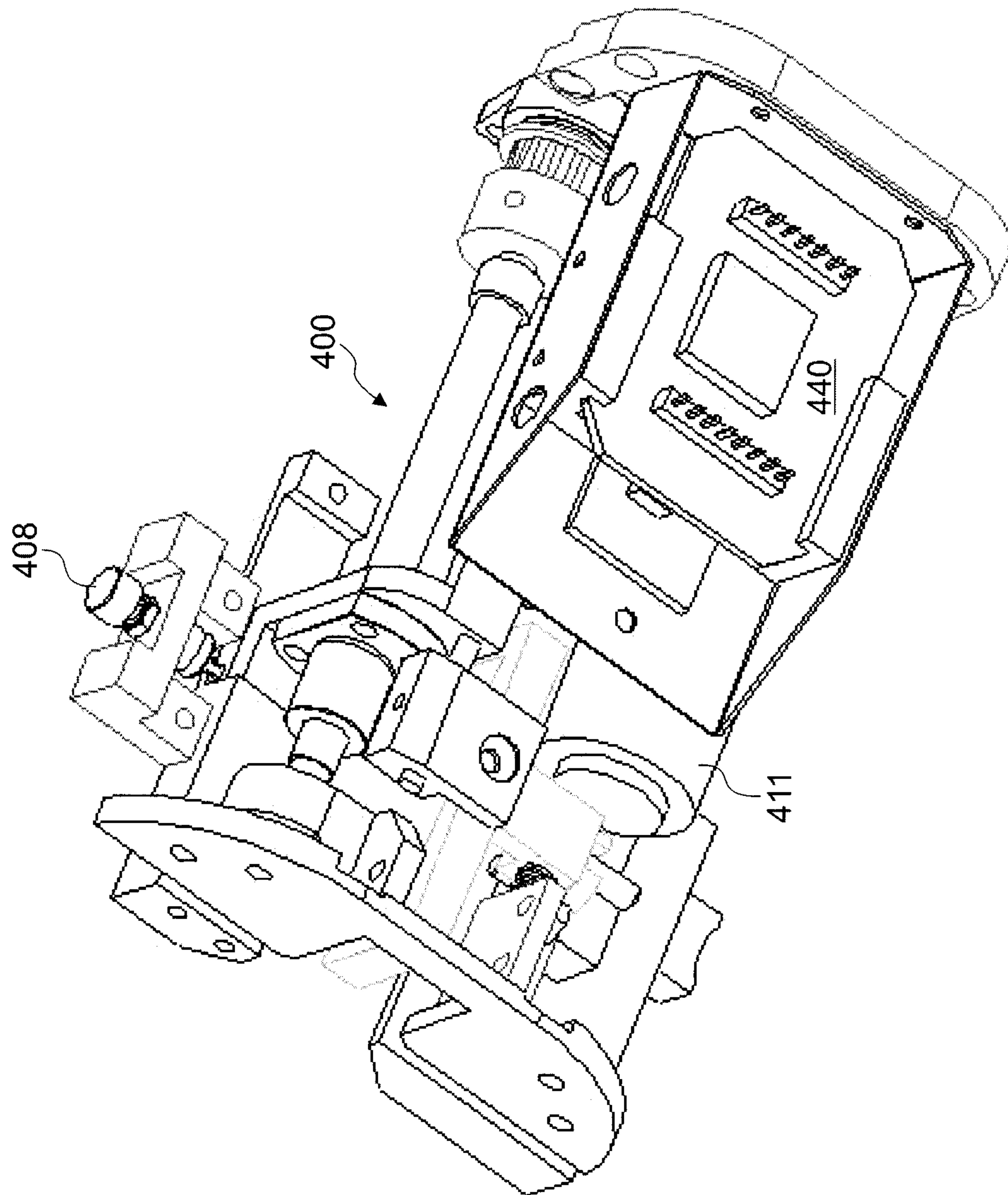


Fig. 20

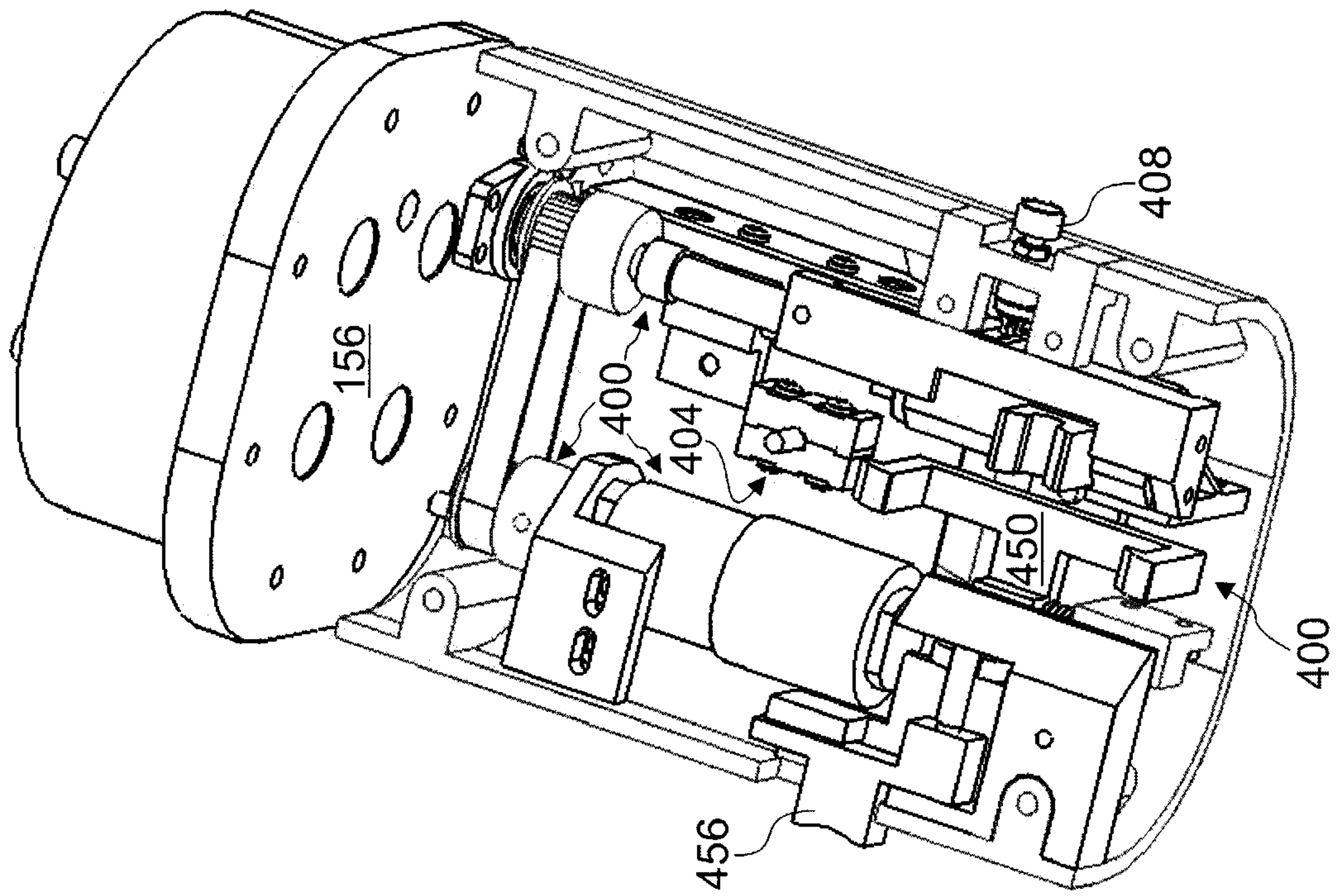


Fig. 21

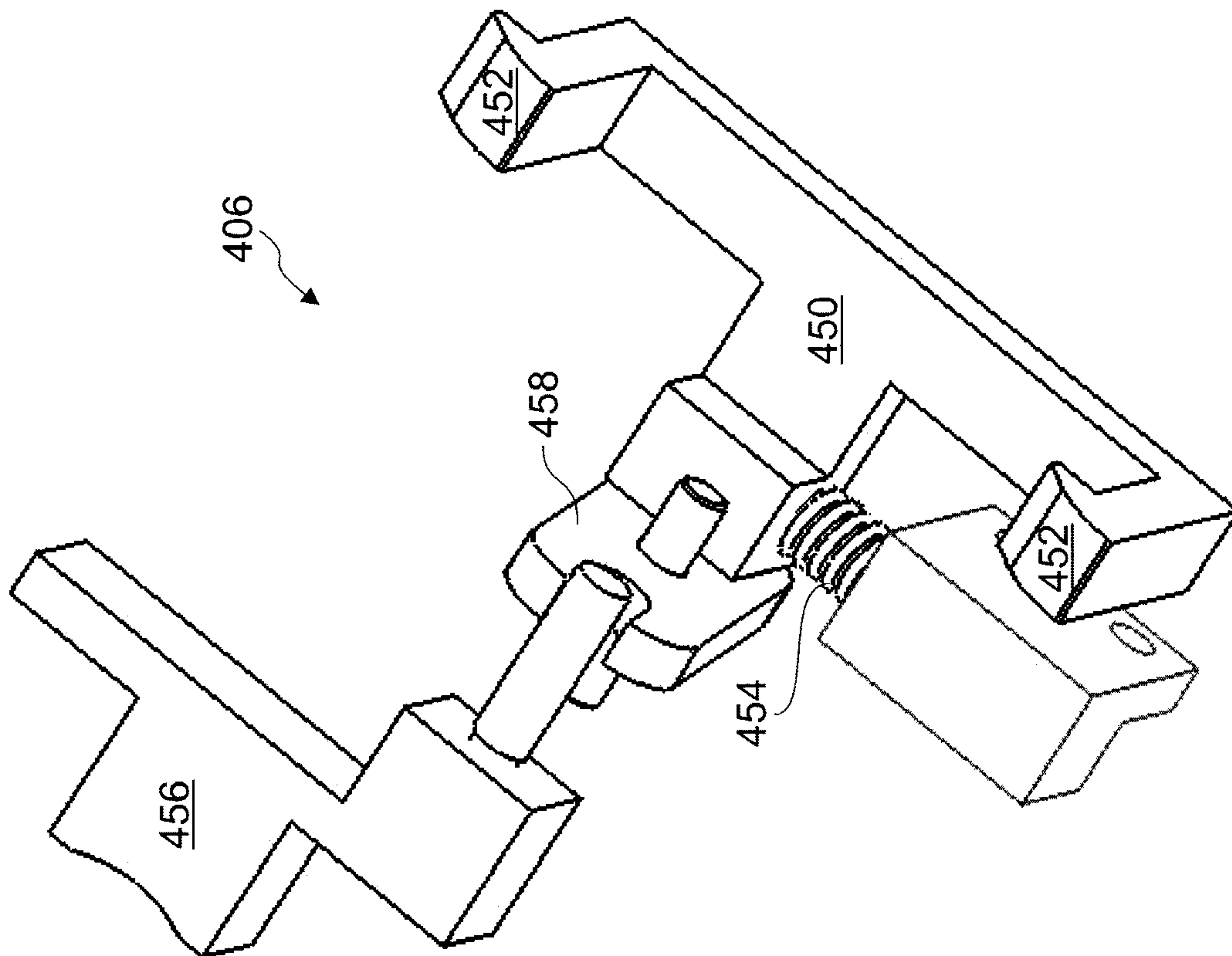


Fig. 22

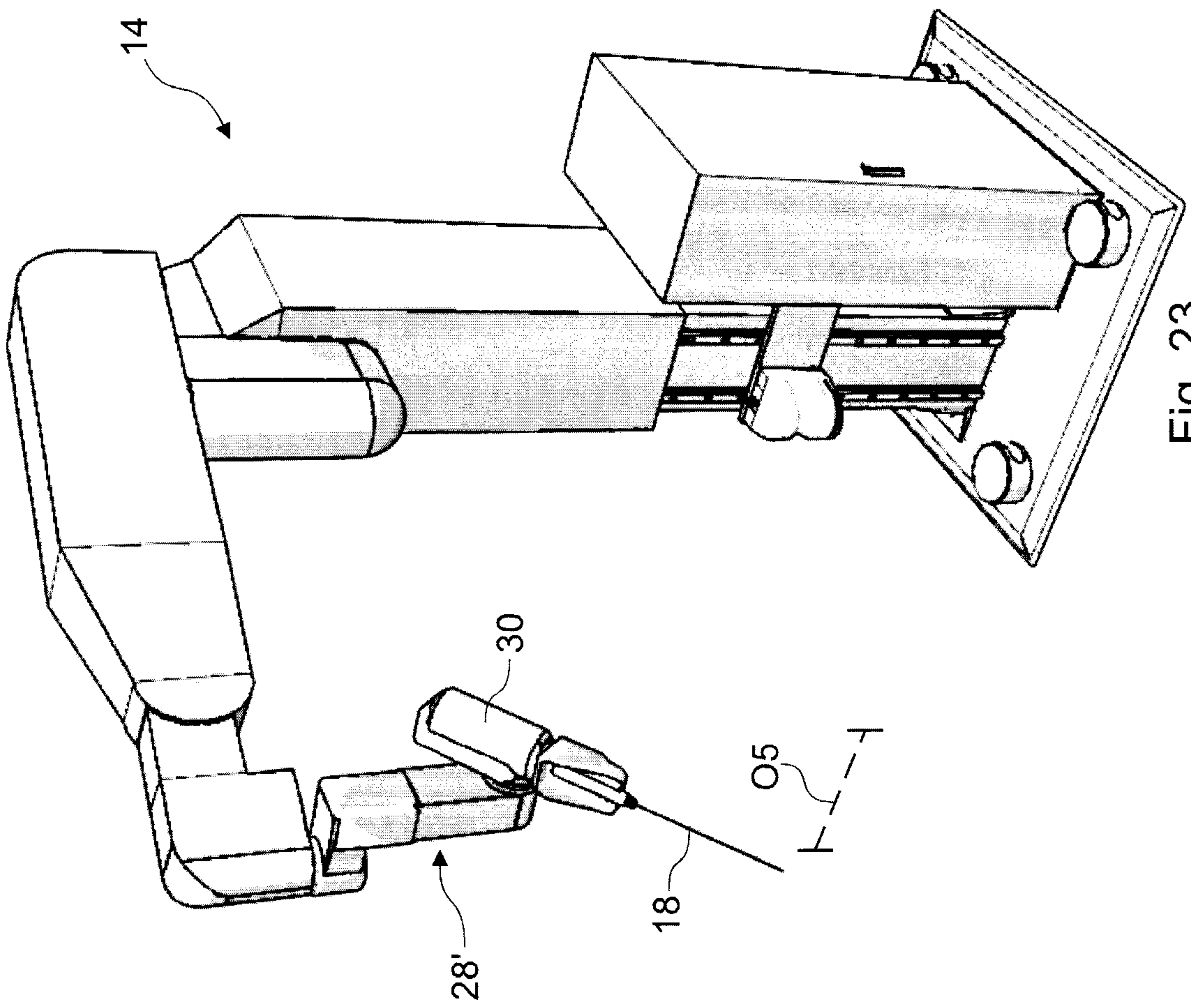


Fig. 23

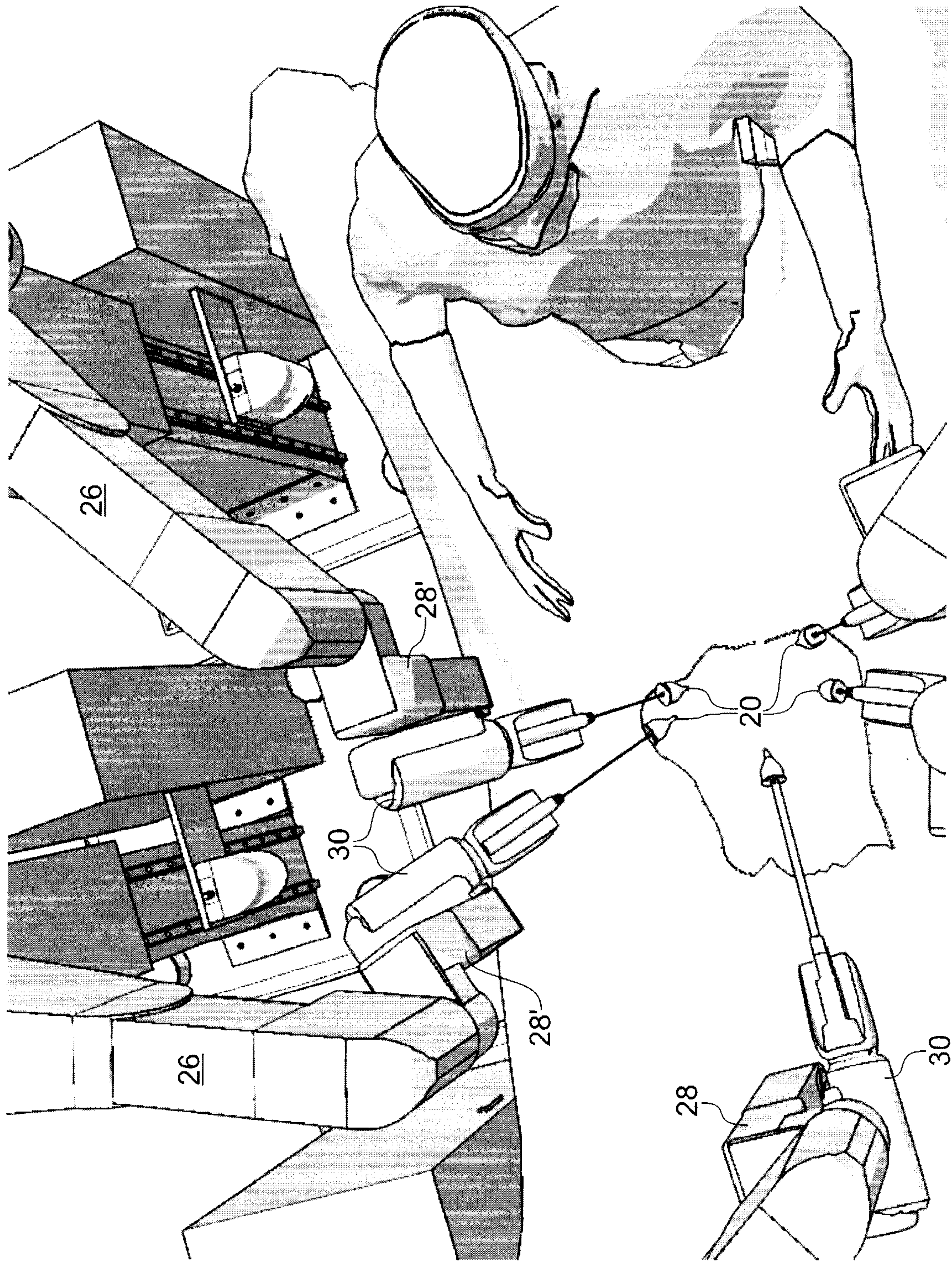


Fig. 24

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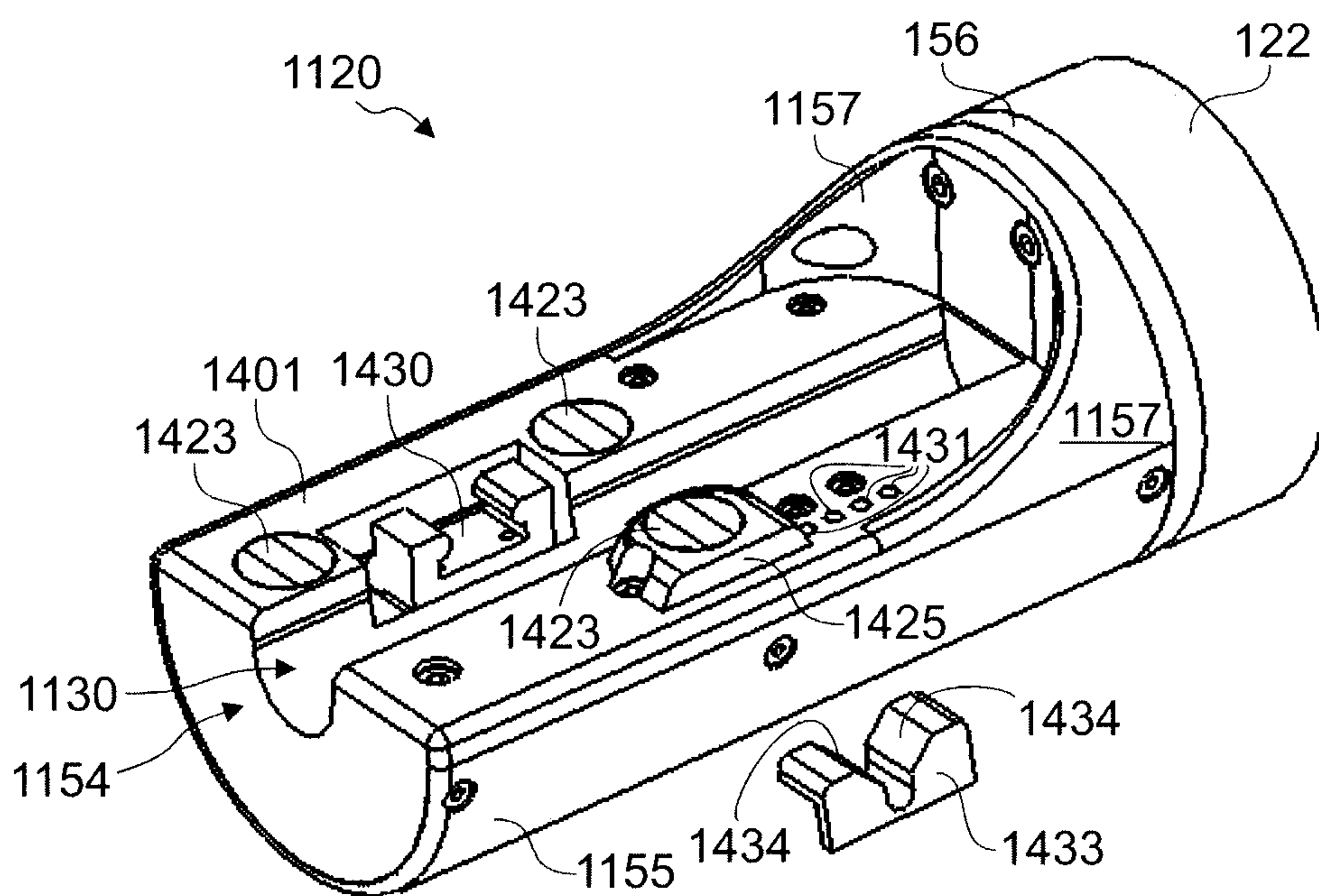


Fig. 25

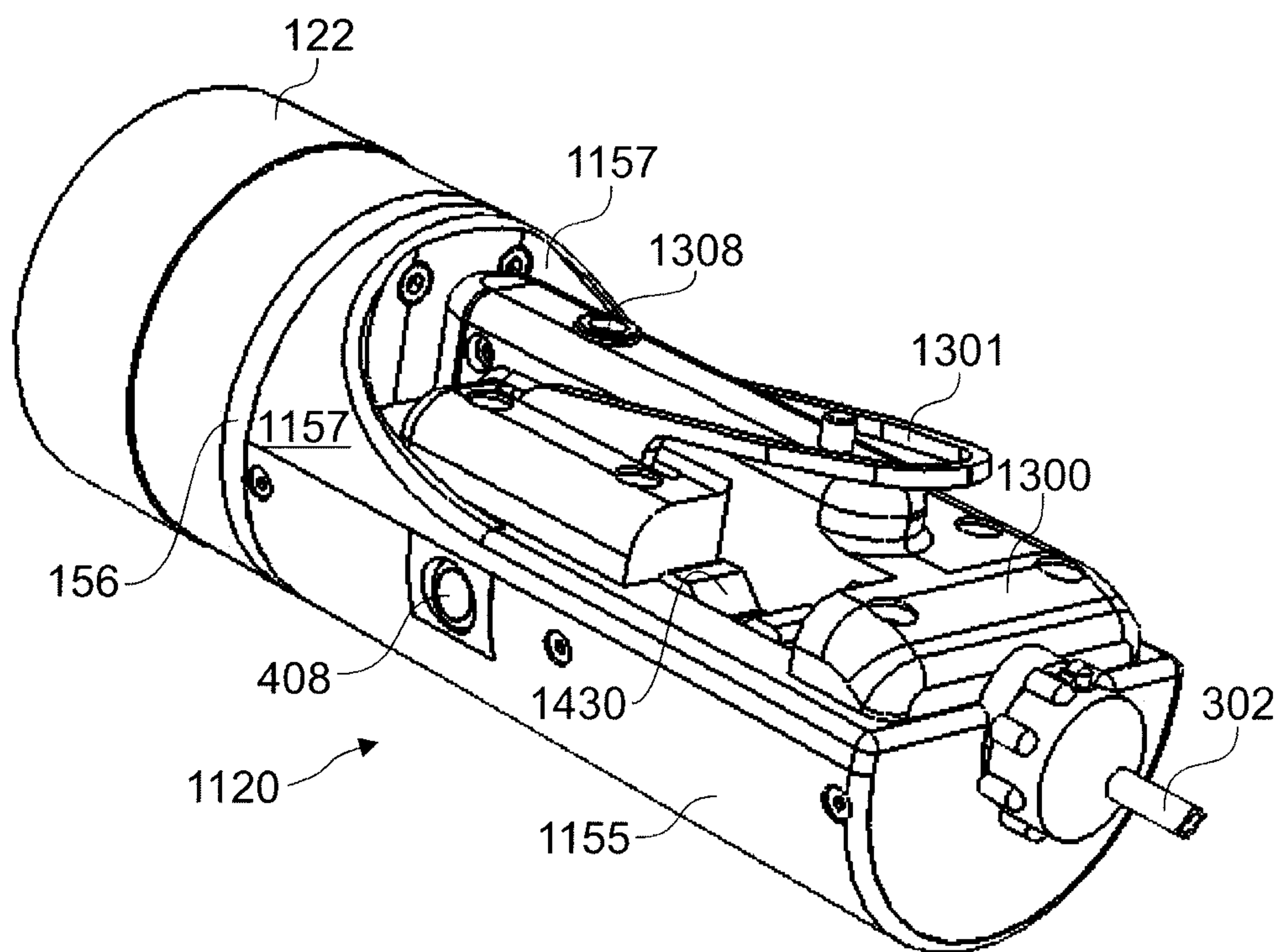


Fig. 26

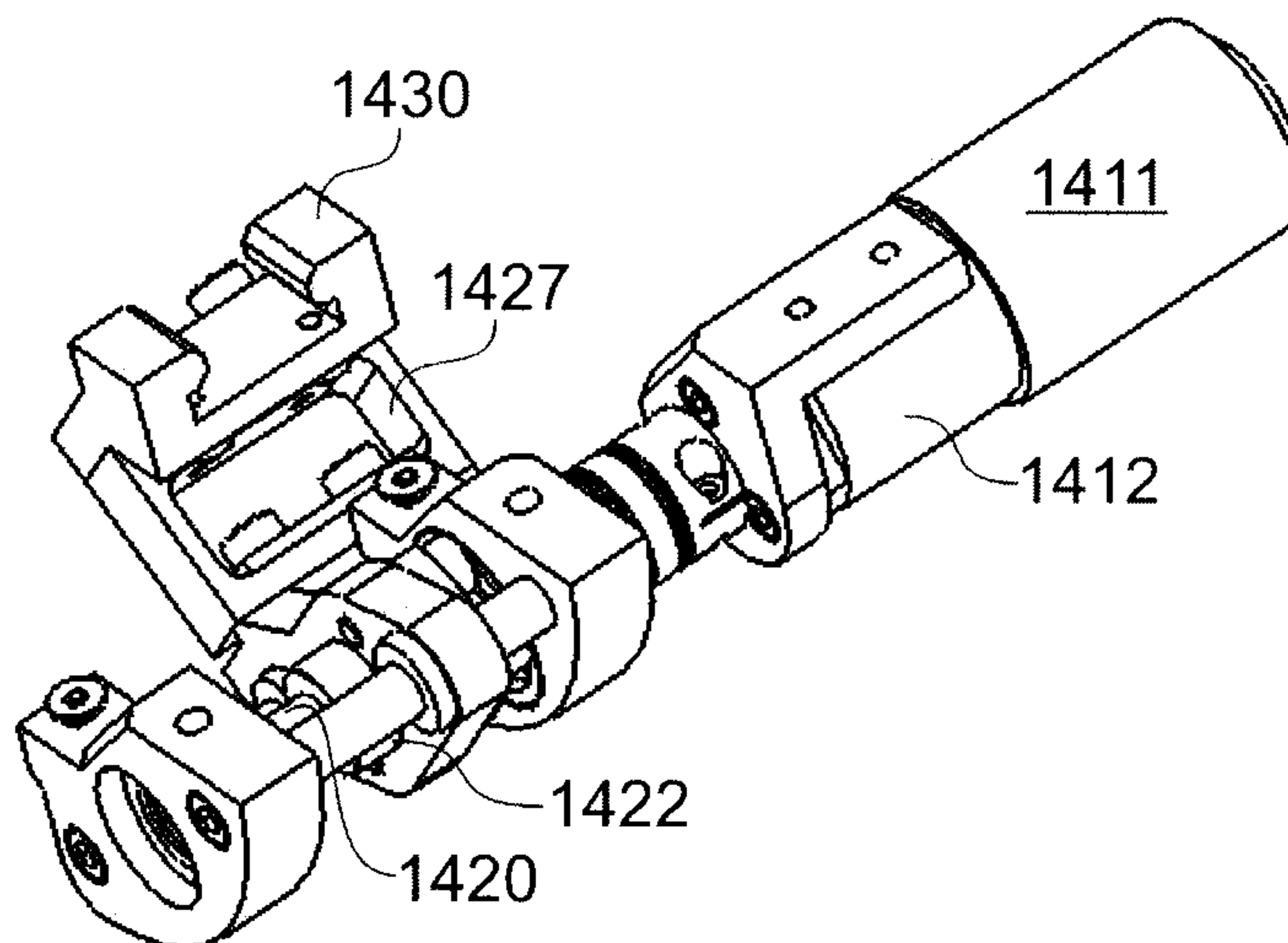


Fig. 27

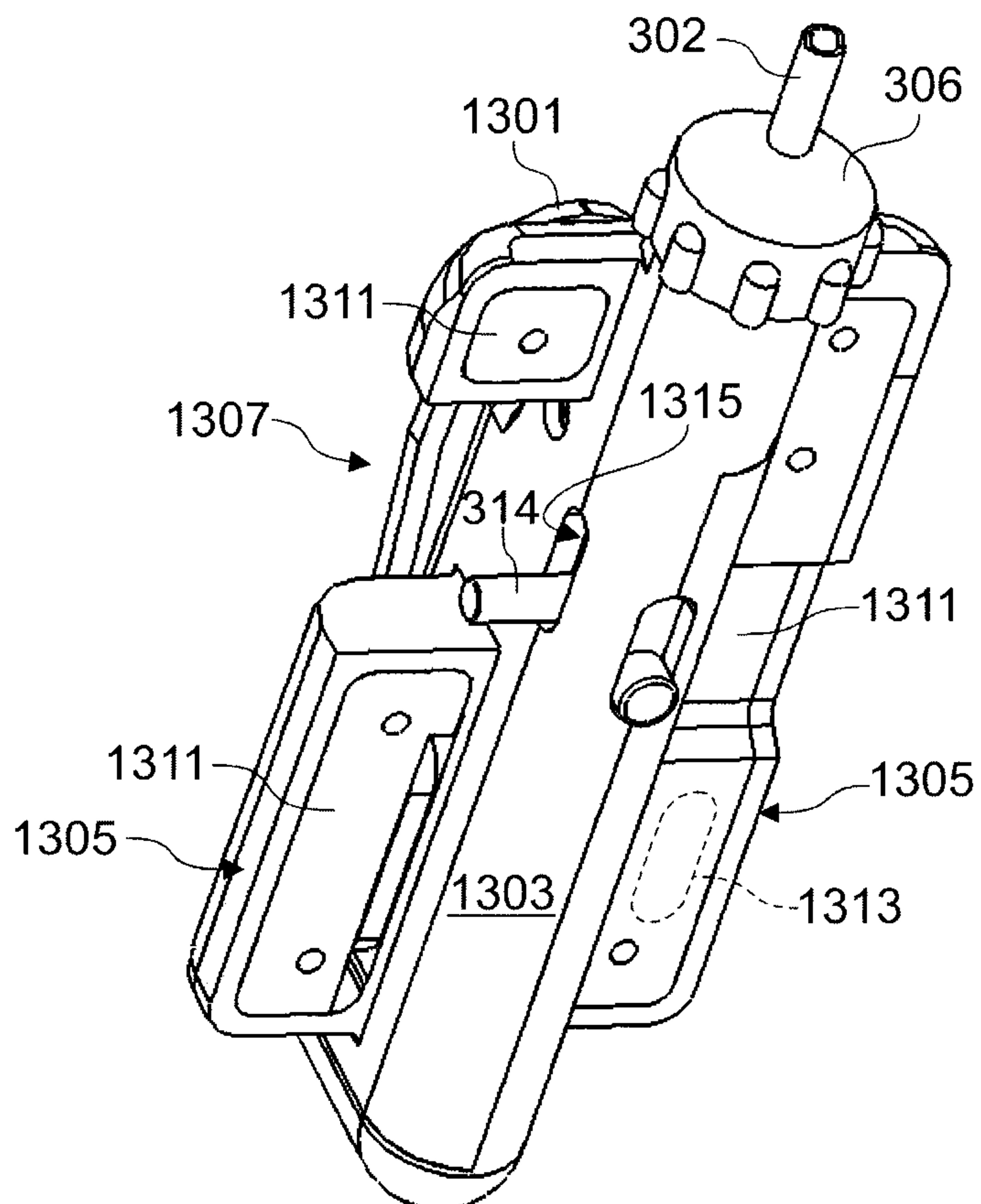


Fig. 28

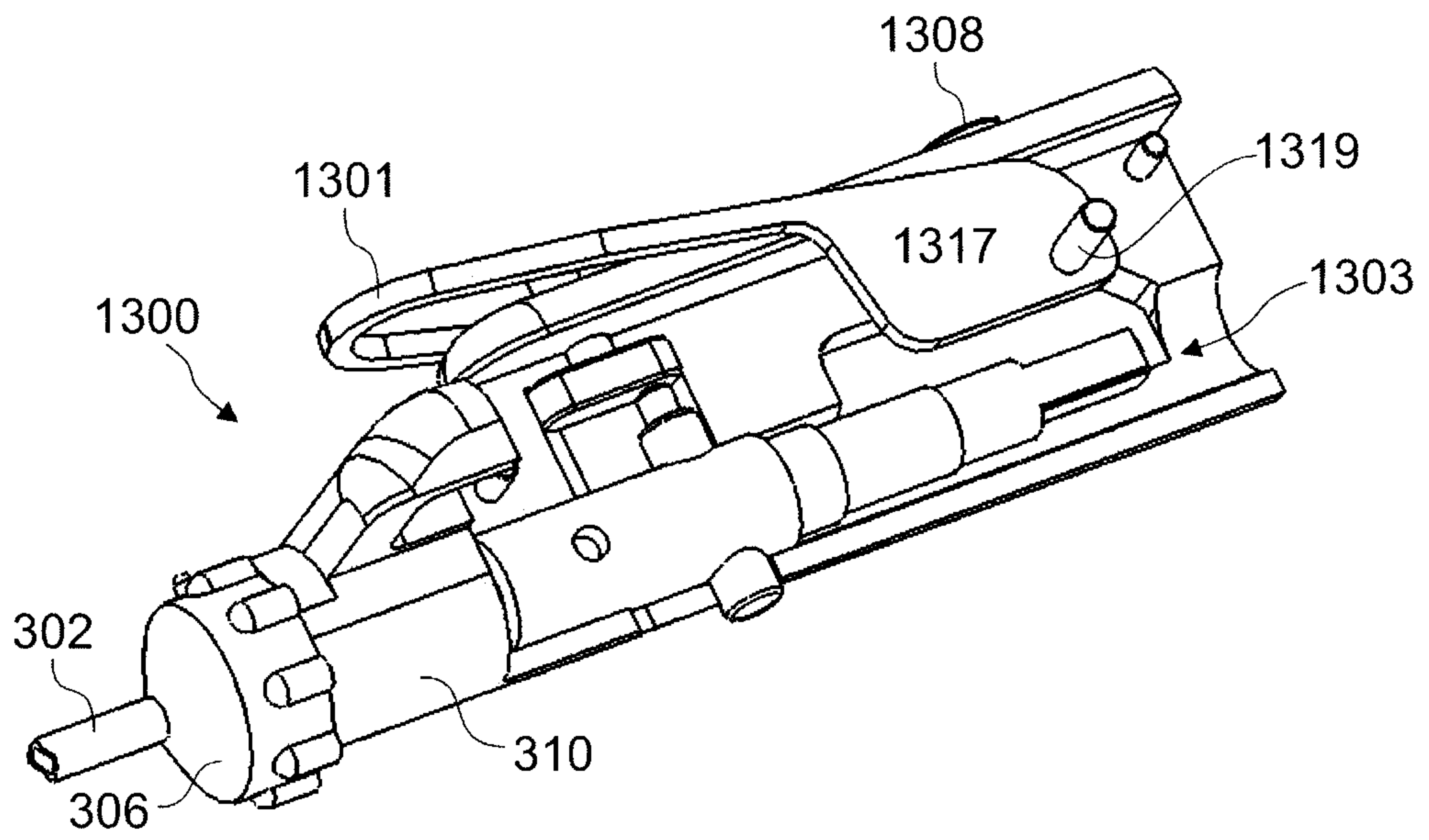


Fig. 29

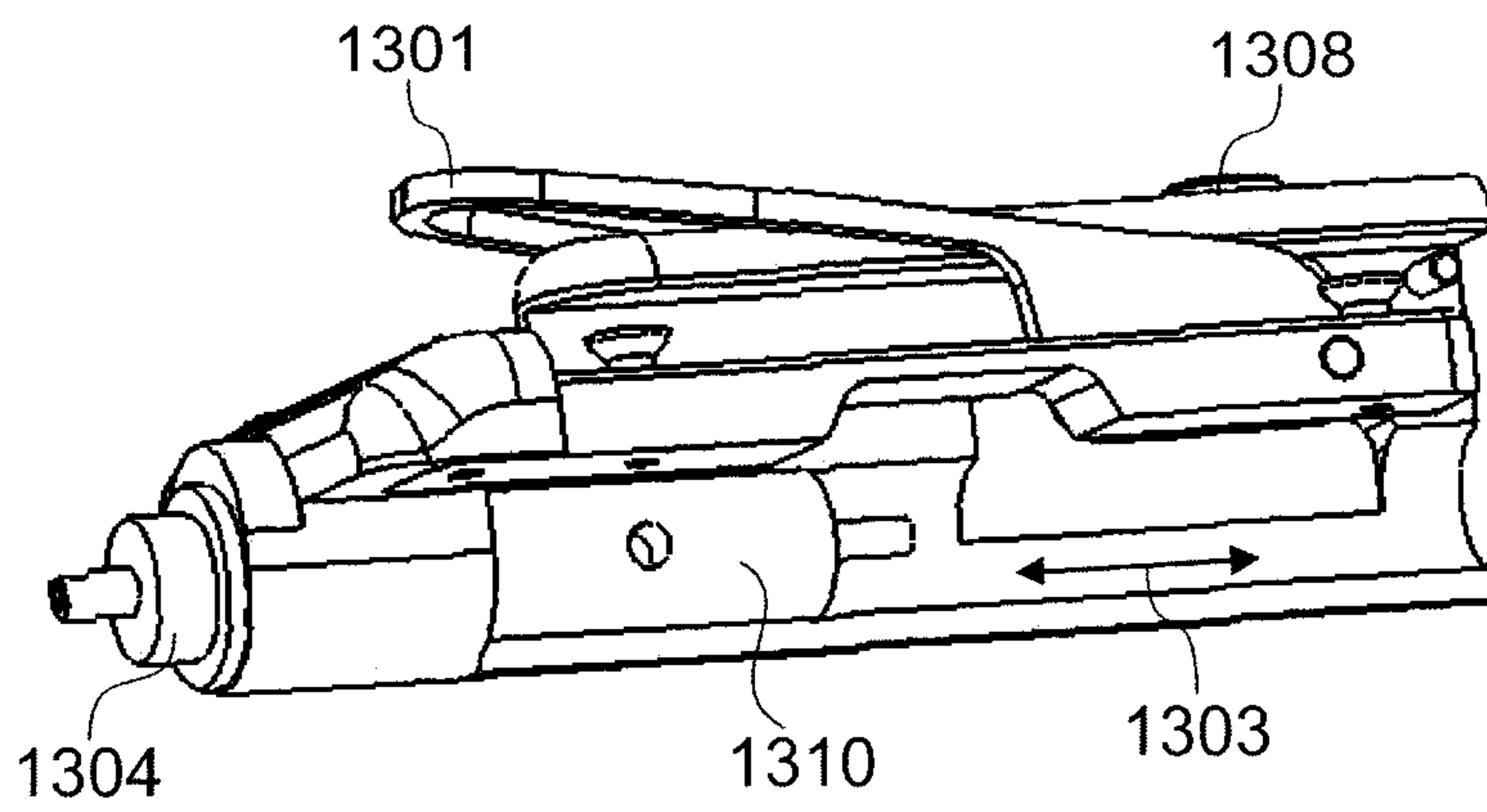


Fig. 30

