



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
08.08.2007 Bulletin 2007/32

(51) Int Cl.:
B25J 9/04 (2006.01) A61B 19/00 (2006.01)

(21) Application number: **06101250.6**

(22) Date of filing: **03.02.2006**

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR
Designated Extension States:
AL BA HR MK YU

(71) Applicant: **The European Atomic Energy Community (EURATOM), represented by the European Commission 1049 Brussels (BE)**

(72) Inventor: **Ruiz Morales, Emilio 21020, Taino (IT)**

(74) Representative: **Schmitt, Armand et al Office Ernest T. Freylinger S.A., B.P. 48 8001 Strassen (LU)**

(54) **Medical robotic system with manipulator arm of the cylindrical coordinate type**

(57) A medical robotic system for performing medical procedures comprises a robot manipulator for robotically assisted handling of a medical instrument, in particular a laparoscopic surgery instrument. The robot manipulator comprises a base (24); a manipulator arm with an essentially vertical part supported by the base and with an essentially horizontal part supported by the vertical part; a manipulator wrist (28) supported by the manipulator arm (26); and an effector unit (30) supported by the manipulator wrist (28) and configured for holding a medical instrument (18). The manipulator arm (26) has a cy-

lindrical PRP kinematic configuration for positioning the manipulator wrist (28). More particularly, the PRP kinematic configuration includes 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.

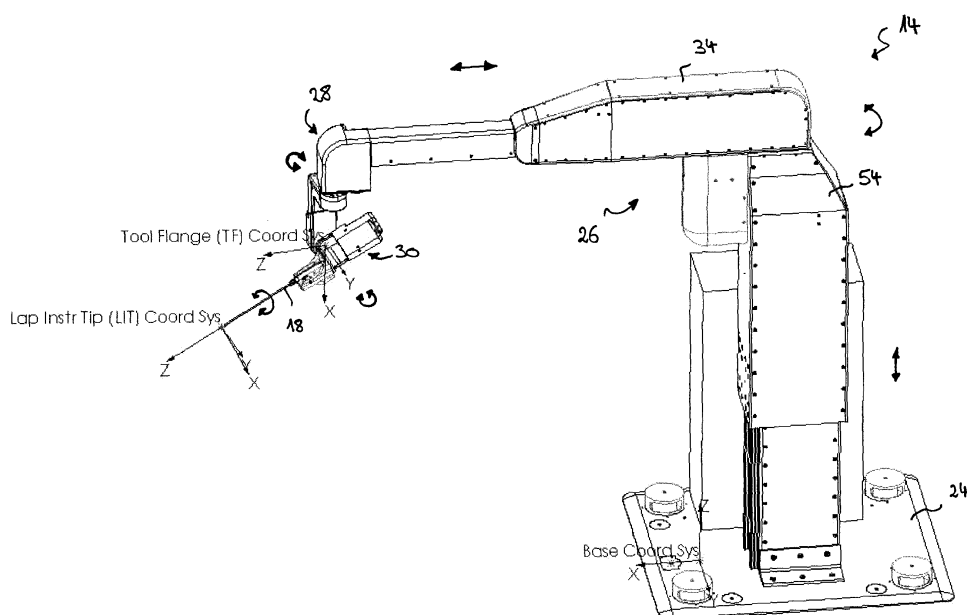


FIG.3

Description**Field of the Invention**

5 **[0001]** 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

10 **[0002]** It is well known that, as opposed to laparotomy, minimally invasive medical procedures 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 techniques, such as laparoscopic techniques.

15 **[0003]** 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 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 **[0004]** 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 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.

25 **[0005]** 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. 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 30 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.

35 **[0006]** 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.

40 **[0007]** 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 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 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.

45 **[0008]** Irrespective of these two specific systems, the mechanical design of manipulators in robotic surgery systems currently leaves significant room for improvement in various aspects among which versatility of the system is but one of many.

Object of the invention

50 **[0009]** 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

[0010] 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 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.

[0011] 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.

[0012] 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.

[0013] 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.

[0014] 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.

[0015] 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.

[0016] 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 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.

[0017] 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, preferably a linear ball screw axis, for actuating the third (P) joint.

[0018] 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.

[0019] 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.

[0020] 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.

[0021] In order to warrant a certain distance from the patient which facilitates access for 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.

[0022] 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.

[0023] More particularly, in a preferred configuration, the fourth (R) joint provides a rotational 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 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 joining a first horizontal portion of the support member to the support plate, and the fifth (R) joint joining 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.

[0024] 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 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 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.

[0025] In order to enable force feedback at a haptic interface of a surgeon, the effector unit 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 the patient's body. The linear and angular accelerometer is used for compensating gravitational and acceleration influence on the force-torque sensor.

[0026] 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 instrument 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.

[0027] 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.

[0028] 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

[0029] 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:

- 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;
- 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;
- 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;
- 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;
- 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;
- 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;
- 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;
- 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 locking mechanism used in the LIA shown in 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.

[0030] In these drawings identical reference numerals are used to identify identical parts throughout.

Detailed description with respect to the figures

[0031] 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.

[0032] 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.

[0033] 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.

[0034] 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.

[0035] 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.

[0036] 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.

[0037] 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 800mm) from the operation table to facilitate surgeon access to the operation table and patient transfer from/to the operation table;
- easy and fast inter-manipulators collision detection computation.

[0038] These and other aspects will become more apparent from the following paragraphs.

[0039] 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 work-spaces 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.

[0040] 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 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 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 sharply scaled down in function of the penetration in the margin area.

[0041] 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 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 oscillations in case joint J1 and/or joint J2 executes abrupt motion.

[0042] 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 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 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.

[0043] 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.

[0044] 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.

[0045] 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.

[0046] 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.

[0047] 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.

[0048] 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.

[0049] 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.

[0050] 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.

[0051] By reference to Figs.11-13, the construction of wrist 28 and more particularly the joints J4 and J5 will be detailed below.

[0052] 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. 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 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 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 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.

[0053] 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 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 transmission 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 02, which may constitute a limiting factor in a multi-robot configuration.

[0054] 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.

[0055] 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.

[0056] 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

[0057] 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 03 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 04 is reduced by configuring the motor-gear assembly 141, 143 to be located closer to the LIA 120.

[0058] 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.

[0059] As shown in Fig. 23 and Fig.24, an alternative design could however present an offset 05 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 05 due to link L5. This negative offset 05 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).

[0060] Some further aspects and advantages regarding the design of the robot manipulator 14 and its components will be detailed below.

[0061] 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.

[0062] 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).

[0063] 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.

[0064] 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.

[0065] 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.

[0066] 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:

Table 1

Fulcrum axis	Max Travel	Max Speed
Yaw Pivot	$\pm 70^\circ$	$100^\circ/\text{s}$
Pitch Pivot	$[+10^\circ - 80^\circ]$	$60^\circ/\text{s}$
Penetration	$[0 \text{ } 200\text{mm}]$	$200\text{mm}/\text{s}$
Roll	$[-360^\circ + 360^\circ]$	$300^\circ/\text{s}$

[0067] 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: "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 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 to adapt to variations of the absolute location of the pivot point 206 due, for instance, to the loss of abdominal pressure.

[0068] 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 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.

Table 2

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

[0069] 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.

[0070] 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.

[0071] 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.

[0072] 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.

[0073] 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).

[0074] The following paragraphs give a more detailed description of the laparoscopic instrument actuator (LIA) 120.

[0075] 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.

[0076] 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.

[0077] 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.

[0078] 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 there from 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.

[0079] 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.

[0080] 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").

[0081] 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.

[0082] 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.

[0083] 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.

[0084] 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 1 mm/sec to 20mm/sec;
- maximum actuation force: 200N;

[0085] 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.

[0086] 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.

[0087] 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.

[0088] 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.

[0089] The design of the catch 450 is best seen in Fig. 22. A spring 454 resiliently urges the catch 450 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 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.

[0090] 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.

[0091] 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.

[0092] 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 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 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.

[0093] As best illustrated by Fig. 14, the insertion procedure of an adapted laparoscopic 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 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.

[0094] 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. 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.

[0095] 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.

[0096] 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.

[0097] 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.

[0098] 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.

[0099] In addition to the aspects described herein above, the medical robotic system 10 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;
- 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;
- 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;
- the medical robotic system 10 enables short instrument change times in order to minimize total intervention time, the design of the LIA 120 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;

- 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.

[0100] 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.

Claims

1. Medical robotic system for performing medical procedures comprising a robot manipulator for robotically assisted handling of a medical instrument, wherein said robot manipulator comprises
 - a base;
 - a manipulator arm having an essentially vertical part supported by said base and an essentially horizontal part supported by said vertical part;
 - a manipulator wrist supported by said manipulator arm; and
 - an effector unit supported by said manipulator wrist and configured for holding a medical instrument;**characterized in that**
 - said manipulator arm has a cylindrical PRP kinematic configuration, with a prismatic (P) first joint for varying the height of said vertical part by providing a translational degree of freedom along an essentially vertical axis, with a revolute (R) second joint for varying the rotational angle between said vertical part and said horizontal part by providing a rotational degree of freedom about an essentially vertical axis, and with a prismatic (P) third joint 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 has a vertical linear guide and a first linear actuator, preferably a linear ball screw axis, for actuating said first (P) joint.
3. Medical robotic system according to claim 2, wherein said third (P) joint has a horizontal linear guide and a second linear actuator, preferably a linear ball screw axis, for actuating said third (P) joint.
4. Medical robotic system according to claim 3 wherein said horizontal part comprises an elongated covering which encloses said horizontal linear guide and said second linear actuator, said horizontal part comprising a beam which telescopes with respect to said covering on one side and supports said wrist on the other side.
5. Medical robotic system according to any one of claims 1 to 4, wherein said second (R) joint has a gear, preferably a harmonic drive gear, a motor, preferably a brushless servo-motor, coupled to the input stage of said gear, and an absolute position sensor coupled to the output stage of said gear.
6. Medical robotic system according to any one of claims 1 to 5, wherein said horizontal part 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 comprises a revolute (R) fourth joint and a revolute (R) fifth joint for orienting said effector unit.
8. Medical robotic system according to claim 7, wherein the axes of rotation of said fourth (R) joint and said second (R) joint are parallel.
9. Medical robotic system according to claim 8, wherein the axis of rotation of said fourth (R) joint is coplanar with the plane formed by the axis of rotation of said second (R) joint and by the axis of translation of said third (P) joint.
10. Medical robotic system according to claim 9, wherein said fourth (R) joint provides a rotational degree of freedom along an essentially vertical axis for setting the yaw angle of said effector unit, and wherein said fifth (R) joint provides

a rotational degree of freedom along an essentially horizontal axis for setting the pitch angle of said effector unit.

- 5 11. Medical robotic system according to claim 10, wherein said wrist comprises a support plate connected to said horizontal part of said arm, and a substantially L-shaped support member, said fourth (R) joint jointing a first horizontal portion of said support member to said support plate, and said fifth (R) joint jointing a second vertical portion of said support member to a connecting means for said effector unit, 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
- 10 12. Medical robotic system according to any one of claims 1 to 11, wherein said effector unit comprises a laparoscopic instrument actuator having means for mounting a surgical instrument to said manipulator and a linear actuation mechanism for actuating a mounted surgical instrument.
- 15 13. Medical robotic system according to claim 12, wherein said effector unit comprises a main support frame for connecting said effector unit to said wrist and a revolute (R) sixth joint which joints said laparoscopic instrument actuator 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.
- 20 14. Medical robotic system according to claim 13, wherein the axes of rotation of said sixth (R) joint and said fifth (R) joint are perpendicular.
- 25 15. Medical robotic system according to claim 13 or 14, wherein said effector unit comprises a sensor assembly 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.
- 30 16. Medical robotic system according to claim 7 or 13, wherein said fourth (R) joint, said fifth (R) joint and/or said sixth (R) joint has a motor, preferably a brushless servo-motor, a gear having an input stage coupled to the shaft of said motor, a belt transmission coupled to the output stage of said gear for transmitting motion to the associated joint, and an absolute position sensor coupled to said belt transmission.
- 35 17. Medical robotic system according to any one of the preceding claims, wherein said base comprises a laser range scanner for detecting intrusion of personnel into the workspace of said manipulator.

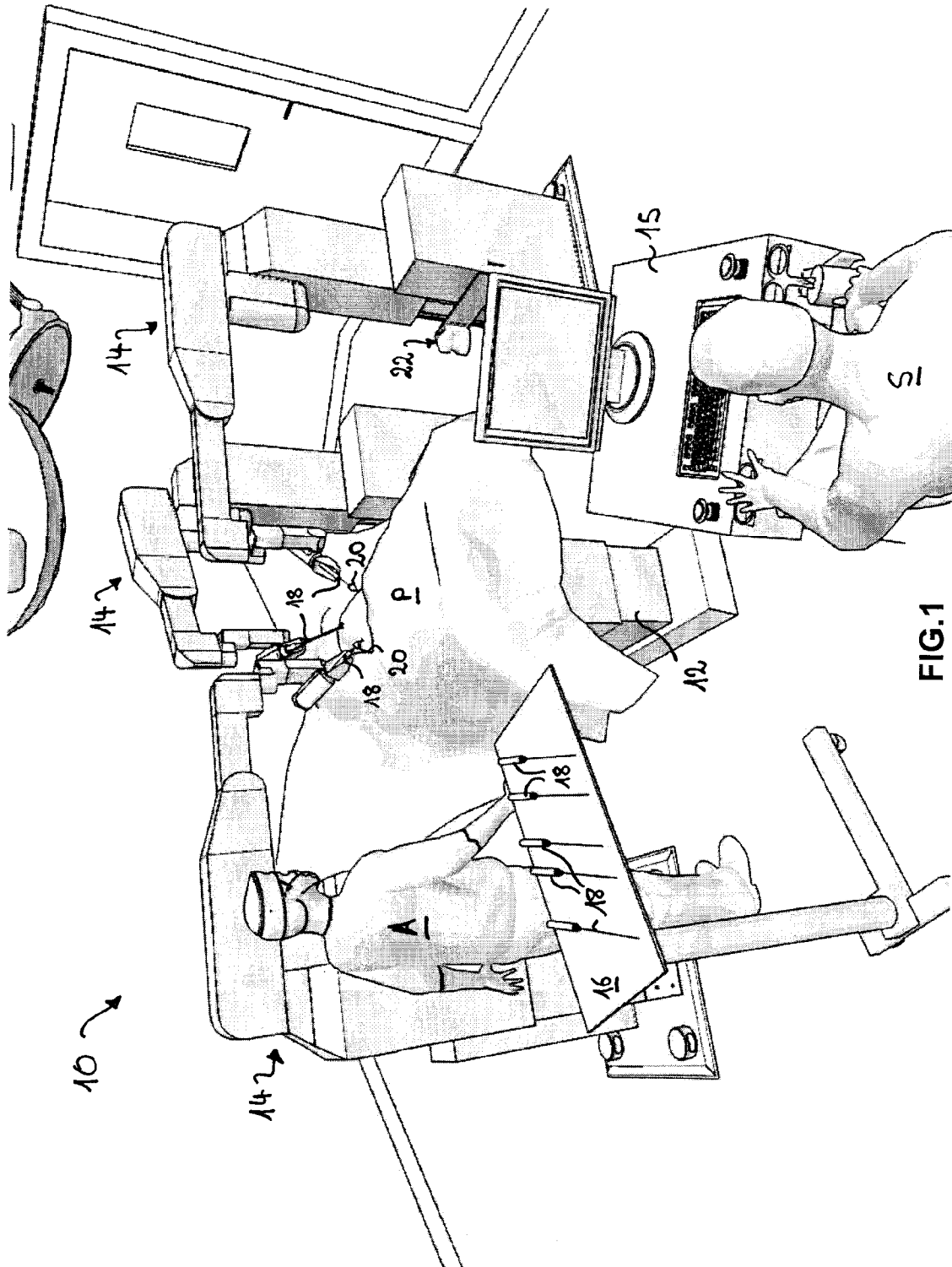
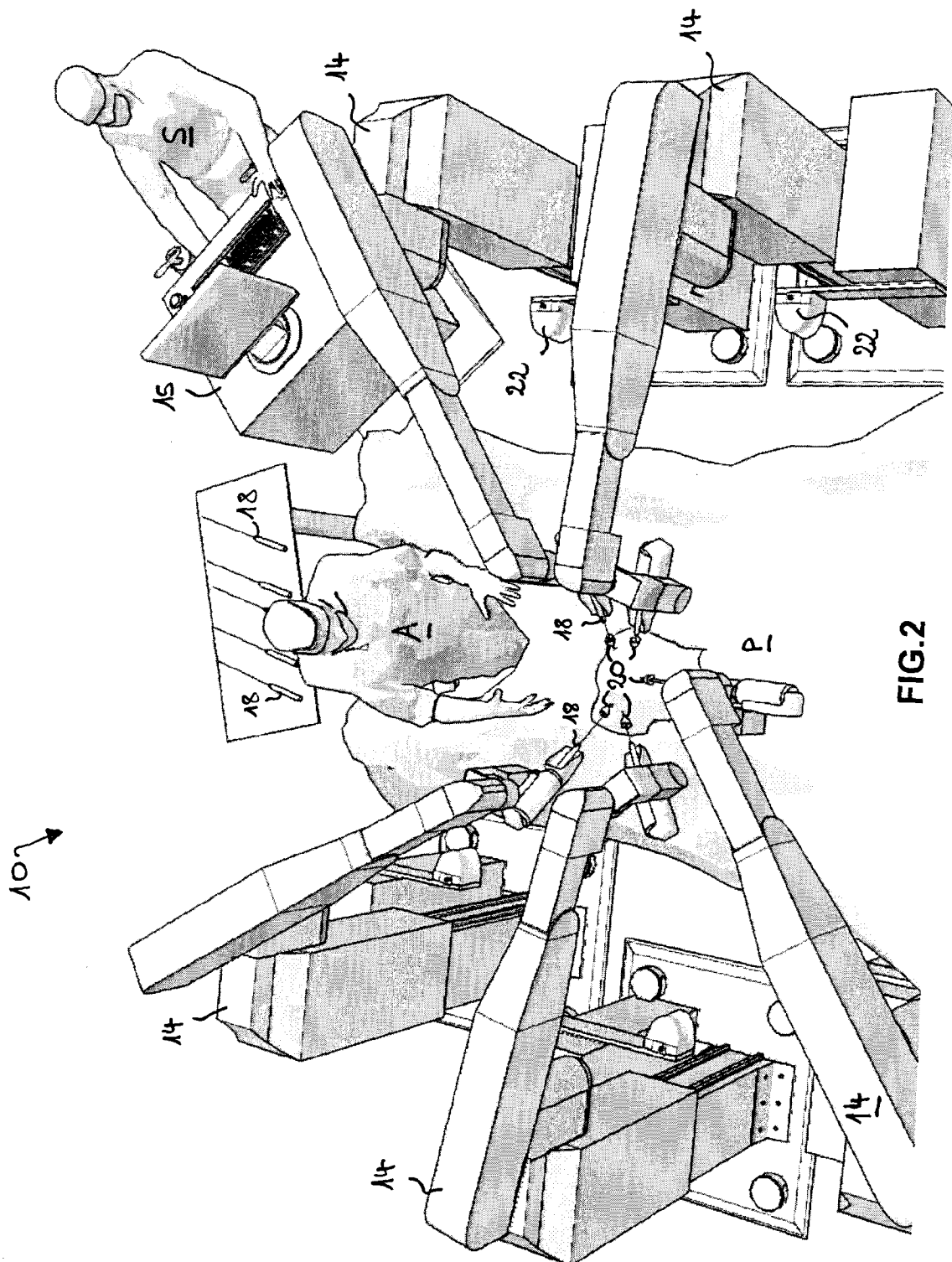


FIG. 1



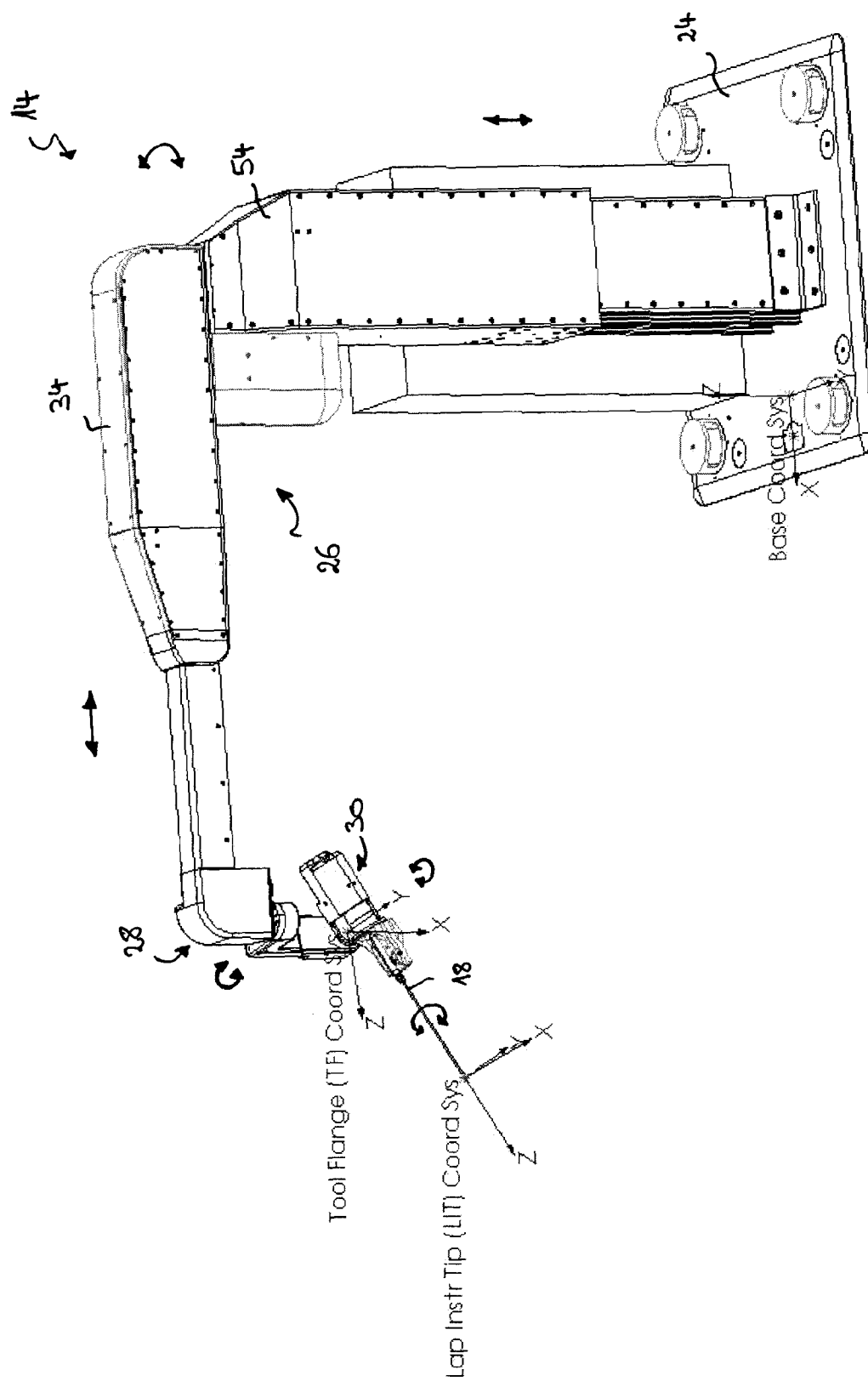
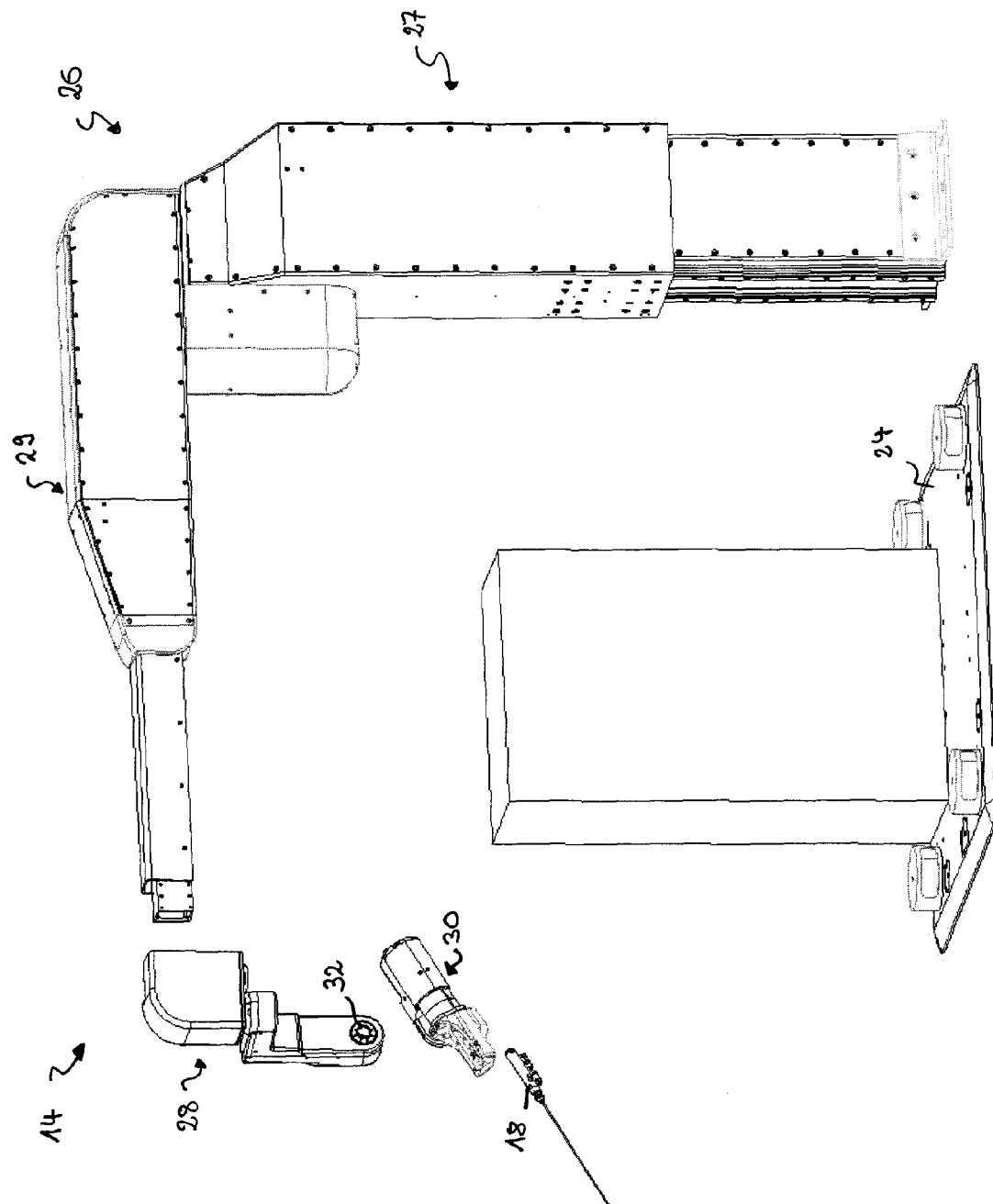


FIG.3



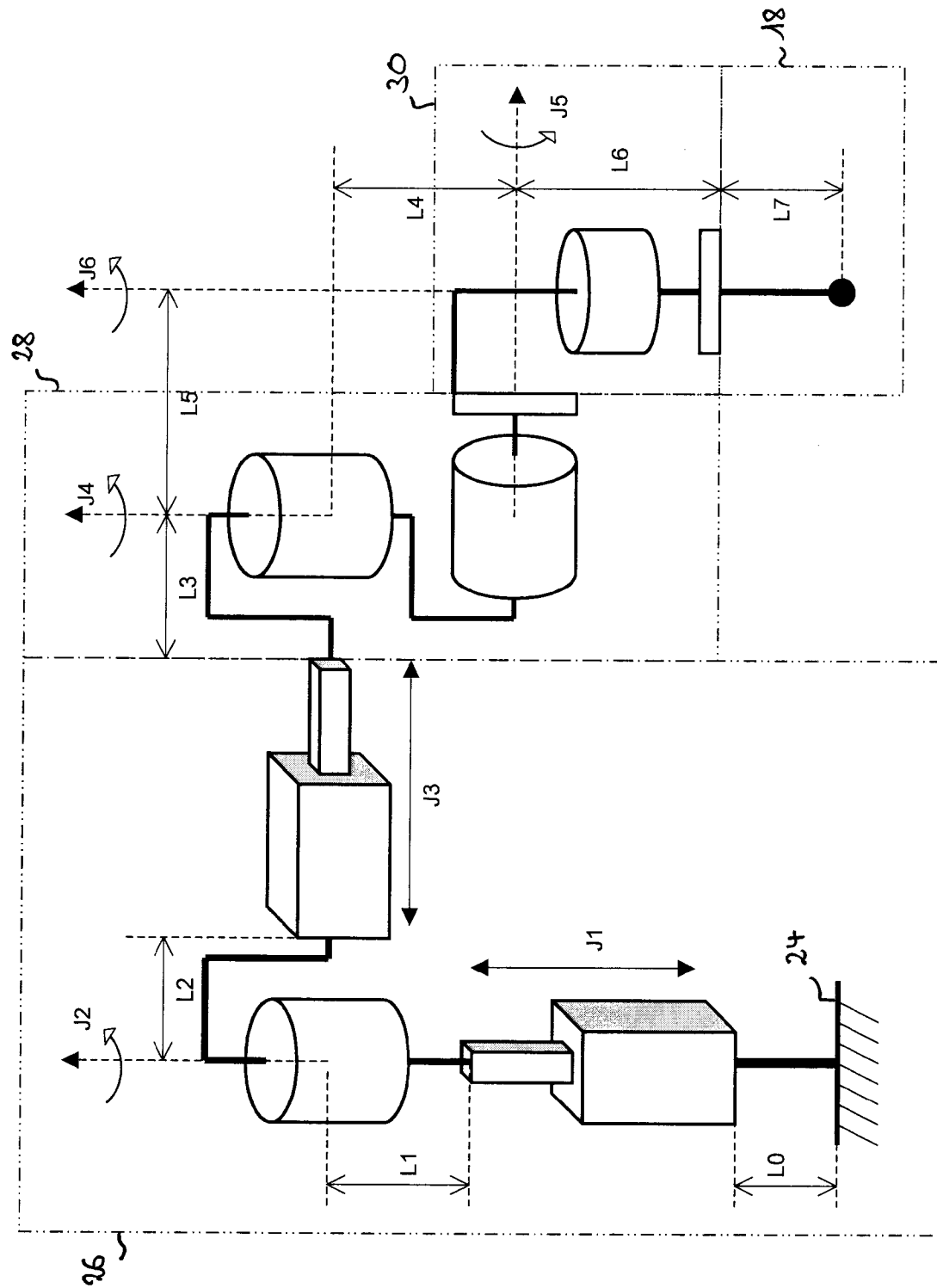


FIG.5

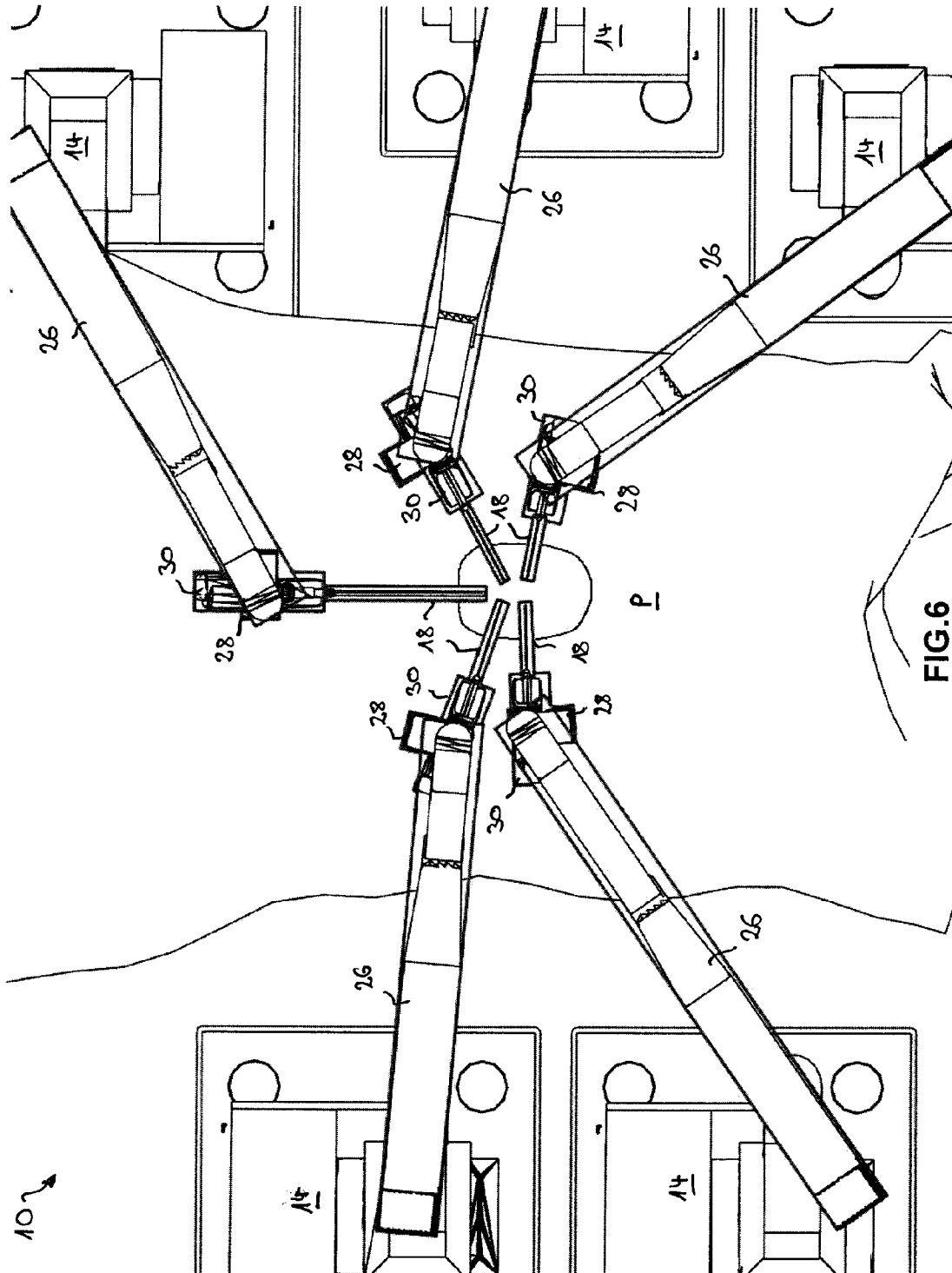


FIG. 6

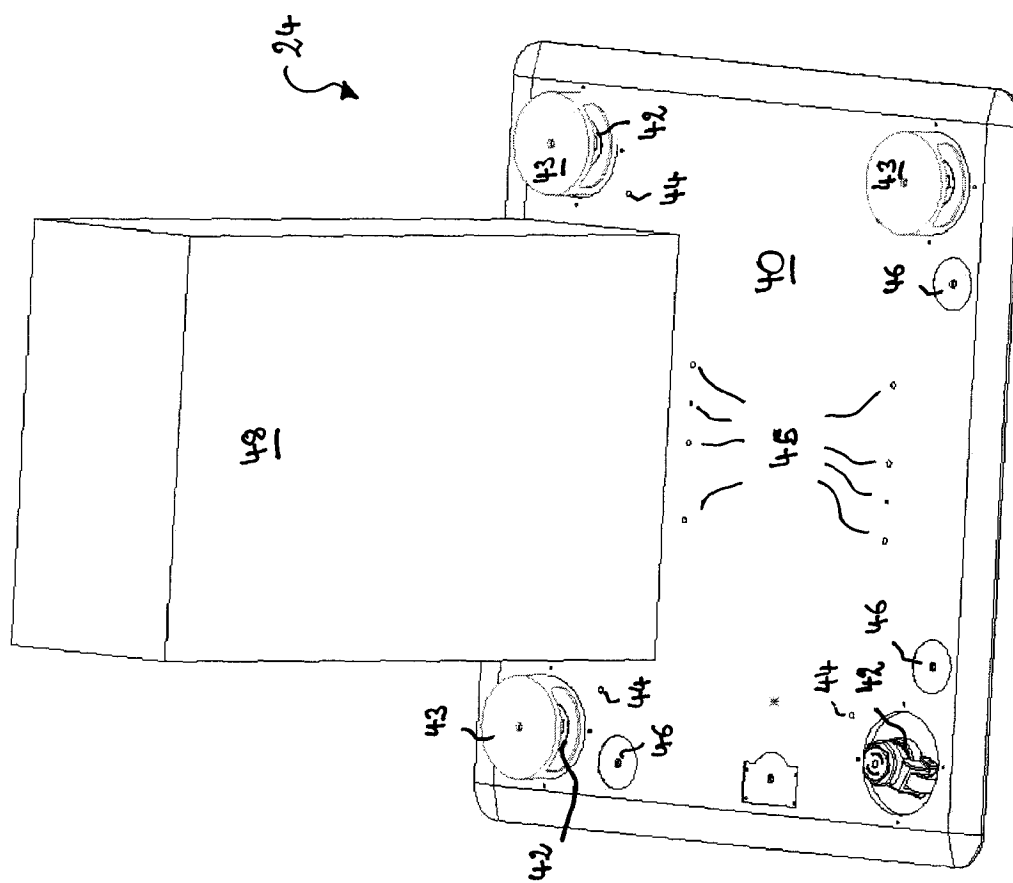
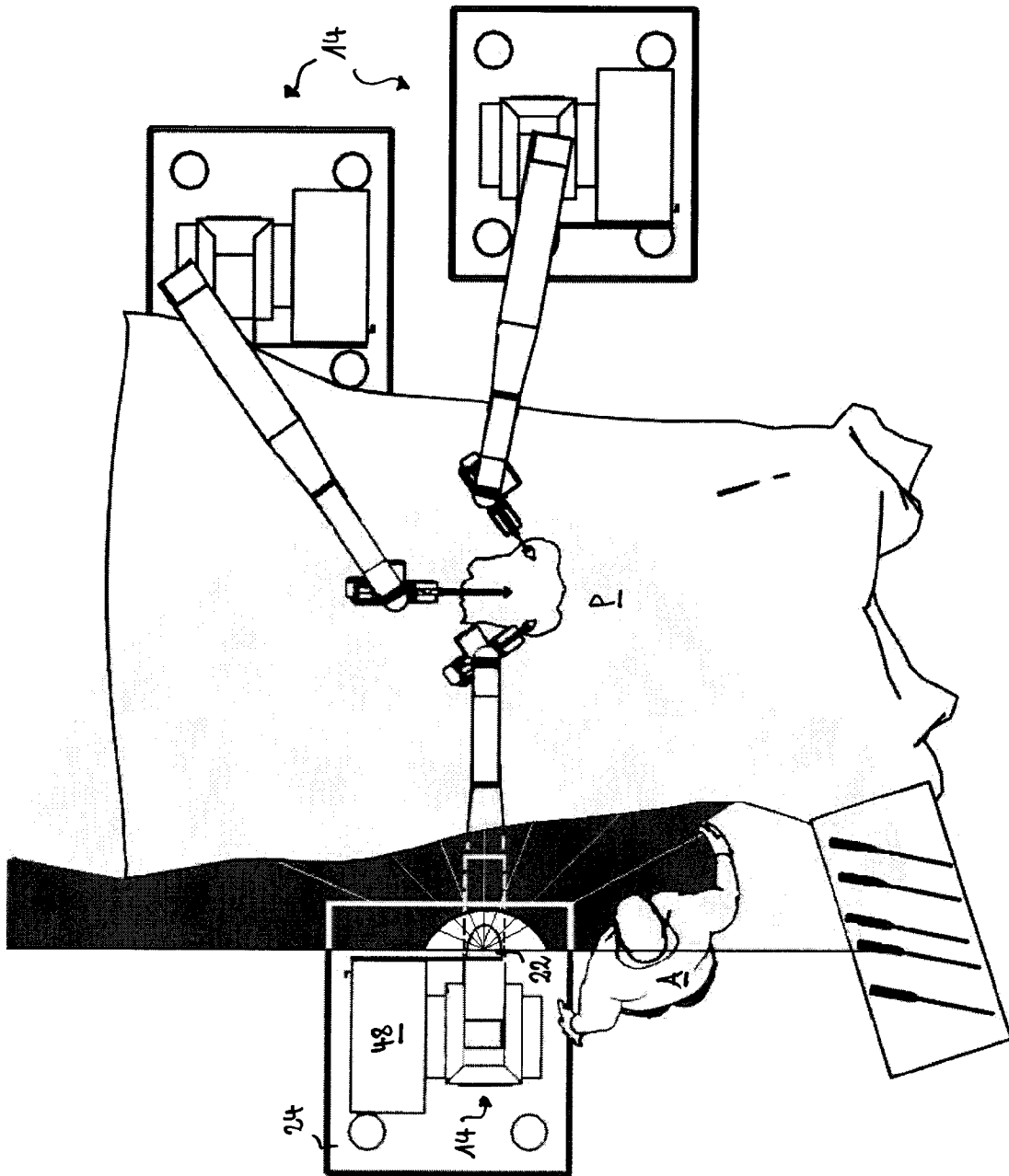


FIG. 7



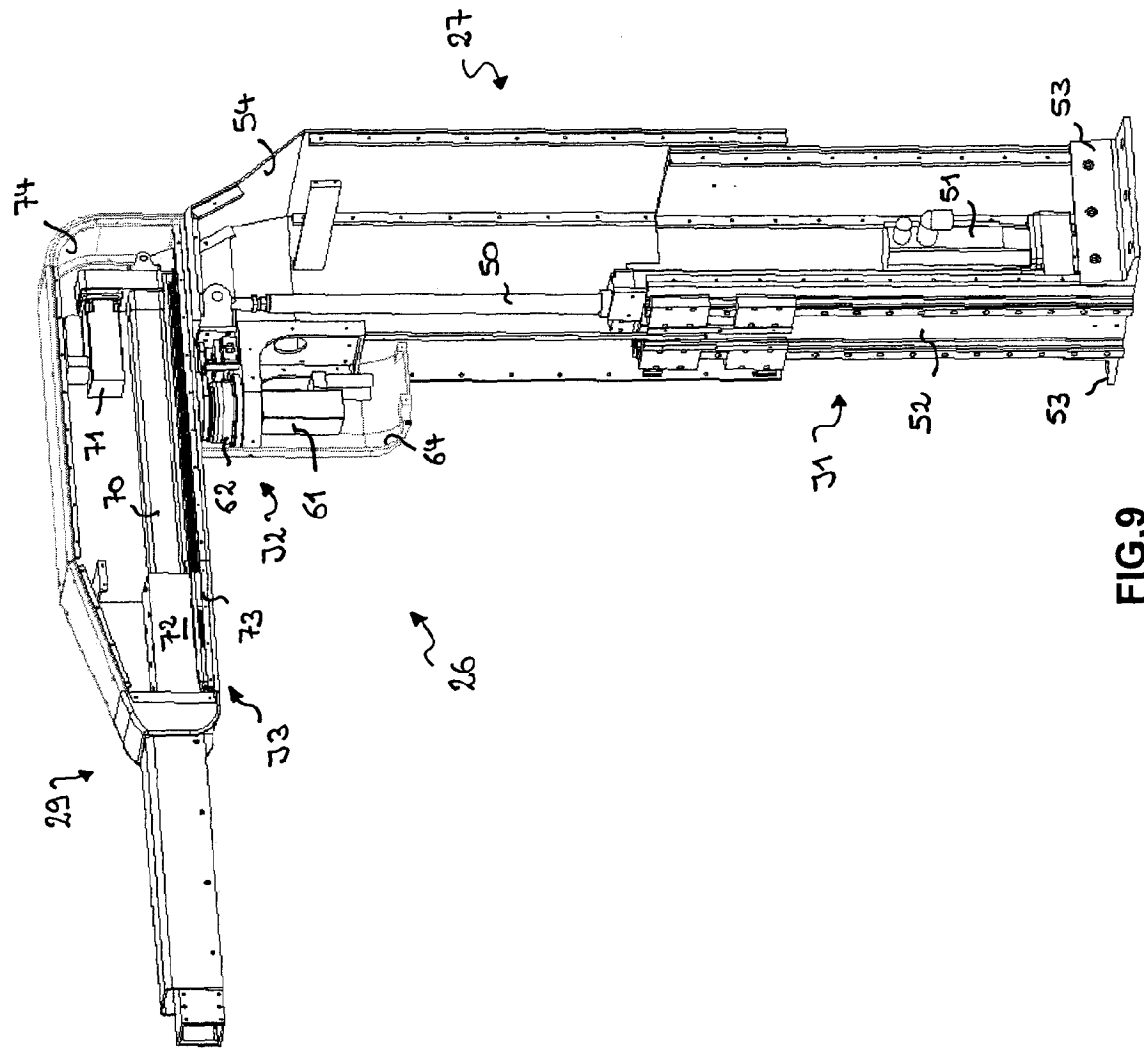


FIG. 9

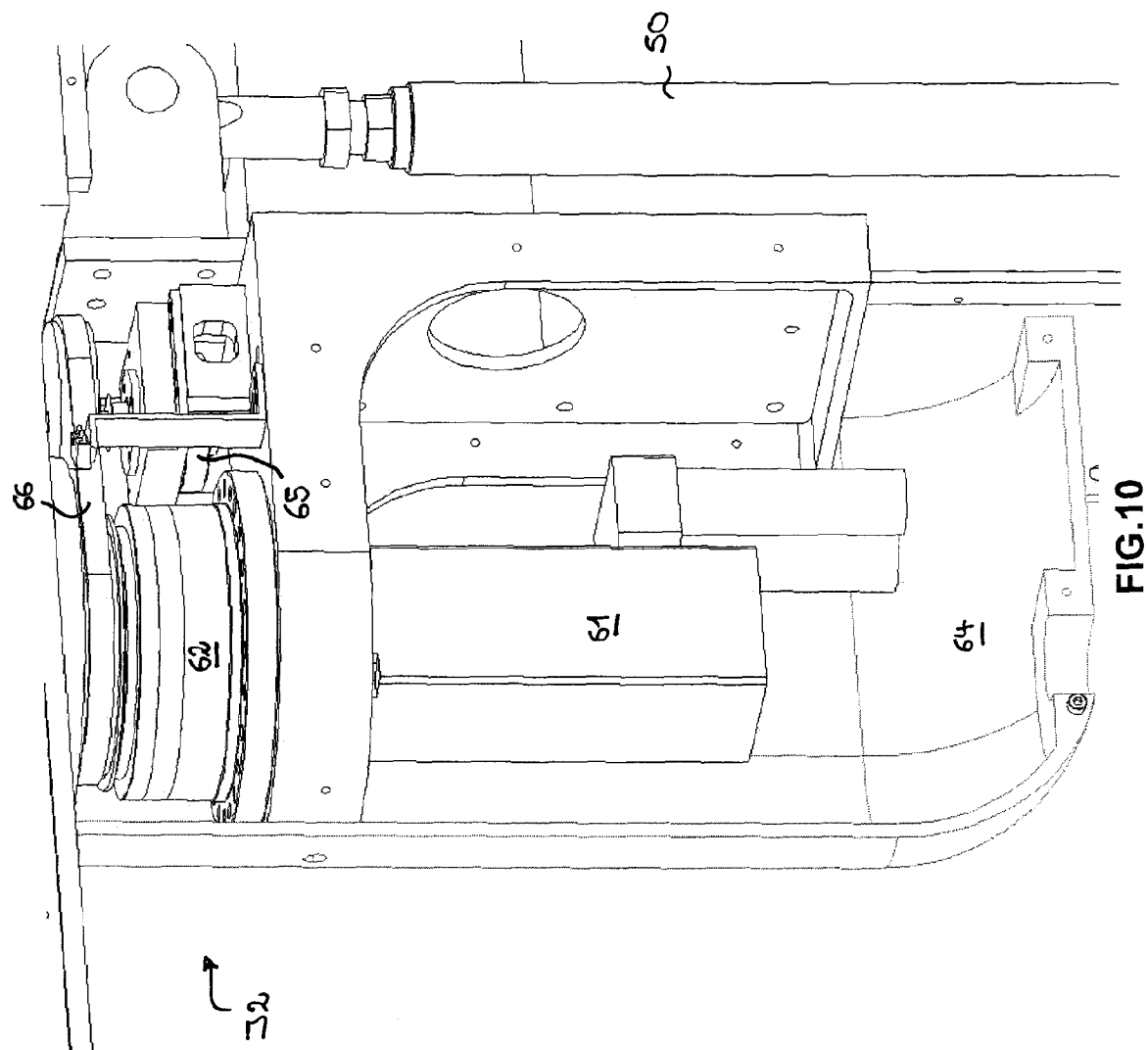


FIG.10

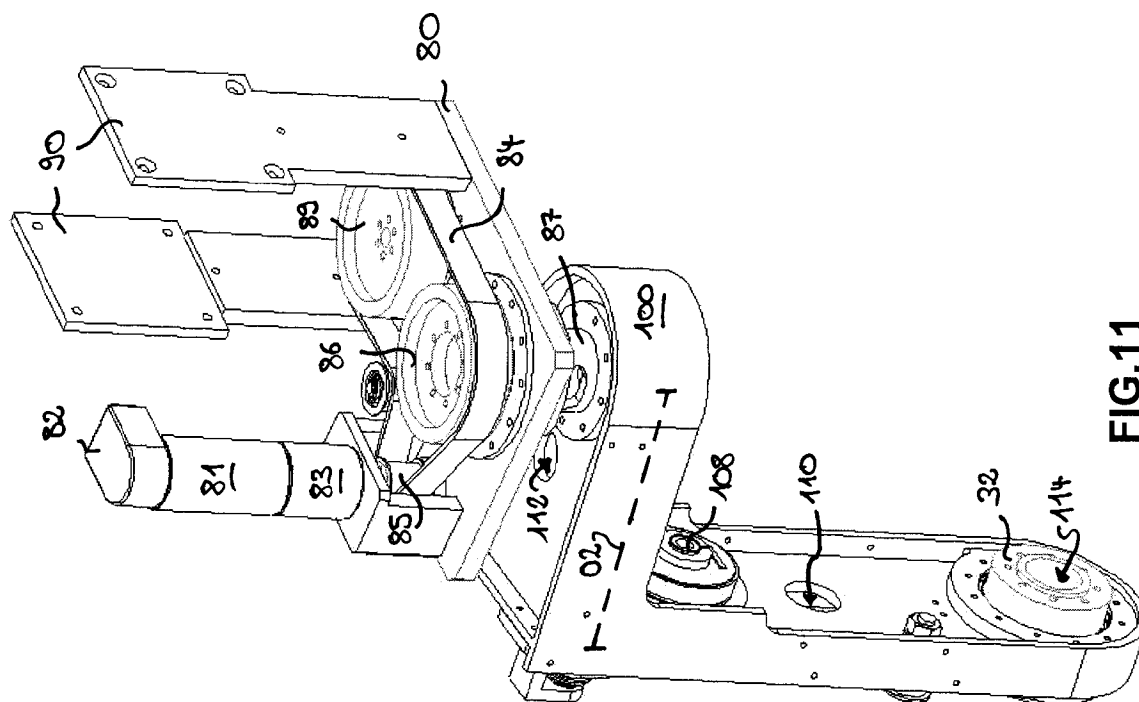


FIG.11

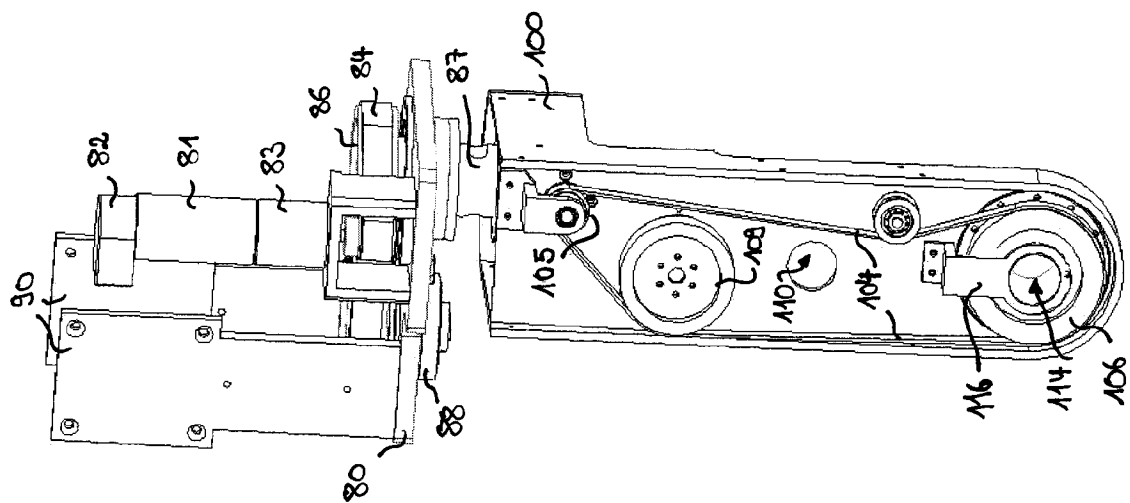


FIG.12

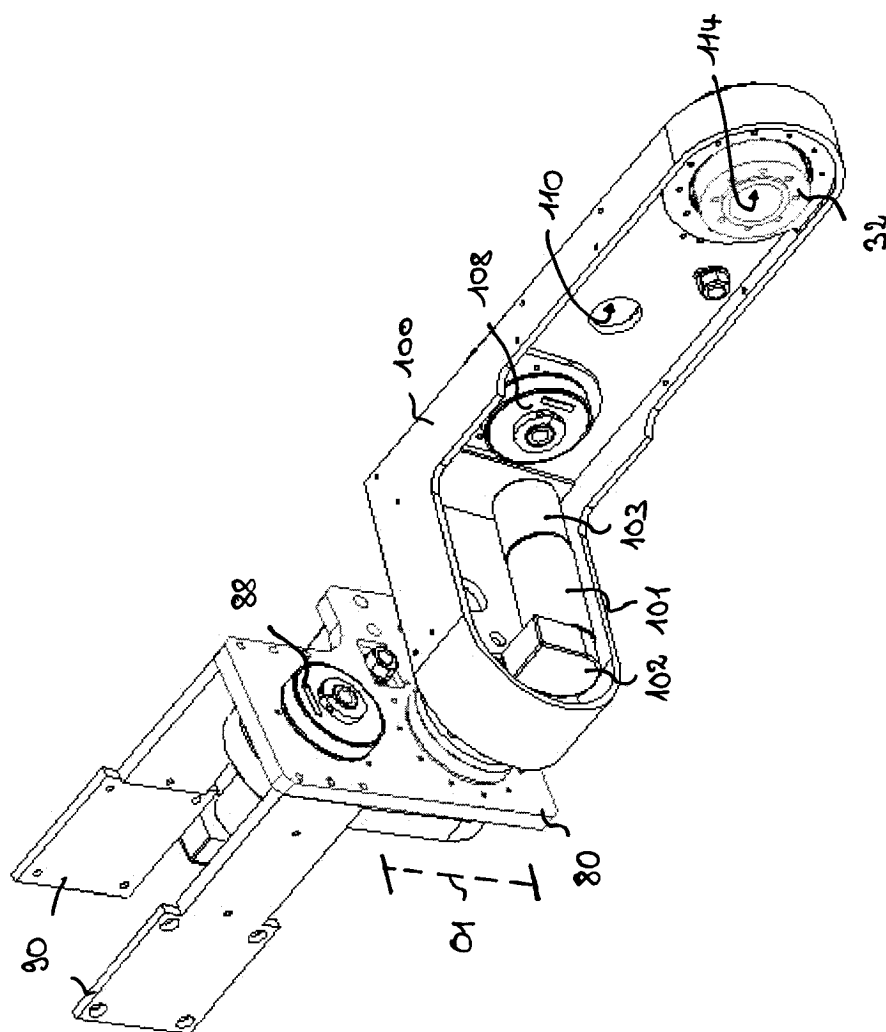


FIG.13

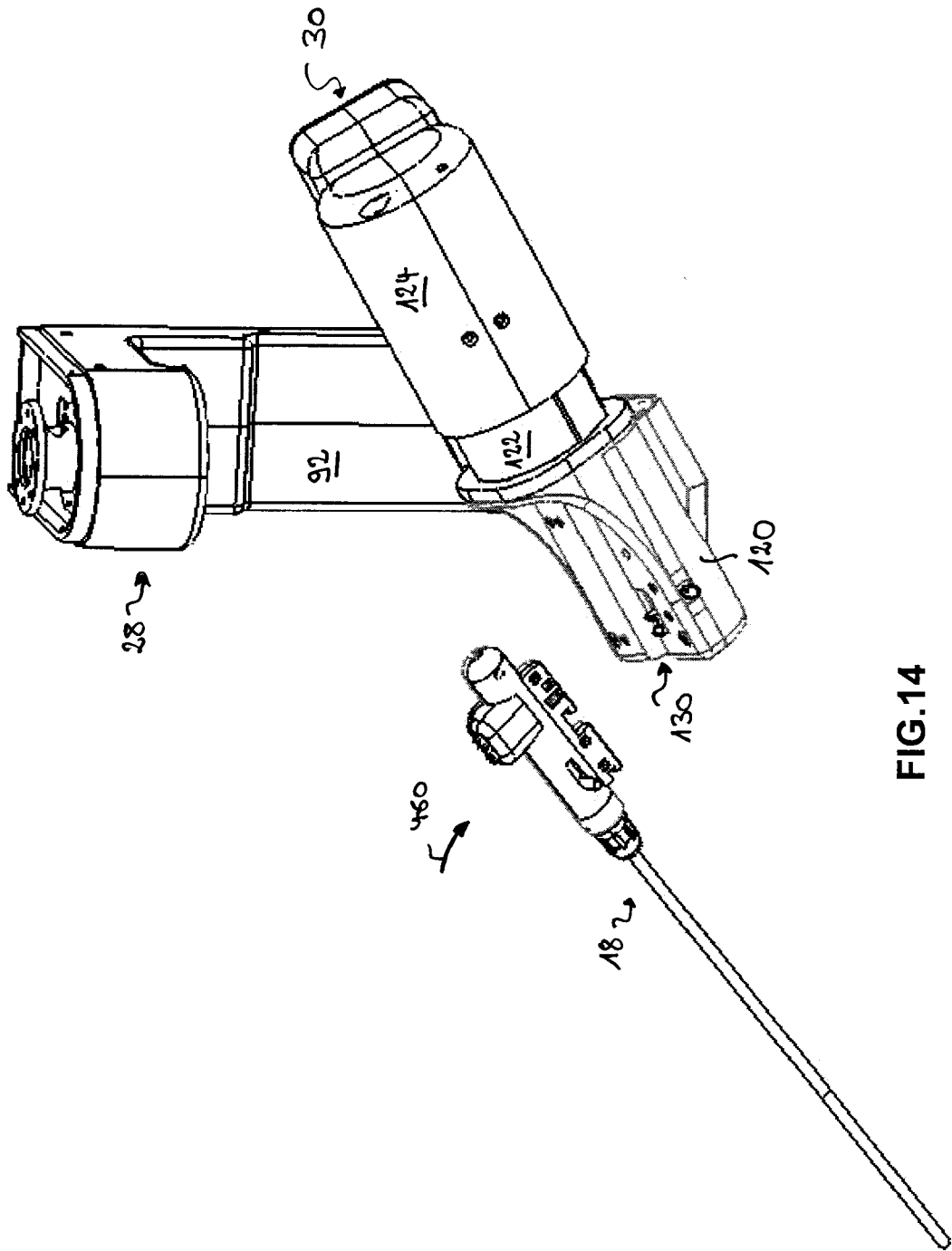


FIG.14

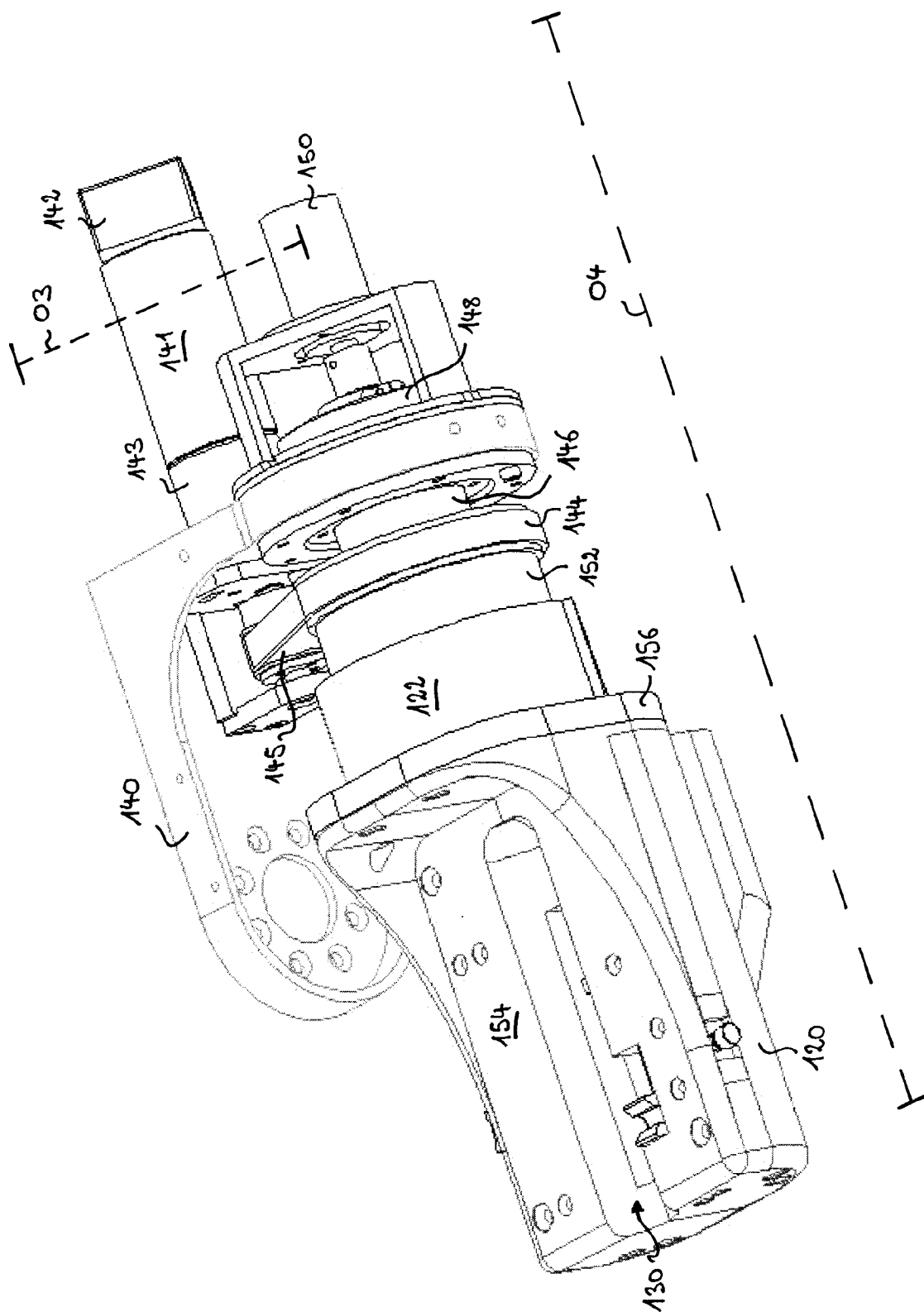


FIG.15

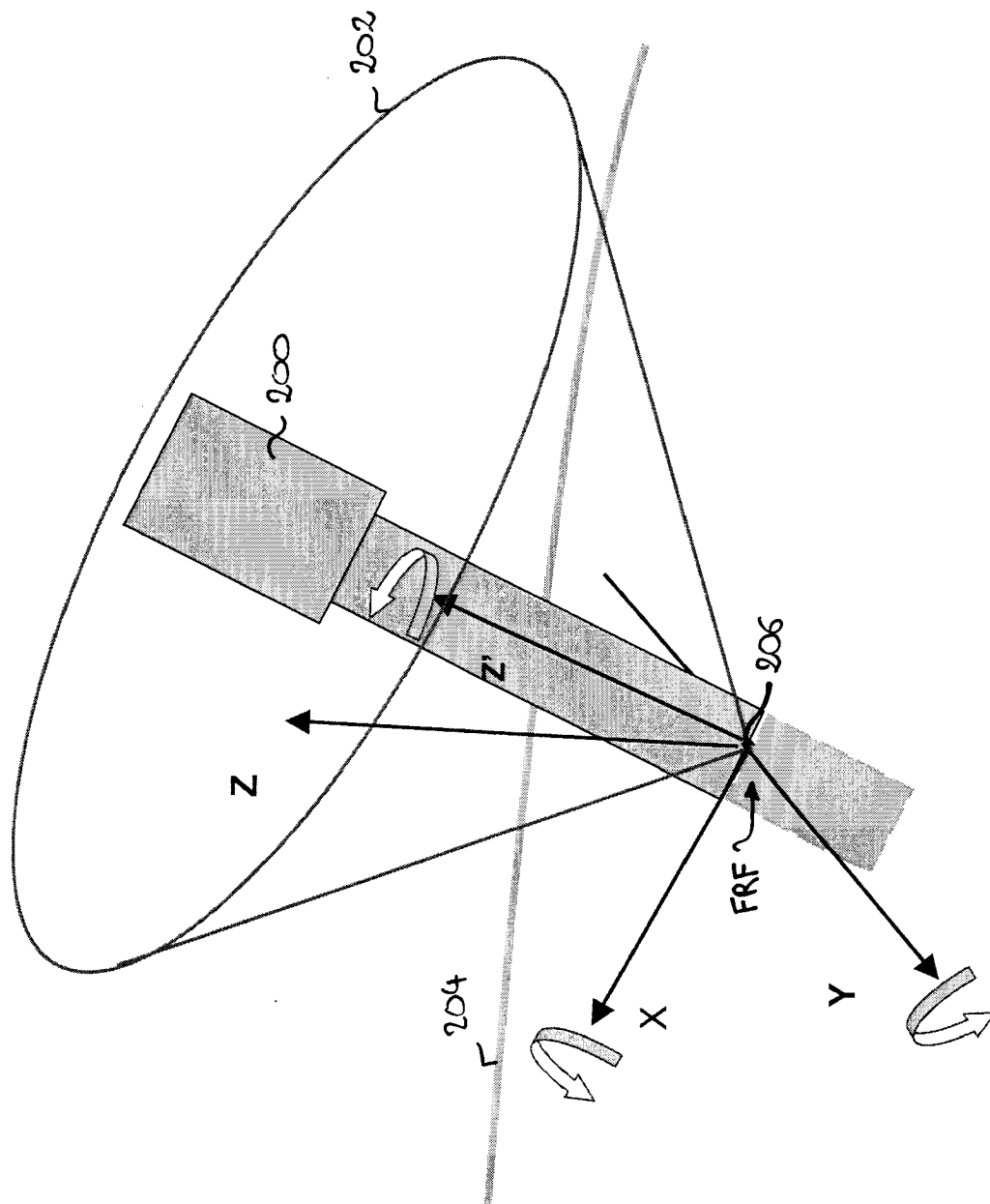


FIG.16

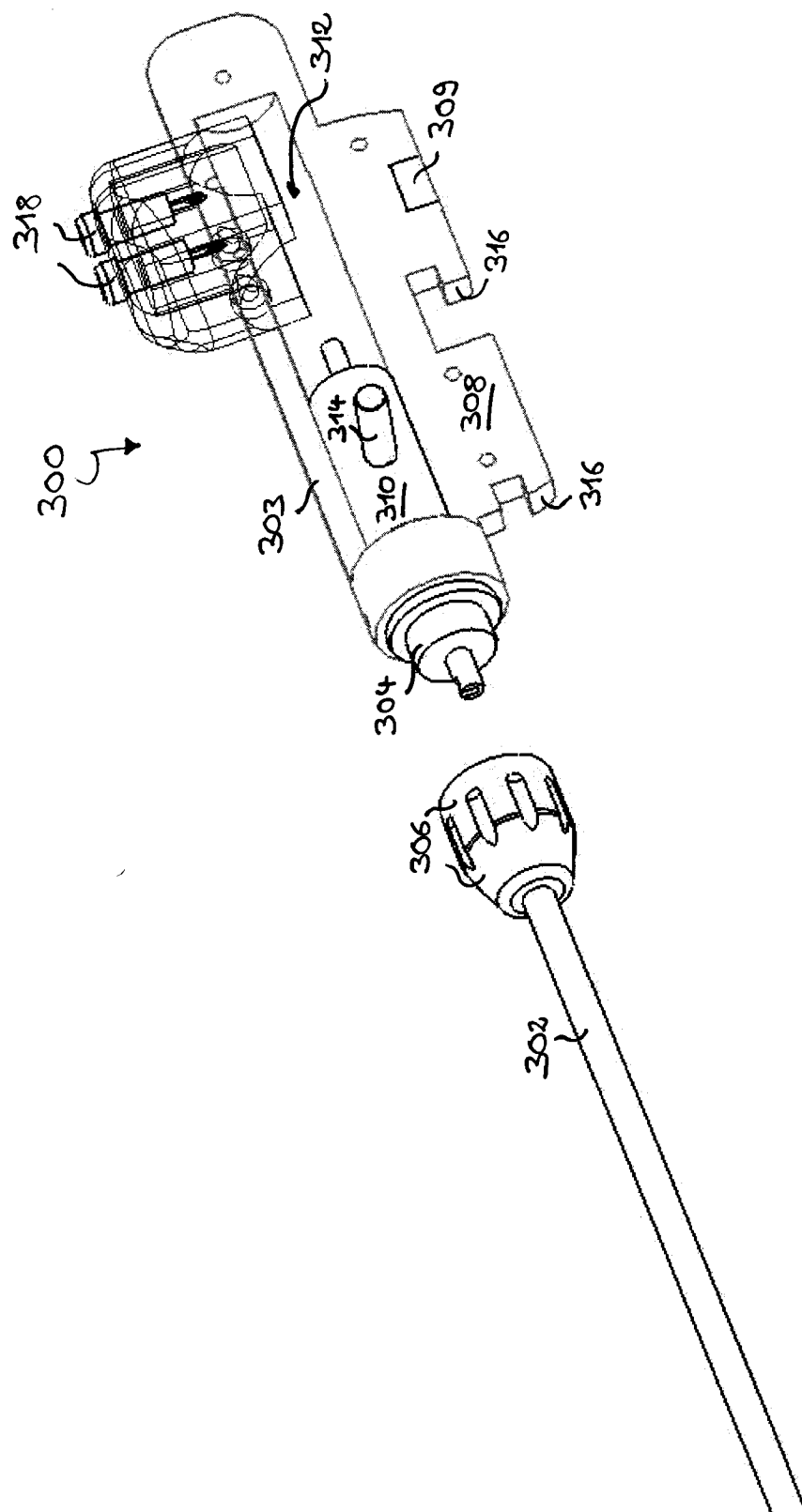


FIG.17

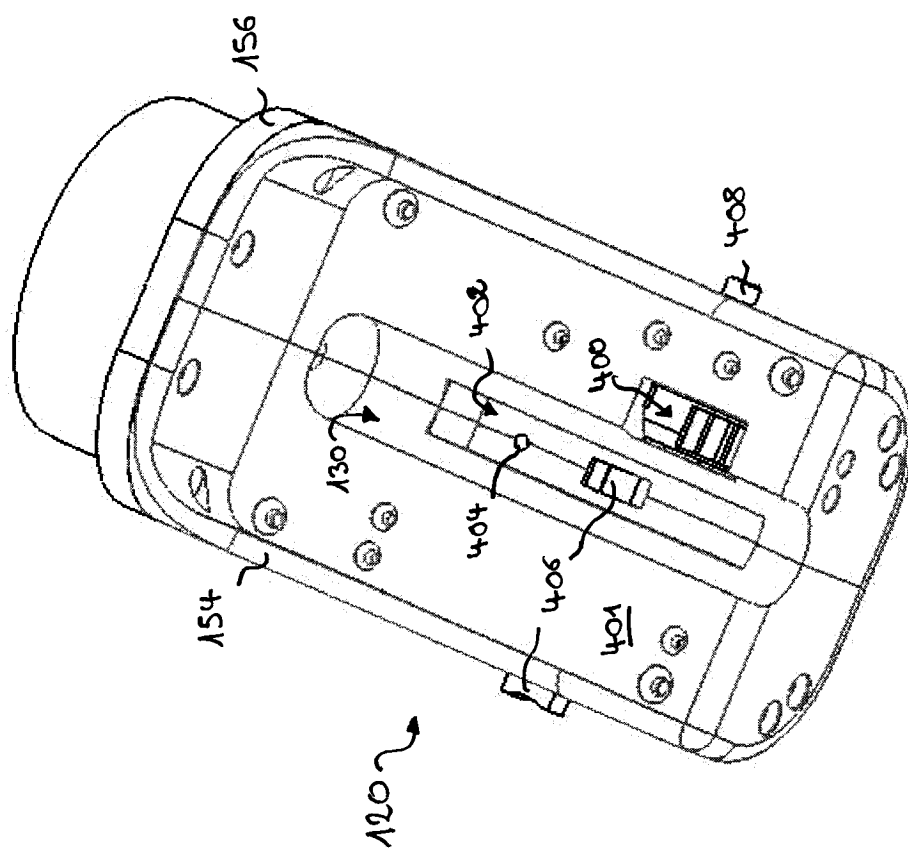


FIG.18

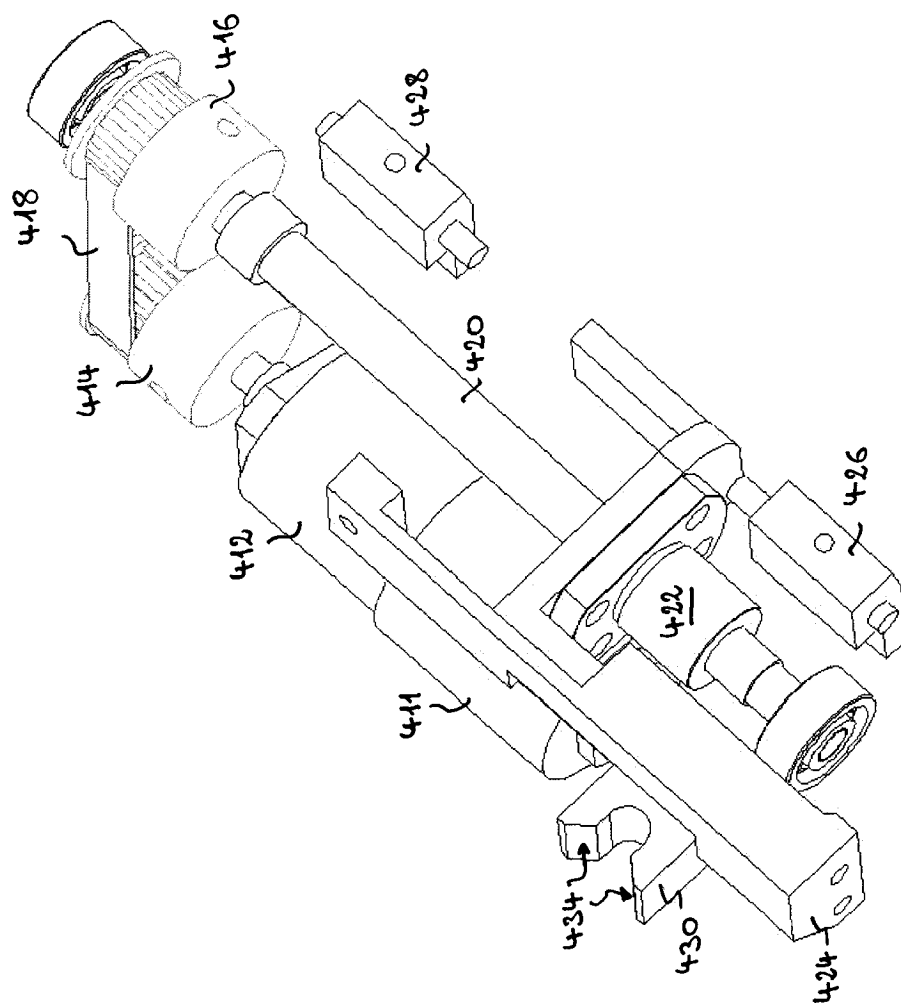


FIG.19

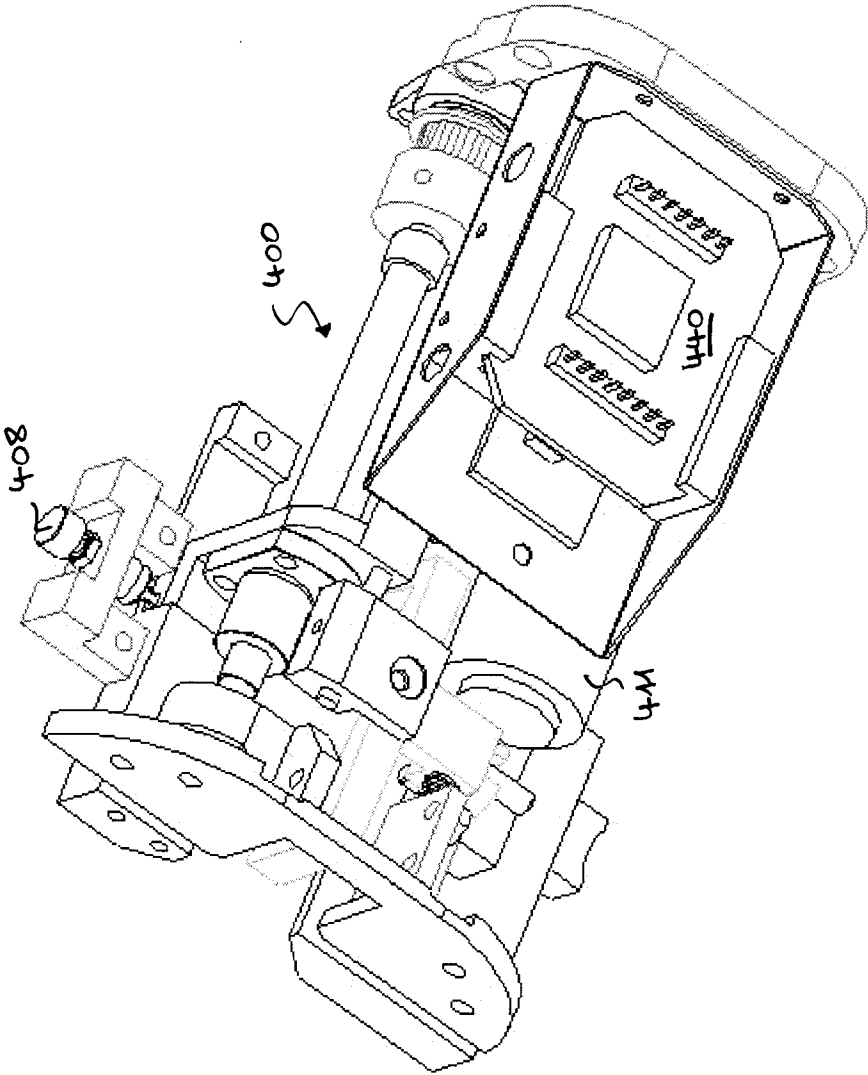


FIG.20

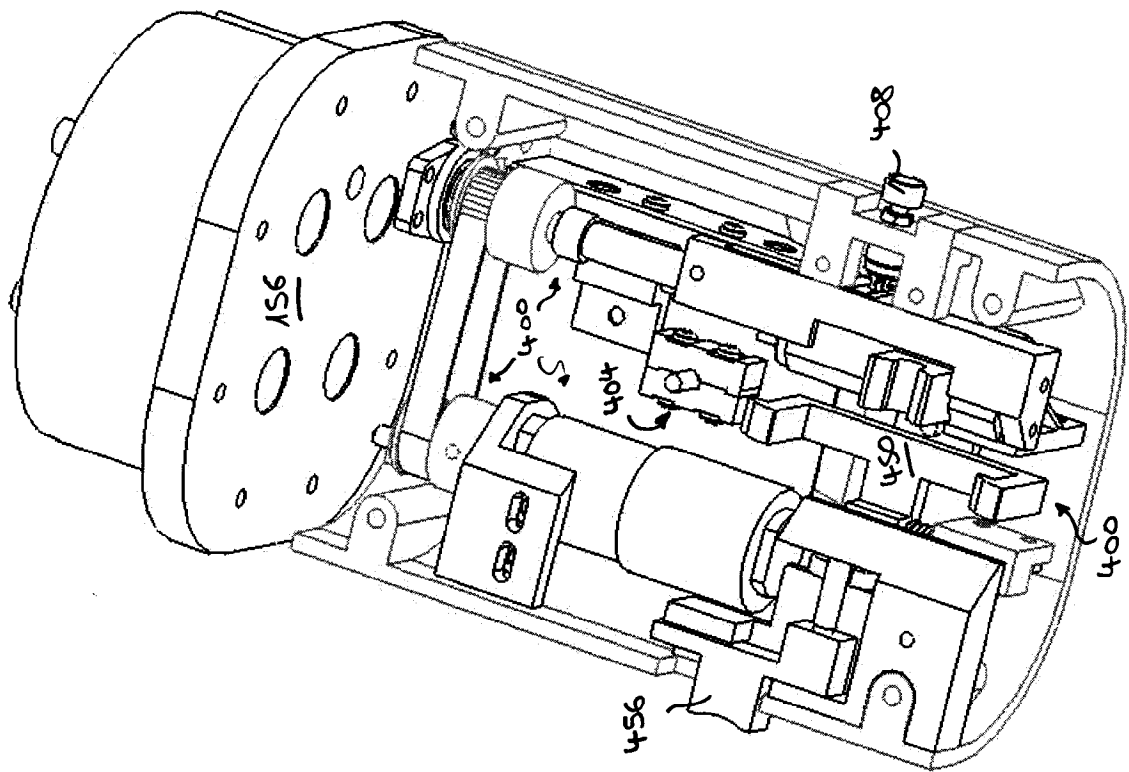


FIG.21

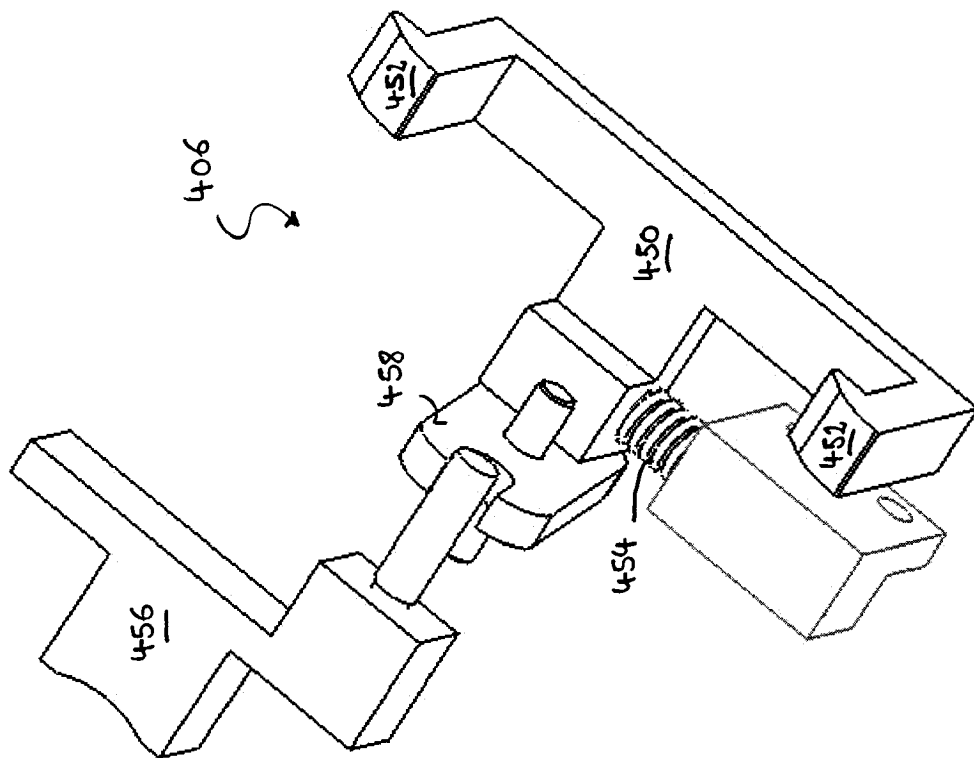
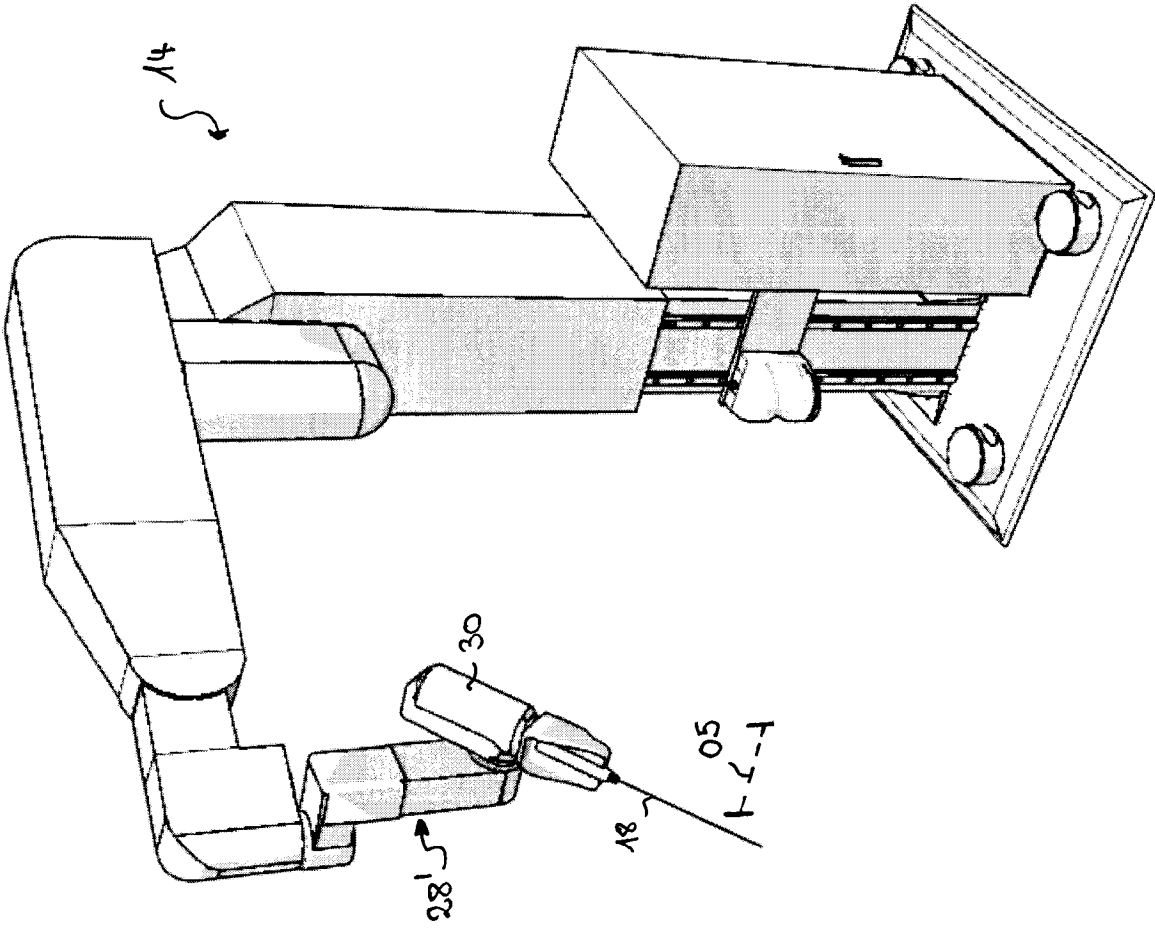
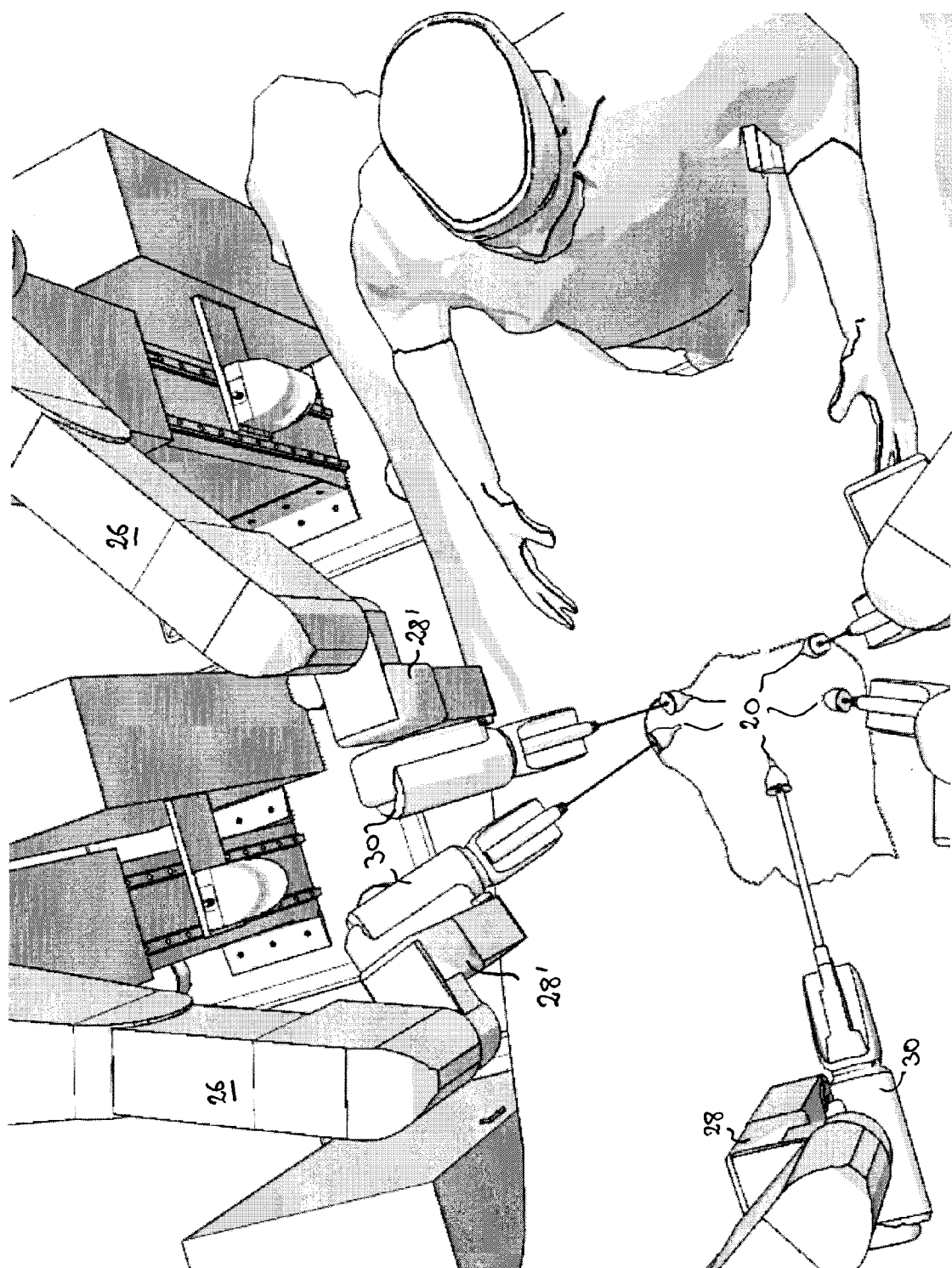


FIG. 22







DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 5 351 676 A (PUTMAN ET AL) 4 October 1994 (1994-10-04) * abstract; figures 3,8,11 *	1-4,7-10	INV. B25J9/04 A61B19/00
Y	US 6 120 433 A (MIZUNO ET AL) 19 September 2000 (2000-09-19) * figures 2,9,11a * * column 5, line 10 - line 17 *	1-5,7	
Y	FARAZ A ET AL: "A robotic case study: optimal design for laparoscopic positioning stands" ROBOTICS AND AUTOMATION, 1997. PROCEEDINGS., 1997 IEEE INTERNATIONAL CONFERENCE ON ALBUQUERQUE, NM, USA 20-25 APRIL 1997, NEW YORK, NY, USA, IEEE, US, vol. 2, 20 April 1997 (1997-04-20), pages 1553-1560, XP010235537 ISBN: 0-7803-3612-7 * table 1 *	1-5,7	
A	BOUAZZA-MAROUF K ET AL: "ROBOTIC-ASSISTED INTERNAL FIXATION OF FEMORAL FRACTURES" PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS. JOURNAL OF ENGINEERING IN MEDICINE. PART H, MECHANICAL ENGINEERING PUBLICATIONS LTD, LONDON, GB, vol. 209, no. H1, 1995, pages 51-58, XP000582781 ISSN: 0954-4119 * figure 5 * * page 54, right-hand column, line 5 - line 18 *	1-5	TECHNICAL FIELDS SEARCHED (IPC) B25J A61B
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 12 July 2006	Examiner Lumineau, S
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 06 10 1250

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

12-07-2006

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 5351676	A	04-10-1994	US 5184601 A	09-02-1993

US 6120433	A	19-09-2000	NONE	

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- US 6659939 B [0005]
- US 6837883 B [0005]
- US 6102850 A [0005] [0013] [0067]
- US 5855583 A [0005] [0013]
- US 5762458 A [0005] [0013]
- US 5515478 A [0005] [0013]
- US 5667323 A, Taylor [0067]

Non-patent literature cited in the description

- Development of actuated and sensor integrated forceps for minimally invasive robotic surgery. **B. KÜBLER ; U. SEIBOLD ; G. HIRZINGER.** Jahrestagung der Deutschen Gesellschaft für Computer- und Roboterassistierte Chirurgie (CURAC. 08 October 2004 [0026]
- **MOLLER.** A Fast Triangle-Triangle Intersection Test. *Journal of Graphics Tools*, 1997, vol. 2 (2 [0039]
- Robot calibration. Chapman & Hall, 1993 [0044]
- Surgeon-Tool Force/Torque Signatures - Evaluation of Surgical Skills in Minimally Invasive Surgery. **J.ROSEN et al.** Proceedings of Medicine Meets Virtual Reality, MMVR-7. IOS Press, January 1999 [0065]

专利名称(译)	具有圆柱坐标型机械臂的医疗机器人系统		
公开(公告)号	EP1815949A1	公开(公告)日	2007-08-08
申请号	EP2006101250	申请日	2006-02-03
申请(专利权)人(译)	欧洲原子能共同体 (欧洲原子能共同体) ， 代表欧洲委员会		
当前申请(专利权)人(译)	欧洲原子能共同体 (欧洲原子能共同体) ， 代表欧洲委员会		
[标]发明人	RUIZ MORALES EMILIO		
发明人	RUIZ MORALES, EMILIO		
IPC分类号	B25J9/04 A61B19/00		
CPC分类号	A61B34/30 A61B34/37 A61B34/71 A61B34/77 A61B90/361 A61B2034/305 A61B2090/064 B25J9/041		
代理机构(译)	SCHMITT, 阿尔芒		
外部链接	Espacenet		

摘要(译)

用于执行医疗程序的医疗机器人系统包括用于机器人辅助处理医疗器械的机器人操纵器，特别是腹腔镜手术器械。机器人操纵器包括底座 (24) ;一个机械臂，其基本垂直的部分由基座支撑，并且基本水平的部分由垂直部分支撑;由操纵臂 (26) 支撑的操纵器腕部 (28) ;效应器单元 (30) 由操纵器手腕 (28) 支撑并且构造成用于保持医疗器械 (18))。操纵臂 (26) 具有圆柱形PRP运动构造，用于定位操纵器腕部 (28))。更具体地，PRP运动构造包括棱柱 (P) 第一关节，用于通过沿基本垂直轴提供平移自由度来改变垂直部分的高度，旋转 (R) 第二关节用于改变第二关节之间的旋转角度。垂直部分和水平部分通过提供围绕基本垂直轴的旋转自由度，以及棱柱 (P) 第三关节，用于通过沿基本水平轴线提供平移自由度来改变水平部分的范围。

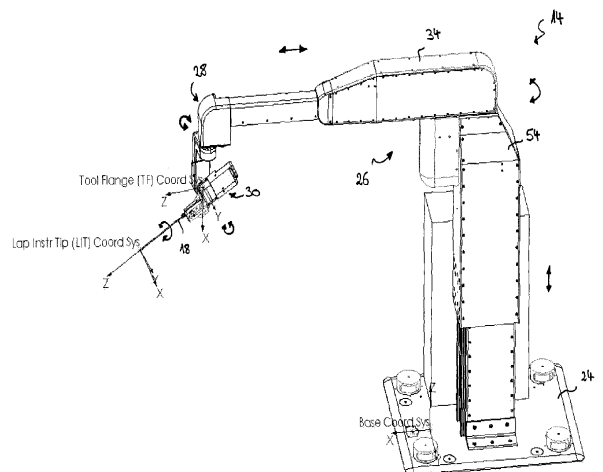


FIG.3