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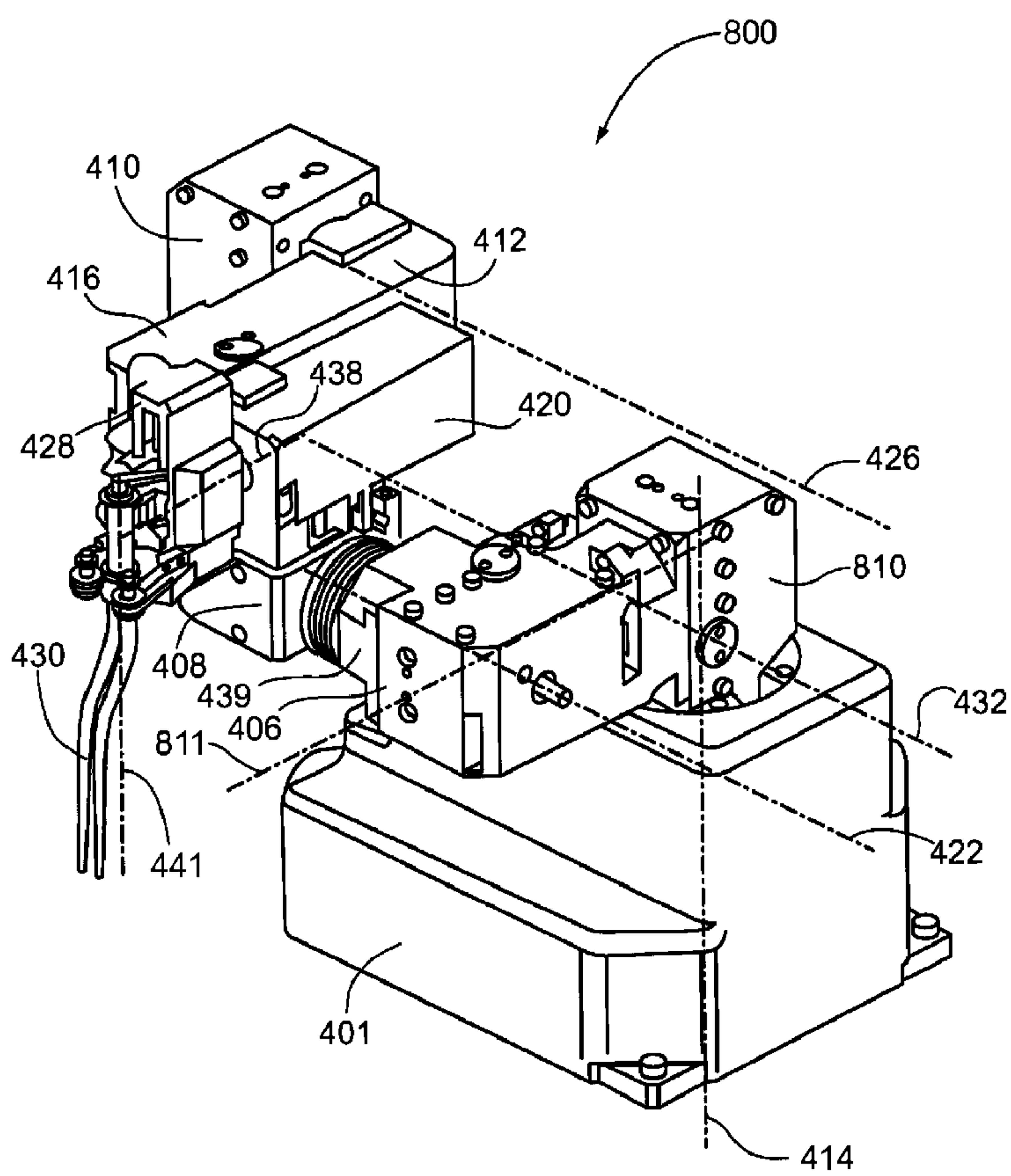

(57) Abrégé/Abstract:
The present invention provides a surgical manipulator including a manipulator arm, an end-effector held by the robotic arm, surgical tools held by the end-effector and manipulator joints, particularly right-angle drive devices for transmitting rotational motion in one axis to a perpendicular axis. The surgical manipulator may have up to seven (7) degrees of freedom by using up to four (4) right-angle drive mechanisms.

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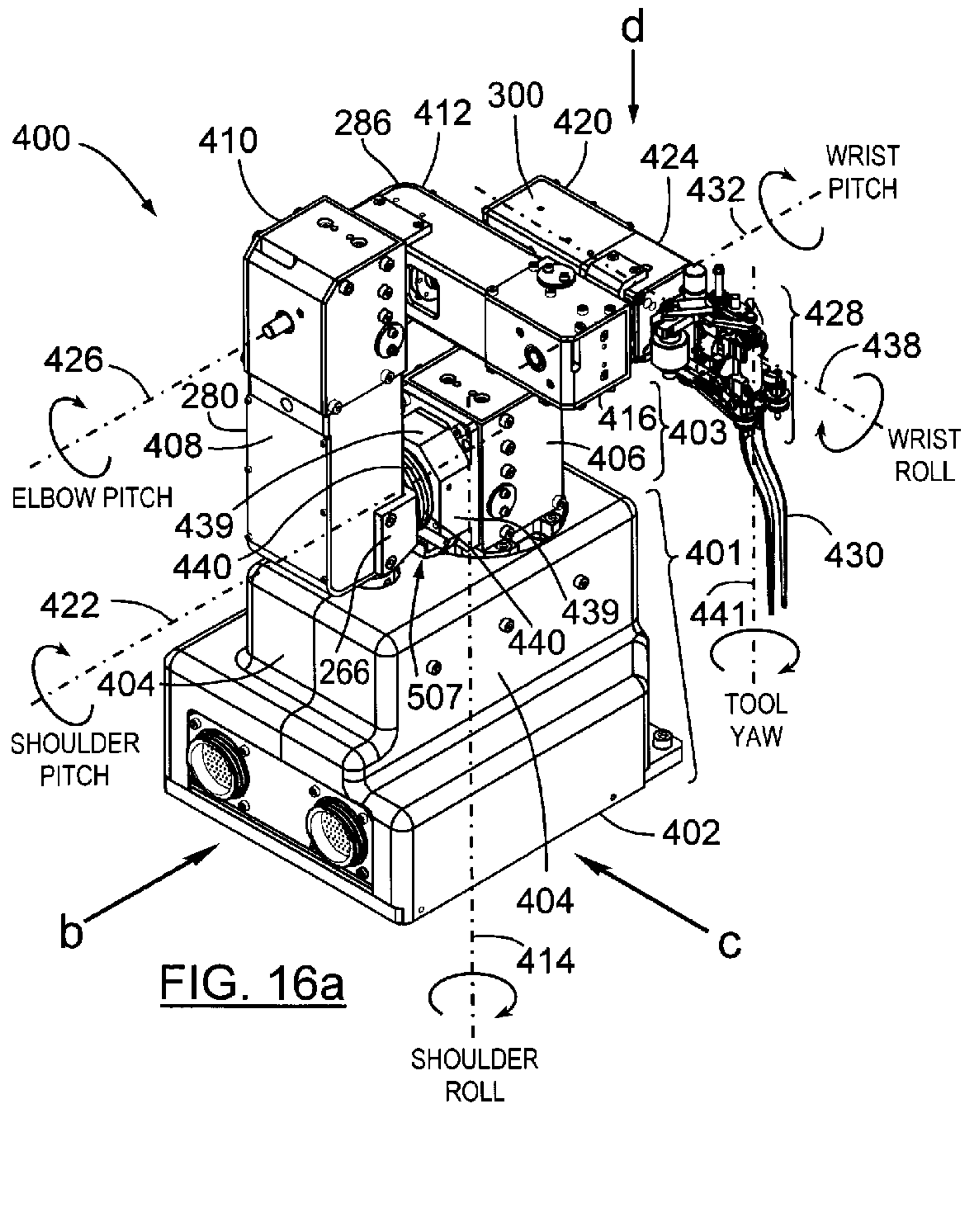

FIG. 16a

(57) Abstract: The present invention provides a surgical manipulator including a manipulator arm, an end-effector held by the robotic arm, surgical tools held by the end-effector and manipulator joints, particularly right-angle drive devices for transmitting rotational motion in one axis to a perpendicular axis. The surgical manipulator may have up to seven (7) degrees of freedom by using up to four (4) right-angle drive mechanisms.

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SURGICAL MANIPULATOR

FIELD OF THE INVENTION

The present invention relates to a surgical manipulator including a manipulator arm, an end-effector held by the manipulator arm, surgical tools held by the end-effector and manipulator joints, particularly right-angle drive devices for transmitting rotational motion in one axis to a perpendicular axis.

BACKGROUND OF THE INVENTION

The goal of surgical manipulator systems is to apply robotic and sensor technologies to improve the quality of patient surgical outcomes in a cost-effective manner. Surgical robotics can attain this goal through repeatable increased spatial resolution and better geometric accuracy of surgical tools positioning by the surgeon, faster operating speed, good ergonomics that can reduce the surgeon's fatigue, and the ability to provide a platform for surgeon training and education.

A number of commercial surgical robotic systems are currently in use including the NeuroArm Magnetic Resonance Imager (MRI) compatible neurosurgical robot by the University of Calgary, the da Vinci and Zeus surgical robots by Intuitive Surgical, the RAMS system by Microdexterity and the Jet Propulsion Laboratory, the Haptic Guidance System by MAKO, the SpineAssist by Mazor Surgical Technologies, as well as ROBODOC of Integrated Surgical Systems. For a list of reference to the existing patents of the above-mentioned systems, refer to the appendix.

The University of Calgary neuroArm system is designed to perform neurosurgery in an MRI environment. It has dual arms, each with 6 Degrees of Freedom in a master-slave configuration. The robot is MR compatible so no magnetic material is used for any part of the robot arm. It also has haptic feedback capability for sensing tool tip forces. Surgical tool changes are performed manually, see United States Patent No. 7,155,316.

The Intuitive Surgical da Vinci system is designed for laparoscopic surgery. It can have up to 5 arms controlled by the surgeon in a Master-slave control configuration. The system is large and heavy with a weight greater than 1000 lbs. There is no haptic feedback and tool changes are performed manually. The Zeus is a discontinued product that was also designed for laparoscopic surgery. Smaller and lighter than the da Vinci, the Zeus also had up to 5 arms in a Master -slave control architecture with no haptic capability and manual tool changes. (di Vinci: patents see attached list; Zeus: US Patent Nos. 05515478, US05553198, US05645520, US06646541, US06714841 etc)

Originally developed by JPL, the Robot-Assisted Micro-Surgery (RAMS) system is being commercialised by MicroDexterity. This telerobotic platform is designed for microsurgery on brain, eye, ear, nose, throat, face, and hand. Clinical tests had been performed on neurosurgery and hand surgery. The dual-arm system is very compact; the manipulator is approximately 25 mm in diameter and 250 mm long. The robot has a Master-slave architecture and exhibits high spatial resolution of 10 microns. The system has indirect pressure and texture sensing of the tool forces using joint encoder information. The surgical tools are changed manually, see US Patent No. 6,702,805.

The MAKO Haptic Guidance System targets knee replacement surgeries by means of a robotic system that assists the surgeon in arthroplasty through keyhole incisions. The FDA-approved system allows surgeon to pre-operatively optimize the size and alignment of knee, and execute surgeon-guided knee sculpturing and implant placing with CT image-guidance, see US patent Publications 20060142657, 07206627, 07139418)

Mazor Surgical Technologies developed the SpineAssist as a minimally invasive guidance systems for pedicle screw insertion as well as other spine related procedures. In the size of a soda can, the SpineAssist is a parallel-platform robot mounted onto the patient's spine or spinous process. Pre-operative planning with CT images is followed by automatic fluoroscope or CT image registration to the robot, after which the positioning device automatically directs its arm in the trajectory planned by the surgeon, with accuracy less than 1.5 mm.

In 1992, Integrated Surgical Systems introduced the ROBODOC, a large orthopedic surgical system intended for use in patients requiring primary cementless total hip replacement surgery. It has a single 6DOF arm that operates automatically using a pre-operatively defined program. It has no haptic feedback capability and tool changes are performed manually, see US Patent Publications 20040142803, 05766126, 06239874, 06349245.

The Pathfinder developed by Prosurgics is a stereotaxy tool-locator with image-guidance capabilitiesfor intracranial neurosurgeries. The arm has six degrees-of-freedom and is passively manipulated by the surgeon without haptic feedback. The single-arm system is mounted on a mobile base. Surgical tools are changed out manually.

Laprotek is a minimally-invasive surgical robotics system. Developed by endoVia, the system is similar to Zeus. It has two four degrees-of-freedom arm teleoperated by joysticks at a console, with visual feedback also available via laparoscopic camera. It has haptic feedback using force sensors at the motors.

There are a number of aspects of the existing state of surgical robotic technology that require major improvements. The development of robot arms that are dexterous, precise and have large workspaces both in how they attain the work site location and when they are inside body cavities and organs. The overall size, weight and volume of most current systems are a major issue in that they have a major detrimental impact on operating room facility space and the support staff who set-up the equipment. Smaller, lighter weight stowable systems are needed. For example, the da Vinci surgical manipulator weighs 1200 lbs (exclusive of the operator interface) and stands approximately 8ft. The Zeus arms are approximately 2ft long and weigh 40 lbs. Total weight of the robot is 120 lbs. (exclusive of the user interface).

The majority of current systems do not provide Haptic feedback. Haptic feedback restores the lost sense of touch for the surgeon and may improve the surgeon's performance in terms of speed and reducing risk of collateral tissue damage.

Manual surgical tool exchange increases the surgical operating time; increasing the time the patient is required to remain under anaesthesia and increasing facility costs. The ability to automatically exchange surgical tools would therefore reduce patient risks and lower operating costs.

The high mechanical power density and small diameter of conventional dc motor servomotors are desirable traits to reduce the physical dimensions of robotic manipulators. However, the drawback of conventional servomotors presently in use in many surgical robots is their long axial length, so a right-angle transmission means is needed if excessive lateral extension of the manipulator arm joints is to be avoided.

Of all the available right-angle transmission components at present, bevel gear pairs deliver high torque and backdrivability, but backlash is typically high and they seldom come in small packages. The traditional standard bevel gear box has large backlash in transmission which is highly undesirable in applications where high precision is required in both directions of motion.

There are several manufacturers offering worm gears in a small package , and integrating with spring-loaded features the gearbox can be backlash free and achieve precise motion, but the lowered efficiency and the odd standard gear ratio increment suggest that more powerful (thus larger in size) motors will be needed. Worm gear boxes can have low-backlash configurations but its indirect proportional relationship between the efficiency versus the gear ratio leads to a bulkier and heavier overall unit, while also the lack of back-drivability is also undesirable in the event of crash recovery or calibration common to robotics applications.

Cable-pulley system provides an alternative to traditional gear-type mechanism, but introduces transmission error if any of the cable segments in the transmission chain is not tensioned properly. Researchers from Massachusetts Institute of Technology and eventually Barrett Technology developed the WAM, or the "whole-arm-manipulation", in which part of the mechanism involves a differential cable-pulley subset that allows for a two degree-of-freedom motion at the same joint driven by two independent motors. Cable within the WAM design is pretensioned at a single-point by turning two coaxial pulleys independently with cable responsible for both directions forming a U-shape turnaround at termination for auto-adjustment of cable length and tensioning automatically. Another differential pulley application can be found at the hoist and drive concept by Power Kinetics, in which cable pretension is accomplished by increasing the physical separation between pulleys. Commissariat a l'Energie Atomique, meanwhile, created a two to three degrees-of-freedom mechanism, using idle pulleys for both redirecting the direction of cable and also tensioning the cable. On the other hand, Roto-Lok mechanism developed by Sagebrush Technology is a parallel drum-drive configuration using cable and pulleys. Springs are presented at each of the cable termination to eliminate transmission slack. For a list of patents on the above-mentioned mechanisms refer to the appendix section. None of the above mentioned inventions can be adapted to a single-actuator right-angle transmission application, and their means of cable tension adjustment all require extra room for additional elements which will lead to the increase in overall size of the transmission module.

Harmonic drives, on the other hand, features zero-backlash, highly repeatable precision, back-drivability, high efficiency, compact size and lightweight. Unfortunately, the mechanism does not allow for a right-angle drive version. No commercially available right-angle transmission in the market currently has both zero-backlash and high efficiency capabilities in a compact in-line package.

Therefore, it would be very advantageous to provide a surgical robotic system employing right angle drives which avoids the above mentioned drawbacks.

SUMMARY OF THE INVENTION

The present invention provides embodiments of a surgical manipulator including a manipulator arm, an end-effector held by the manipulator arm, surgical tools held by the end-effector and manipulator joints, particularly right-angle drive devices for transmitting rotational motion in one axis to a perpendicular axis.

In one aspect of the invention there is provided surgical manipulator, comprising:

a) a base and a first right angle drive mechanism mounted on said base, a shoulder-roll drive mechanism located in said base for rotating said first right-angle drive mechanism about a shoulder-roll axis,

said first right-angle drive mechanism including a first input pulley and a first output pulley mounted substantially perpendicular to said first input pulley, said first right-angle drive mechanism including a first bi-directional coupling mechanism for coupling said first input pulley and said first output pulley, a first drive mechanism coupled to said first input pulley for rotating said first input pulley about a first input axis wherein rotation of said first input pulley is translated into rotation of said first output pulley by said first bi-directional coupling mechanism about a shoulder-yaw axis which is substantially perpendicular to said first input axis;

a second right-angle drive mechanism coupled to said first output pulley of said first right angle drive mechanism, said second right-angle drive mechanism including a second input pulley and a second output pulley mounted substantially perpendicular to said second input pulley, said second right-angle drive mechanism including a second bi-directional coupling mechanism for coupling said second input pulley and said second output pulley,

a second drive mechanism coupled to said second input pulley for rotating said second input pulley about a second input axis wherein rotation of said second input pulley is translated into rotation of said second output pulley by said bi-directional coupling mechanism about a shoulder-pitch axis which is substantially perpendicular to said first input axis;

b) a robotic upper arm being mounted at one end thereof to said second output pulley so that when said second output pulley is rotated, said robotic upper arm rotates about said shoulder-pitch axis, a third right-angle drive mechanism mounted in said robotic upper arm, said third right-angle drive mechanism including a third input pulley and a third output pulley mounted substantially perpendicular to said third input pulley, said third right-angle drive mechanism including a third bi-directional coupling mechanism for coupling said third input pulley and said third output pulley said third right-angle drive mechanism including a third drive mechanism coupled to said third input pulley for rotating said third input pulley about a third input axis, wherein rotation of said third input pulley about said third input axis is translated into rotation of said third output pulley by said bi-directional coupling mechanism about an elbow-pitch axis substantially perpendicular to said third input axis;

c) a robotic fore arm mounted on said third output pulley of said third right-angle drive mechanism so that when said third output pulley is rotated, said robotic fore arm rotates about said elbow-pitch axis, a fourth right-angle drive mechanism mounted in said robotic fore arm, said fourth right-angle drive mechanism including a fourth input pulley and a fourth output pulley mounted substantially perpendicular to said fourth input pulley, a fourth bi-directional coupling mechanism for coupling said fourth input pulley and said fourth output pulley, said fourth right-angle drive mechanism including a fourth drive mechanism coupled to said fourth input pulley for rotating the fourth input pulley about a fourth input axis, wherein rotation of said fourth input pulley about said fourth input axis is translated into rotation of said fourth output pulley by said bi-directional coupling mechanism about a wrist-pitch axis substantially perpendicular to said fourth input axis;

d) a robotic wrist mounted on said fourth output pulley of said fourth right-angle drive mechanism so that when said fourth output pulley is rotated, said robotic wrist rotates about said wrist-pitch axis, said robotic wrist including an actuation mechanism coupled to a wrist output shaft for rotating said robotic wrist output shaft about a wrist-roll axis; and

e) an end-effector mounted to said wrist output shaft, said end-effector including gripping means for releasibly gripping a surgical tool wherein when said actuation mechanism is engaged said end-effector is rotated about said wrist-roll axis.

The present invention also provides a surgical manipulator system, comprising:

a) a base and a first right-angle drive mechanism mounted on said base, a shoulder-roll drive mechanism located in said base for rotating said first right-angle drive mechanism about a shoulder-roll axis, said first right-angle drive mechanism including a first input pulley and a first output pulley mounted substantially perpendicular to said first input pulley, said first right-angle drive mechanism including a first bi-directional coupling mechanism for coupling said first input pulley and said first output pulley, a first drive mechanism coupled to said first input pulley for rotating said first input pulley about a first input axis wherein rotation of said first input pulley is translated into rotation of said first output pulley by said first bi-directional coupling mechanism about a shoulder-pitch axis which is substantially perpendicular to said first input axis;

b) a robotic upper arm being mounted at one end thereof to said first output pulley so that when said first output pulley is rotated, said robotic upper arm rotates about said shoulder-pitch axis, a second right-angle drive mechanism mounted in said robotic upper arm, said second right-angle drive mechanism including a second input pulley and a second output pulley mounted substantially perpendicular to said second input pulley, said second right-angle drive mechanism including a second bi-directional coupling mechanism for coupling said second input pulley and said second output pulley, a second drive mechanism coupled to said second input pulley for rotating said second input pulley about a second input axis wherein rotation of said second input pulley is translated into rotation of said second output pulley by said second bi-directional coupling mechanism about a elbow-pitch axis which is substantially perpendicular to said second input axis;

c) a robotic fore arm mounted on said second output pulley of said second right-angle drive mechanism so that when said second output pulley is rotated, said robotic fore arm rotates about said elbow-pitch axis, a third right-angle drive mechanism mounted in said robotic fore arm, said third right-angle drive mechanism including a third input pulley and a third output pulley mounted substantially perpendicular to said third input pulley, said third right-angle drive mechanism including a third bi-directional coupling mechanism for coupling said third input pulley and said third output pulley, a third drive mechanism coupled to said third input pulley for rotating said third input pulley about a third input axis wherein rotation of said third input pulley is translated into rotation of said third output pulley by said third bi-directional coupling mechanism about an wrist-pitch axis substantially perpendicular to said third input axis;

d) a fourth right-angle drive mechanism mounted on said third output pulley of said third right-angle drive mechanism, said fourth right-angle drive mechanism including a fourth input pulley and a fourth output pulley mounted substantially perpendicular to said fourth input pulley, said fourth right-angle drive mechanism including a fourth bi-directional coupling mechanism for coupling said fourth input pulley and said fourth output pulley, a fourth drive mechanism coupled to said fourth input pulley for rotating said fourth input pulley about a fourth input axis and wherein rotation of said fourth input pulley is translated into rotation of said fourth output pulley by said fourth bi-directional coupling mechanism about a wrist-yaw axis substantially perpendicular to said fourth input axis;

e) a robotic wrist mounted on said fourth output pulley of said fourth right-angle drive mechanism so that when said fourth output pulley is rotated, said robotic wrist rotates about said wrist-yaw axis, said robotic wrist including an actuation mechanism coupled to a wrist output shaft for rotating said robotic wrist output shaft about a wrist-roll axis; and

f) an end-effector mounted to said wrist output shaft, said end-effector including gripping means for releasibly gripping a surgical tool wherein when said actuation mechanism is engaged said end-effector is rotated about said wrist-roll axis.

The present invention also provides a surgical manipulator system, comprising;

a) at least first and second surgical manipulators as disclosed above;

b) left and right hand controllers with the right hand controller being associated with the first surgical manipulator and the left hand controller being associated with the second surgical manipulator, said at least first and second hand controllers being configured to be operated by a surgeon;

c) communication system coupling said left and right hand controllers to said at least first and second surgical manipulators for translating movement of said left and right hand controllers to scaled movement of said at least first and second surgical manipulators; and

d) a vision system focused on a work area including an area of a patient to be operated on and focused on the end-effectors and associated surgical tools attached to said at least two surgical manipulators, said vision system including display means for displaying images of said work area to a surgeon.

A further understanding of the functional and advantageous aspects of the invention can be realized by reference to the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be more fully understood from the following detailed description thereof taken in connection with the accompanying drawings, which form a part of this application, and in which:

Figure 1 is an isometric view of an assembled right-angle drive system constructed in accordance with the present invention;

Figure 2 is an exploded, disassembled view of the right-angle drive system of **Figure 1**;

Figure 3a is an isometric view of the output shaft forming part of the right angle drive;

Figure 3b is a side view of the output shaft of **Figure 3a**;

Figure 3c is a view of the output shaft along the arrow **3c** in **Figure 3b**;

Figure 4a is an isometric view of a mid-housing forming part of the right angle drive;

Figure 4b is a front view of the mid housing of **Figure 4a**;

Figure 4c is a cross sectional view along the line **A-A** of **Figure 4b**;

Figure 4d is equivalent to the view direction of **Figure 4c** but showing all surface features of the mid housing;

Figure 4e is a bottom view of **Figure 4b** along the arrow **4e**;

Figure 4f shows a bearing mounting on the output shaft of **Figure 3a** mounted in the mid-housing of **Figure 4a**;

Figure 5a is an isometric view of an output pulley forming part of the right angle drive;

Figure 5b is a front view of the output pulley of **Figure 5a**;

Figure 5c is a bottom view of **Figure 5b**;

Figure 5d is a cross sectional view along the line **A-A** of **Figure 5b**;

Figure 5e is a detail view of **Figure 5d** showing the details of the tensioning mechanism;

Figure 5f is a top view of **Figure 5b**;

Figure 6a is an isometric view of an input pulley forming part of the right angle drive;

Figure 6b is a front view of the input pulley of **Figure 6a**;

Figure 6c is a top of **Figure 6a**;

Figure 6d is a cross sectional view along the line **C-C** of **Figure 6b**;

Figure 6e is a cross sectional view along the line **B-B** of **Figure 6b**;

Figure 6f is a view of the cable termination subassembly with a loop sleeve crimped fitting;

Figure 6g is a cross-section view of the input and output pulleys of **Figures 5a** and **6a** illustrating the grooved circumference on both the input and output pulley for the cable wrapping;

Figure 7a shows an isometric view of an idler shaft forming part of the right angle drive;

Figure 7b shows a front view of the idler shaft of **Figure 7a**;

Figure 8 shows the relative positions of the input and output pulleys perpendicular to each other and the driving cables and idlers for converting rotational motion of the input pulley into rotational motion of the output shaft oriented perpendicular to the input axis;

Figure 9a shows an isometric view of a tensioning screw forming part of the right angle drive;

Figure 9b shows a cross-sectional view along line **9b** of **Figure 9d**;

Figure 9c shows the side view of the tensioning screw of **Figure 9a**;

Figure 9d shows the front view of the tensioning screw of **Figure 9a**;

Figure 10a shows the front view of the assembled right-angle drive;

Figure 10b shows the cross-sectional view of **Figure 10a** along the line **A-A** of **Figure 10a**;

Figure 10c shows the detailed view of section **C** in **Figure 10b** for the idler subassembly;

Figure 11a shows the assembled side view of the right-angle drive with the output pulley front face;

Figure 11b shows a cross-sectional view of **Figure 11a** along line **B-B** of **Figure 11a** for the output elements;

Figure 11c shows a cross-sectional view of **Figure 11a** along line **C-C** of **Figure 11a** for the input elements and the top idler subassembly;

Figure 12 shows a side cross-sectional view of the input elements;

Figure 13 shows the opposite assembled side view to **Figure 11a**;

Figure 14 shows a perspective view from a top-front angle of the assembled right-angle drive of **Figures 1** and **2** without the cover and idler caps;

Figure 15 shows a perspective view from a top-rear angle of the assembled right-angle drive without the cover and idler caps;

Figure 16a is an isometric view of a surgical robot forming part of the present invention;

Figure 16b is a side view looking along arrow **b** of **Figure 16a**;

Figure 16c is a front view looking along arrow **c** of **Figure 16a**;

Figure 16d is a top view looking along arrow **d** of **Figure 16a**;

Figure 16e is another an isometric view of the surgical manipulator similar to **Figure 16a** but looking from the opposite direction;

Figures 17a to **17e** show details of the manipulator base forming a shoulder-roll joint assembly;

Figure 17a is an isometric view of the manipulator base without the cover;

Figure 17b is a top view of **Figure 17a** along the arrow **b**;

Figure 17c is a front cross-section view of **Figure 17b** along the line **c-c** showing the actuation components of the shoulder-roll joint;

Figure 17d is a side cross-section view of **Figure 17b** along **d-d** showing the actuation components of the shoulder-roll joint;

Figure 17e is a front cross-section view of **Figure 17b** along **e-e** showing the actuation components of the shoulder-roll joint and showing the cover **402**;

Figures 18a to **18e** show details of the manipulator shoulder with the right angle drive mounted on top of the shoulder-roll driven shaft forming a shoulder-pitch joint assembly;

Figure 18a is an isometric view of the manipulator shoulder;

Figure 18b is a front view of **Figure 18a** along the arrow **b;**

Figure 18c is a top view of **Figure 18a** along the arrow **c;**

Figure 18d is a cross-section view of **Figure 18c** along the line **d-d;**

Figure 18e is a side view of **Figure 18a** along the arrow **e**

Figures 19a to **19e** show details of the manipulator lower arm and the right angle drive mounted at the front of the manipulator lower arm forming an elbow-pitch joint assembly;

Figure 19a is an isometric view of the lower manipulator arm;

Figure 19b is a front view of **Figure 19a** along the arrow **b;**

Figure 19c is a side view of **Figure 19a** along the arrow **c**;

Figure 19d is a top view of **Figure 19a** along the arrow **d**;

Figure 19e is a cross-section view of **Figure 19c** along the line **e-e**;

Figures 20a to **20e** show details of the manipulator upper arm and the right angle drive mounted at the front of the manipulator upper arm forming a wrist-pitch joint assembly;

Figure 20a is an isometric view the manipulator fore arm;

Figure 20b is a side view of **Figure 20a** along the arrow **b**;

Figure 20c is a bottom cross-section view of **Figure 20b** along line **c-c**;

Figure 20d is a top view of **Figure 20a** along the arrow **d**;

Figure 20e is a back cross-section view of **Figure 20b** along **e-e**;

Figures 21a to **21e** show details of the manipulator wrist forming a wrist-roll joint assembly;

Figure 21a is an isometric view of the wrist;

Figure 21b is a top view of **Figure 21a** along the arrow **b**;

Figure 21c is a front cross-section view of **Figure 21b** along line **c-c**;

Figure 21d is a front view of **Figure 21a** along the arrow **d**;

Figure 21e is a side cross-section view of **Figure 21b** along line **e-e**;

Figure 21f to **21i** show the concept of different configurations with a seventh degree-of-freedom and the modularity of joint units making up the manipulator arm;

Figures 21fa and **21fb** show two isometric views of the original six degrees-of-freedom manipulator configuration shown in Figure 16a to 16e;

Figures 21ga and 21gbshow two isometric views of the one seven degrees-of-freedom manipulator configuration with a shoulder-yaw joint introduced to that of the configuration shown in **Figure 21f**;

Figures 21ha and **21hb** show two isometric views of the one seven degrees-of-freedom manipulator configuration with a wrist-yaw joint introduced to that of the configuration shown in **Figure 21f**;

Figure 21i shows an isometric view of the exploded joint units of the original six degrees-of-freedom manipulator configuration shown in **Figure 21f** in which the modular components include quick connectors/disconnectors for rapid assembling and disassembling;

Figure 21j shows the concept of modular end-effector with various functions attaching to the same manipulator arm;

Figures 22a to **25b** show details of the surgical forcep tools;

Figure 22a is an isometric view of a first embodiment of a surgical tool;

Figure 22b is a side view of the surgical tool of **Figure 22a**;

Figure 22c is a bottom cross-sectional view along the line **c-c** of **Figure 22b** with the surgical tool in the open position;

Figure 22d is a bottom cross-sectional view along the line **c-c** of **Figure 22b** with the surgical tool in the closed position;

Figure 22e is a back cross-sectional view along the line **e-e** of **Figure 22a**;

Figure 23a is an isometric view of an alternative embodiment of a surgical tool in the opened position;

Figure 23b is an elevational view of the surgical tool of **Figure 23a**;

Figure 24a is an isometric view of an alternative embodiment of a surgical tool in the closed position;

Figure 24b is an elevational view of the surgical tool of **Figure 24a**;

Figure 25a is an isometric view of another alternative embodiment of a surgical tool; and

Figure 25b is an elevational view of the surgical tool of **Figure 25a**.

Figure 26a is an isometric view of an assembled end-effector holding a surgical tool forming part of the present invention;

Figure 26b is a disassembled view of the end-effector and surgical tool;

Figure 26c is a front view of **Figure 26a**;

Figure 26d is a side view of **Figure 26a** showing the force-path of the pinch force as a result of tool-actuation;

Figure 26e is a cross-sectional view of the assembled end-effector holding a surgical tool along the line **c-c** of **Figure 26c** showing the load-path of the tip force monitored by the force-moment sensor;

Figure 27a is a top view of the tool-yaw subassembly;

Figure 27b is a bottom view of the tool-yaw subassembly;

Figure 27c is a top view of the assembled end-effector;

Figure 27d is a bottom view of the assembled end-effector;

Figure 27e is a top view of the main end-effector body;

Figure 27f is a cross-sectional view of **Figure 27e** along the line **f-f** showing the load-path of the tip force monitored by the force-moment sensor;

Figure 28a is a top view of the tool actuator;

Figure 28b is a cross-sectional view of the tool actuator along the line **b-b** of **Figure 28a**;

Figure 29a is a front view of the tool holder;

Figure 29b is a cross-sectional view of the tool holder along line **b-b** in **Figure 29a**;

Figure 29c is an isometric view of the tool holder;

Figure 29d is a top view of the tool holder showing the tool ejection wings in the engaged configuration;

Figure 29e is a top view of the tool holder showing the tool ejection wings in the ejected configuration;

Figure 29f is an isometric view of the end-effector releasing the tool at the tool tray; and

Figure 30 is a schematic diagram showing the operation concept of a dual-manipulator telerobotic system controlled by a surgeon in a typical operating theatre.

DETAILED DESCRIPTION OF THE INVENTION

Generally speaking, the systems described herein are directed to a surgical manipulator apparatus. As required, embodiments of the present invention are disclosed herein. However, the disclosed embodiments are merely exemplary, and it should be understood that the invention may be embodied in many various and alternative forms. The Figures are not to scale and some features may be exaggerated or minimized to show details of particular elements while related elements may have been eliminated to prevent obscuring novel aspects. For purposes of teaching and not limitation, the illustrated embodiments are directed to a surgical manipulator apparatus.

The surgical manipulator apparatus comprises a multi-jointed robotic arm, with the different booms connected to right angle drive units, and surgical end-effectors connected to a robotic wrist unit. Each of these components will now be described in detail.

1) RIGHT ANGLE DRIVE UNIT

Referring first to **Figure 1**, an isometric view of an assembled right-angle drive system is shown generally at **10** which includes a housing comprised of a chassis **14** and a cover **16**. Referring particularly to **Figure 2**, the right angle drive system **10** includes an output pulley **20**, an output shaft **26** on top of which the output pulley **20** is mounted to, a mid housing **22**, a pair of idler units **78**, **86**, **84**, **80a/b**, **82a/b**, an optical encoder **46**, and an input pulley **54** mounted on a drive mechanism which preferably comprises a harmonic-drive **56**.

Referring to **Figure 2** and **Figures 3a** and **3b**, the optical encoder **46** is mounted on shaft section **38** of output shaft **26** for measuring rotational displacement of the output shaft **26**. The typical optical encoder **46** measuring system includes a light source, a code disk rotating about an internal or external precision ball bearing and an optical light sensor. The code disk has a series of opaque and transparent markings which spatially encode the angular position of the shaft section **38** that may be configured to provide the absolute or relative angular position of the shaft. A light source shines through the code disk and onto the optical light sensor. Every angular position has coded dark spots and light spots on the code disk which interrupt the light beam on the optical light sensor, from which electronic signals are generated. The electronic signals are amplified and converted into angular position/speed data which can be used by a control system.

For an incremental encoder embodiment, all the markings on the code disc are identical, and electronic signals are generated in the form of pulses which are counted by the controller to determine the relative positioning or differentiated against time to obtain speed. For an embodiment which uses an absolute encoder, each marking on the code disc is distinctively formed by a series of lines, and the resulting electronic signal from the light detection of the optical sensor will be a unique binary code which makes absolute position sensing possible.

The harmonic-drive **56** is mounted to the chassis **14**, and on the output flange **98** of the harmonic-drive **56** an input pulley **54** is mounted and has an axis of rotation perpendicular to that of the output pulley **20**. The harmonic-drive **56** is used to introduce high reduction ratio to the overall right-angle drive **10**. The cable-pulley system thus is only responsible for the angled transmission of motion from the input to the output side and thus forms a bi-directional coupling mechanism since rotation of the input shaft about its axis in one direction causes rotation of the output shaft about its axis in one direction, and rotation of the input shaft by the drive mechanism in the other direction causes rotation of the output shaft about its axis in the other direction.

Figures 6a to **6e**, and **Figure 12** show details of the input pulley **54**. Input pulley **54** includes two sections, an auxiliary section **130** and a main section **132** with the auxiliary section **130** having a larger diameter than the main section **132** to accommodate for the vertical locations of the main idlers **80a**, **80b** and auxiliary idlers **82a**, **82b** (**Figure 1**). Sections **130** and **132** have circular grooved circumferences **134** and **136** with spiral continuous grooves **160** (**Figure 6g**) on the surfaces to provide friction between the cable and the input pulley **54** such that the driving torque for the pulley by the cable is distributed evenly about the pulley and not completely relying on the termination at the looped crimped fittings **101** (**Figure 6f**) located inside the pockets **138** and **140**. The cables are terminated at the input pulley **54** by threading into the corresponding lateral access holes **141a**, **141b**, **141c**, **141d** and through the pockets **140a**, **138a**, **140b**, **138b** respectively.

The loop crimp fittings **101** provided by the cable manufacturer are crimped onto the tip of the cables with each forming a loop at the other end of the fitting as shown in **Figure 6f**. Each fitting together with the loop hides inside the pockets **138a**, **138b**, **140a**, **140b**, in which when each cable is under tension its fitting will ride up against the internal wall of the pocket and maintain the cable tension.

Referring to **Figures 6a**, **6g**, **8** and **11c**, cable **92b** (**Figure 8**) is wrapped around the main section **132** (**Figure 6a**) of the input pulley **54** along the circular groove section **160** (**Figure 6g**) which is machined on the circumferential surface **136** in a spiral helical path along the center of rotation of the pulley. The direction of which cable **92b** winds around the surface **136** (**Figure 6a**) is counter-clockwise starting from the lateral access hole above the loop sleeve termination pocket **138a** and looking into the input pulley **54** in the view direction of **Figure 6b**. When the cable **92b** is inside the groove **160**, the surface friction in between the two assists in the input pulley **54** driving the cable **92b** with tension which in turn drives the output pulley **20**, thus relieving some of the stress concentrated at the loop sleeve fitting **101** (**Figure 11c**) where the cable is terminated. The adjacent groove section **161**(**Figure 6g**), which is wound around by cable **92a** (**Figure 8**) clockwise, may or may not be continuous with section **160** depends on the axial length of the main cable section **132**. The identical relationship applies to the auxiliary cable section **130** as groove section **162** (**Figure 6g**) is for cable **90b** (**Figure 8**) winding counter-clockwise and groove section **163** (**Figure 6g**) is for cable **90a** (**Figure 8**) winding clockwise.

Referring to **Figures 3a**, **3b** and **3c**, the output shaft **26** includes a cylindrical housing **36** and a shaft **38** extending from the rear face **40** of the output shaft **26** and the rear face **40** includes a circumferential shoulder **42** of a larger diameter than the diameter of cylindrical housing **36**. There is a centered hole **28** located on a front face **30** to receive therein a centering dowel **32** which forms the rotating output seen in **Figure 1** protruding from the center of output pulley **20**. Referring to **Figure 4f**, a radial ball-bearing **59** is mounted on shaft **38** between which the shoulder **42** of the output shaft **40** the encoder **46** is sandwiched.

Referring to Figures **4a** to **4f**, the mid-housing **22** includes a pair of circular bores **70** and **72** which are match-machined to be perfectly concentric to each other for the angular-contact ball-bearings **24** shown in **Figure 1**. The diameter **68** which is smaller than that of **70** and **72** is sized according to the recommended outer ring shoulder landing diameter specified by the bearing manufacturer. Details of the mounting and preloading of the angular-contact ball-bearing pair **24** inside mid-housing **22** will be described later. Mid-housing **22** includes an idler support section **74** (**Figure 4a**) having two holes **76**, one on the top surface and the other on the bottom surface for receiving idler shafts **78** which are part of the main idler mechanisms, shown in **Figure 2**.

Referring to **Figures 4f** and **11b**, the two angular-contact ball-bearings **24** are mounted inside the bearing seats **70**, **72** in a back-to-back configuration (best seen in **Figure 4f**). The bearings **24** are seated with their respective outer ring **139** inside the concentric bore **72** and **70**. The locknut **60** is turned on the output shaft **26** via a threaded section **43** (**Figure 3a**), which provides loading from the locknut 60 via the output shaft **26** to the inner ring **142** of the bearing adjacent to the locknut 60 (see **Figure 4f**). The loading will be transmitted from the inner ring **142** through the balls **143** and to the outer ring **139** of that bearing, following the load path outlined along **140** shown in dotted lines, and end up back at the output shaft **26** again at the flange **40** (**Figure 3b**). The preload is completed when the inner gap inside the raceway of the bearings **24** between the balls **143** and the inner ring **142** and outer ring **139** is eliminated by the motion of the locknut **60** towards the bearing pairs along the output shaft **26** as a result of the turning of the locknut **60**. This procedure is carried out by means of the use of a torque wrench to tighten the locknut **60** on output shaft **26**, using a torque level recommended by the bearing manufacturer for installation.

Figures 5a to **5f** inclusive show details of the output pulley **20**. Output pulley **20** includes two sections **110** and **112** with the auxiliary section **110** having a larger diameter than the main section **112** to accommodate for the vertical locations of the main **80a**, **80b** and auxiliary idlers **82a**, **82b**. Sections **110** and **112** have circumferences **114** and **116** respectively with continuous spiral grooves **160** (of **Figure 6g**) on the surfaces to provide friction between the cable and the output pulley **20** in order to distribute the driving torque evenly about the pulley **20** and relieve stress on the termination at the tensioning screws **94a**, **94b** and **96a**, **96b** thereby reducing the possibility of detachment. **Figure 11a** shows the front view of the drive unit showing the positioning of the tensioning screws in the holes **144a**, **144b**, **146a** and **146b**.

Referring to **Figures 5a**, **6g** and **8**, cable **92b** (**Figure 8**) is wrapped around the main section **112** (**Figures 5a** and **8**) of the output pulley **20** along the circular groove **160** (**Figure 6g**) which is machined on the circumferential surface **116** (**Figure 5a**) in a spiral helical path along the center of rotation of the pulley **20**. The direction of which cable **92b** winds around the surface **116** is counter-clockwise starting from the lateral access hole above the tensioning screw hole **146a** and looking into the output pulley **20** at the output load interface surface. When the cable **92b** is inside the groove **160**, the surface friction in between the two assists in driving the output pulley **20** to rotate counter-clockwise when the cable **92b** is under tension, thus relieving some of the stress concentrated at the tensioning screw **96b** inside the tensioning screw hole **146a** where the cable is terminated. The adjacent groove section **161** (**Figure 6g**), which is wound around by cable **92a** (**Figure 8**) clockwise, may or may not be continuous with groove **160** depending on the axial length of the main section **112**. The identical relationship applies to the auxiliary section **110** as groove section **162** (**Figure 6g**) is for cable **90b** (**Figure 8**) winding counter-clockwise and groove section **163** (**Figure 6g**) is for cable **90a** (**Figure 8**) winding clockwise.

The tensioning screw 96a inserts into hole **144a** of output pulley **20**, which sits on the shoulder **145a** (**Figure 5d**) that supports the tensioning screw **96a** under loading from the counter-clockwise auxiliary cable **90b**. The cable **90b** accesses the output pulley **20** through the lateral hole **147** (**Figure 5f**), wraps around the tensioning screw 96a for up to three windings, and passes through the hole **154** (**Figure 9a**) of the tensioning screw **94a**. It is noted that the only difference among screws **94a**, **94b**, **96a** and **96b** is the axial location of hole **154**. There are two lateral holes **147** on the output pulley **20** for each of the tensioning screws, the choice between the pair will determine the direction of cable winding on the tensioning screws and thus the direction of rotation of the tensioning screws for tightening their respective cable. Turning setscrew **97** (**Figure 11b**) in tapped hole **159** (**Figure 9b**) of the tensioning screw pinches the cable **90b** and deforms the tip of the cable **90b** until it is jammed inside the hole **154** and secured by the setscrew **97**. To allow room for maneuvering the cable **90b**, the entire subassembly of tensioning screw 96a and the setscrew **97** is taken outside of the output pulley **20** after threading the cable through the lateral access hole **147** to complete the cable windings and setscrew securing before being put back to the hole **144a**.

Once the cable **90b** and the tensioning screw **96a** are inside hole **144a**, the cable tension can be adjusted by turning the tensioning screw **96a** clockwise by means of a screwdriver engaging at the slot **158** of the tensioning screw (**Figure 9b**). After the desired cable tension is reached a washer **99** (**Figure 1**) and hex nut **100** (**Figure 1**) are placed onto the threaded section **156** (**Figure 9b**) of the tensioning screw **96a** to fix the rotary position of the tensioning screw 96a with respect to the output pulley **20**. The cable tension can be guaranteed if the tensioning screw cannot be turned counter-clockwise without loosening up the hex nut. This is accomplished by selecting the lateral access hole **147** from the pair for each tensioning screws on the output pulley **20** such that the tensioning screw will always need to be turned clockwise to tighten the cable tension.

Specifically, if the tensioning screw attempts to turn counter-clockwise due to the cable tension, the washer and hex nut will attempt to rotate as a unit with respect to the output pulley but friction against the front face of the output pulley will resist the rotation and thus any rotation of the tensioning screw **96a** will be done with the washer **99** and hex nut **100** remaining static to the output pulley **20**, resulting in the hex nut compressing against the output pulley via the tensioning screw and consequently resisting any further counter-clockwise rotation of the tensioning screw **96a**. Provided the friction against between the output pulley front face and the washer **99** and the hex nut **100** is greater than that between the internal thread of hex nut 100 and the external thread section **156** of tensioning screw **96a** (of **Figure 9a**), the cable tension will not loosen up on its own. This can be ensured by the large surface area of the flat washer **99**, with which the tensioning screw **96a**, the washer **99** and the hex nut **100** will not rotate counter-clockwise as a unit, thereby guaranteeing the tensioning of that particular cable section. The load carried by the right-angle drive is mounted to the front face of the output pulley **20**, via the bolt holes **150** and the timing dowel holes **151**, shown in **Figures 5a** and **5b**. To locate the center-of-rotation of the output pulley **20**, the load can use the center dowel **32** of **Figure 1**. **Figure 5e** shows details of the tensioning mechanism at output pulley **20**.

The flexible cables **90b** and **92b** may be low-stretch/pre-tensioned cables, which may or may not be metallic, to minimize transmission loss due to elastic stretching of the cables.

Referring again to **Figure 2**, the idler mechanisms each include main idlers **80a** and **80b**, and auxiliary idlers **82a** and **82b**, and it is noted that main idlers **80a** and **80b** and auxiliary idlers **82a** and **82b** may or may not be identical depending on the relative position of the idler shaft **78** with respect to both the input pulley **54** and output pulley **20**, and auxiliary idler spacer **84** that separates the main idlers **80a**, **80b** and auxiliary idlers **82a**, **82b**, and two flange radial ball-bearings **86** to allow free rotation of both the main idlers 80a, **80b** and auxiliary idlers **82a**, **82b** independent of each other. **Figures 7a** and **7b** show the idler shafts **78** which include a circumferential ridge **79** located near one of the ends of the shaft **78** so that the two shafts are inserted into holes **76** a distance equal to the distance from that particular end to the ridge

79, best seen in **Figure 10c**. A lock nut **60** is located between the output pulley **20** and the angular-contact ball-bearing **24** located closest to the output pulley **20** for retaining that particular bearing in mid-housing **22**, see **Figure 4f**.

Figure 8 shows the relative positions of the input pulley **54** and the output pulley **20**. The idler shafts **78** are located in holes **76** of section **74** of mid housing **22**, best seen in **Figures 2** and **4a**. In the cable-driven right-angle drive, the input axis **58** defined by the harmonic-drive **56** (see **Figure 15**) and output axis **180** defined by the output shaft **26** (**Figure 11b**) are aligned perpendicular to each other. The transmission between the input and output pulleys **54** and **20** respectively is carried out by the cable-pulley system including input pulley **54** and output pulley **20**, main idlers **80a**, **80b** and auxiliary idlers **82a**, **82b** and cables **90a**, **90b** and **92a**, **92b**, in which these two sets of cables correspond to the two directions of rotation.

Referring to **Figure 8**, (and **Figure 11a** for the tensioning screws referred to below) there are a total of four independent cable sets including: 1) auxiliary cable **90a** responsible for clockwise rotation of the output pulley **20** which is associated with auxiliary idler **82a** and auxiliary tensioning screw **94a**; 2) auxiliary cable **90b** which is responsible for counter-clockwise rotation of the output pulley **20** which is associated with auxiliary idler **82b** and auxiliary tensioning screw **96a**; 3) main cable **92a** which is responsible for clockwise rotation of the output pulley **20** which is associated with main idler **80a** and main tensioning screw **94b**; and 4) main cable **92b** responsible for counter-clockwise rotation of the output pulley **20** which is associated with main idler **80b** and main tensioning screw **96b**. Each cable can be independently tensioned, but when used to transmit rotational motion between the input and output shafts the main and auxiliary cable pairs work together for each direction to reduce tension in each cable set. The two sets of cables reduce the cable tension to improve cable reliability and provide redundancy to improve safety should one cable break.

Referring again to **Figure 8**, when the input pulley **54**, driven by the output flange **98** of the harmonic-drive **56**, rotates counter-clockwise (when looking at the back of the harmonic-drive **56**), the counter-clockwise main cables **92b** and auxiliary cable **90b** are under tension from the end through the lateral access holes **141b**, **141a** (**Figure 6a**) respectively with the terminations at the crimped fittings **101** situated inside the pockets **138a**, **140a** respectively on the input pulley **54**, being diverted into a right-angle change of direction by the main idlers **80b** and auxiliary idlers **82b**, and pulls on other end of the cables at the setscrew **97** termination(**Figure 5e**) on the main tensioning screws **96b** and auxiliary tensioning screws **96a** and hence cause the output pulley **20** and dowel **32** connected to output shaft **26** to rotate counter-clockwise looking at the front face of the output pulley **20**. Whereas the other set of cables unwind in the opposite direction since clockwise main cable **92a** and auxiliary cable **90a**, beginning at the input pulley **54** at the crimped fittings terminations **101** through the lateral access holes **141d** and **141c** (**Figure 6a**) respectively, are diverted into a right-angle change of direction by the main idler **80a** and auxiliary idler **82a**, and are terminated on the output pulley **20** at the setscrew **97** on the main tensioning screws **94b** and auxiliary tensioning screws **94a**.

Cables **90a**, **90b** and **92a**, **92b** are preferably low-stretch/pre-tensioned cables to minimize motion loss due to elastic deformation of the cables under tension. Referring to **Figures 1**, **2**, **10b** and **10c**, when assembled, idler caps **62** and **64** are bolted to the top and bottom of housing cover **16** which support the idler shafts **78** on their free ends opposite to those at the holes **76** on the mid-housing **22**. The Idlers **80a**, **80b** and **82a**, **82b** mounted on the idler shafts thus can maintain their radial positions with respect to the input pulley **54** and output pulley **20** even when the cables are under tension.

Figure 13 shows a view from the back of the drive unit opposite to the output face from which dowel **32** projects. As can be seen, bearing **59** rotates in hole **61** (of **Figure 2**) located in the back wall of chassis **14**.

Figures 14 and **15** show isometric views of the drive unit without the cover **16** thereby showing the placement of the cable drive system, shown in **Figure 8**, now placed in the chassis **14**. There is a slight difference in structure of the output pulley **20** of the right-angle drive in **Figure 14** and **15** compared to right-angle drive **10** in **Figure 1**. In **Figure 14** and **15**, the output pulley **20** includes a raised guide **21** integrally formed on the outer surface of pulley **20**. The right-angle drive shown in **Figure 14** and **15** is larger than the right-angle drive **10** in **Figure 1** because it is used in both the shoulder-pitch joint as the right-angle drive **406** and the elbow-pitch joint as the right-angle drive **410**.

The load at the elbow-pitch and shoulder-pitch joints are substantially higher than that at the wrist-pitch joint due to the difference in component weight each joint is carrying, hence the pulleys **20** and **54** need to be enlarged to compensate for the higher torque so the stress in the driving cable sets

90a, **90b**, **92a**, **92b** can be reduced. Thus the overall size of the right-angle drive **10** in **Figure 1**, while applicable to the wrist-pitch joint, is required to be increased as a result for the elbow-pitch and shoulder-pitch joints to become the variation shown in Figure **14** and **15**. The excessive loading at the shoulder-pitch joint compared to that at the elbow-pitch joint is partially compensated for by the counterbalance torsion spring **440** as shown in **Figure 18d**. Referring to **Figure 18d**, the raised guide **21** on output pulley **20** of right-angle drive unit **406** is used for guiding the internal axle **505** of the shoulder support **439** to be coupled with the output pulley **20**, forming a combined drive shaft to rotate the output bracket **266**. The raised guide **21** on the output pulley **20** of the right-angle drive unit **410** for the elbow-pitch joint is not used **(Figure 19e)**.

The cable driven right-angle drive **10** disclosed herein has several advantageous features. Specifically, it is a low-to-medium load, lightweight unit which may be retrofitted into the joints of existing modular robotic arm systems. The use of the drive cables **90a**, **90b** and **92a**, **92b** provide a backlash-free bidirectional rotation. The drive, by incorporating harmonic-drive **56**, provides a back-lash free motor input. The drive unit is compact and lightweight, and has an in-line or offset input/output configuration. In an in-line configuration the input and output axes are coplanar whereas in an offset configuration the planes of the input and output axes are parallel but offset in direction normal to the planes. The relative alignment error between the input and output axis can be compensated by the tensioning of the cables. The unit uses redundant cables for safety, uses a simple cable tensioning mechanism and is highly cost-effective since it is of simple construction and does not require expensive gearing and alignment.

In another embodiment of the pulleys **20** and **54**, both the input and output pulleys can have any number of differential diametrical sections other than the two shown for this design. Provided there would be a pair of idler pulley subassembly to go with each section of cable transmission, more sections of cable transmission can be introduced to the input and output pulleys as long as the other physical constraints are satisfied. Additional sections of cable will provide more security to the overall integrity of the transmission, but the size of the module will inevitably be increased.

A gear ratio may be introduced using a miniature harmonic gear located at the input pulley, and the load is mounted directly on the front face of the output pulley. Additional devices such as angular motion sensors and motor brakes may be fitted onto the output pulley drive shaft to make a compact module. The module can be sized to the targeted load capacity using off-the-shelf components readily available in various sizes from multiple vendors.

Thus, the present invention provides a compact yet highly efficient module for right-angle transmission by combining cable-pulley systems and harmonic drive technology. The cable-pulley drive system provides high fidelity while the harmonic drive contributes to the high power density and back-drivability. In light to medium duty load applications, this module will enable miniature actuators and sensors while outperforming conventional bevel or worm gearing. The mechanism itself is simple yet robust, highly modular and flexible in interfacing. Redundant cables add safety to the design and the accessibility of the input and output transmission axes facilitate integration of auxiliary devices into a compact integrated unit. The design has simple components and does not need expensive gear cutting technology. No other existing technology can compete in terms of positional accuracy, size and weight, efficiency, modularity, ease of reconfiguration, integration and maintenance.

Thus, the present invention provides a right-angle drive which exhibits little or no backlash, simple and robust design, highly repeatable precision, high efficiency, back-driveability, a high gear ratio, compact size and lightweight for a right-angle drive.

While a preferred embodiment of the present invention is the right-angle drive where the input pulley **54** and output pulley **20** rotate in planes that are perpendicular to each other so that the rotational motion of the input shaft is converted to rotational motion about an axis perpendicular to the input rotational axis, it will be understood that other angles are possible. Particularly, the housing chassis **14**, cover **16**, mid-housing **22** and the other components can be made to accommodate any fixed angle between the input and output axis as long as the cable routing is not compromised. Thus, while the preferred nominal angle between input and output is 90 degrees, it will be appreciated that other angles are possible. In addition, because flexible cables are being used in which the tension can be adjusted, it will be appreciated that the user can reconfigure the housing to adjust the input and output axis at the preferred angle so that as the input and output pulleys are locked in position to give the desired angle, the cable tension of each cable is adjusted accordingly to either take up the slack in the cables caused by repositioning the input and output pulleys with respect to each other.

For example, one method to facilitate tensioning of the screws for different angles is to have the tensioning screws continuously torqued by a built-in spring. The screw may also have a ratchet to prevent counter-rotation of the tension screw making the rotation unidirectional. Therefore any "slack" in the cable may be removed by the spring and the ratchet prevents further slackening. The spring is selected to have sufficient torque to tension the cable adequately. The spring or a ratchet can both provide cable tensioning, regardless of whether the input and output pulleys are configured for right-angle transmission or some other angle. With a spring, the cable is constantly under tension without any manual adjustment, but a very strong spring is preferred for tensioning. A ratchet mechanism also gives unidirectional rotation, that is, the direction to further tighten the cable tension, such that it is guaranteed no cable loosening will happen under normal circumstances.

A difference between a ratchet tensioning mechanism and the cable tension mechanism shown in **Figure 5e**, is that the ratchet mechanism is a discrete system, meaning that the number of “locking” rotary positions the screw can sit at depends on the number of teeth on the ratchet, whereas the screw/nut tensioning mechanism illustrated in Figure 5e has an infinite number of positions possible for “locking” purpose once the cable tension is set. The screw/nut tensioning requires manual adjustment, whereas automatic tension adjustment is possible using a ratcheting mechanism. Thus spring or ratchet or screw/nut mechanisms are all possible embodiments of the cable tensioning device.

2) SURGICAL MANIPULATOR

Figures 16a to **21e** show the surgical manipulator arm **400** in its entirety and all the various components making up the arm. **Figure 16a** shows an isometric view of a six degrees-of-freedom surgical robot shown generally at **400** forming part of the present invention. **Figures 16a** and **16e** show two different isometric views of manipulator **400** while **Figures 16b**, **16c** and **16d** show back, side and top views respectively of manipulator **400**. The basic exterior structure of manipulator **400** will be discussed with respect to **Figures 16a** to **16e** and details of the internal structure of each of these components will be discussed with respect to **Figures 17a** to **21e**.

Referring to **Figure 16a**, the base **401** of the surgical robot **400** contains the shoulder-roll joint with axis **414** and part of the shoulder-pitch joint with axis **422**. Referring to **Figures 17a** to **17e**, manipulator shoulder base **401** includes a mounting plate **200** for table-top installation, a support housing **202** mounted on base plate **200** for both the shoulder-roll and shoulder-pitch joints, and a driven spur gear **204** for rotation about axis **414** (also shown in **Figure 16a**) which together with shoulder-pitch housing **252** **(Figure 17c)** form part of the shoulder-pitch joint (refer to description in the next paragraph). The shoulder-pitch housing **252** is mounted inside support housing **202** by a pair of angular-contact ball bearings **500**, with an optical encoder **503** coupled to the extension **258** of the housing **252** to measure the shoulder-roll joint output position. Straight-tooth spur gear **204** is rotationally driven by a smaller-sized pinion **206** with which it is meshed. The pinion **206** is an anti-backlash gear with springs **216** that eliminates gaps between mating gear teeth when meshing with the driven gear **204**. Via the hub **214** and subsequently the shoulder-roll drive shaft **220**, pinion **206** is mounted to, and driven by, a motor **212** mounted below gear **206** and secured to housing **202**. A gear ratio exists between the gear **204** and pinion **206** which depends on the difference in their respective diameters. The motor **212** is a combination of harmonic-drive, an optical incremental encoder (measuring input motor position) and a DC brushless motor. The harmonic-drive **56** supplies additional gear ratio between the motor **212** input to the resulting output motion at the drive shaft **220** to further reduce the speed of the gear **204**.

Referring to **Figure 17c** in particular, to provide fail-safe braking, a power-off brake **208** is coupled to the motor **212**, at which the armature of the brake **222** is connected to the shoulder-roll drive shaft **220** just below the motor **212**. The brake **222** is mounted onto the brake support **210**, which is then secured on the mounting plate **200**. Upon braking or emergency stop situation, power supplied to the brake **208** will be cut, the armature **222** of the brake **208** will stop rotating by the magnetic field generated inside the brake **208**, and thus the drive shaft **220** will cease all motion and the entire shoulder-roll joint can be stopped as a result.

Motor **212** may include a servo motor integrated with a harmonic gear and an angular encoder for measuring rotational displacement of the motor shaft **220** coupled to said pinion gear.

Referring to **Figures 18a** to **18e**, the shoulder-pitch joint includes a right-angle drive **406** which is mounted on top of upper base **404** (**Figure 16a**). The structure and operation of the right angle drive shoulder-pitch joint **406** has been described above in the section entitled Right-Angle Drive. The spur gear **204** and the shoulder-pitch housing **252** form part of the shoulder-roll structure, as described in the previous paragraph. Referring to **Figure 18d**, the spur gear **204** acts as the interface between the right-angle drive **406** and the input actuating components, which include a DC brushless motor **250**, with an interface plate **253** at the rear at which a power-off electro-magnetic brake **254** is attached, and an incremental optical encoder **256** mounted to the brake **254** directly which measures the motor input position.

Upon braking, the power-off brake **254** will act in a similar fashion as its counterpart in the shoulder-roll joint in that the motor **250** rotation will be stopped via the connected rear end of the motor output shaft. The front end of the output shaft of the motor **250** is connected to the harmonic-drive **56** of the right-angle drive **406**, which rotates the input pulley **54** and drives the output pulley **20**, as described in the Right-Angle Drive section. At the output side of the right-angle drive **406**, the shoulder support **439** is mounted to the chassis **14** of the drive **406**, which has an internal axle **505** supported by a pair of angular-contact ball bearings **504** and coupled with the output pulley **20** of the right-angle drive **406**. At the outside end of the axle **505**, a mounting bracket **266** is mounted, at which the lower arm of the manipulator **408** is attached to, resulting in the lower arm **408 (Figure 16a)** rotating about the shoulder-pitch axis **422**.

To assist the motor **250** in moving the lower arm **408** and the remaining components attached above it about the shoulder-pitch joint against gravity, a torsion spring **440** (**Figures 16a, 18b and 18e**) is mounted on the shoulder support **439** and the lower arm **408** which serves as a counterbalance as the lower arm **408** rotates in the indicated direction about the shoulder-pitch axis **422**. Referring to **Figures 18b,** and **18e** in particular, the counterbalance spring **440** has one leg supported by a bracket **507**, while the other leg rotates together with the lower arm **408** (seen in **Figure 16a**). The spring **440** will be loaded only when the lower arm **408** is rotating forward, as illustrated along the direction of the arrow in **Figure 18e**. All components attach to bracket **266** rotates as a unit about axis **414** (seen in **Figure 16a**) for the shoulder-roll joint.

Referring to **Figures 16a**, **16e**, **19a** to **19e**, attached to the upper end of the lower manipulator arm **408** is an elbow-pitch right-angle drive **410** of the same structure and operation as that of the shoulder-pitch joint as described in the previous paragraph. An upper arm **412** is mounted to the bracket **282** on top of the output pulley **20** (**Figure 19e**) of the elbow-pitch joint right-angle drive **410** so that the rotational motion of the input pulley **54** (**Figure 19e**) to the drive unit **410** is translated into rotational motion of the upper arm **412** about the elbow-pitch axis **426**. As seen in **Figure 19e**, a DC brushless motor **460**, an interface plate **462** with the power-off brake **464**, and the incremental optical encoder **466** residing inside housing **280** are identical to their counterparts in the shoulder-pitch joint **250**, **253**, **254** and **256** respectively (**Figure 18d**) both in configuration and operation.

Referring to **Figures 16a**, **16e**, **20a** to **20e**, attached to the upper end of the manipulator fore arm **412** is a wrist-pitch right-angle drive **416** of similar structure and operation as that of the elbow and shoulder-pitch joints but smaller in size. A wrist **420** (**Figures 16a**) is mounted to the bracket **288** on top of the output pulley **20** (**Figure 20c**) of the wrist-pitch joint right-angle drive **416** so that the rotational motion of the input pulley **54** (**Figure 20c**) to the drive unit **416** is translated into rotational motion of the wrist **420** about the wrist-pitch axis **432**. The internal configuration of the fore arm **412** is similar to that of the lower arm **408**, in which the DC brushless motor **470**, interface plate **471** with the power-off brake **471** residing inside housing **286** are similar to their counterparts **460**, **462** and **464** of the lower arm **408** but smaller in size and having the same operating principle. The incremental encoder **473** is identical to the encoder **466** of the lower arm **408**.

Referring now to **Figures 21a** to **21e** and particularly **Figure 21e**, wrist unit **420** includes a housing **300** containing an actuation mechanism which includes a motor **302**, interface plate **480**, brake **304**, encoder **306** being configured to operate in the same way as their counterparts **470, 471**, **472** and **473** in the wrist-pitch joint assembly described in the previous paragraph. The actuation mechanism within wrist **420** also includes the wrist output shaft housing **424** which encloses a harmonic-drive **482** identical to that of the wrist-pitch right-angle drive **416**, an output shaft **484** at the outside end of which the end-effector **428** is connected, and an incremental encoder **483** which is identical to encoder **46** in **Figure 20c** being used in the wrist-pitch right-angle drive **416**. The end-effector **428** is driven by the actuation mechanism, specifically motor **302** to rotate about the wrist-roll axis **438** via the gear-reduction by the harmonic-drive **482**.

Thus the six degrees-of-freedom of the manipulator are all accounted for: shoulder-roll axis **414**, shoulder-pitch axis **422**, elbow-pitch axis **426**, wrist-pitch axis **432**, wrist-roll axis **438** and tool-yaw axis **441** (which will be discussed in detail in the Surgical End-Effector Section hereinafter). The linkages of the manipulator **400** are arranged in an offset configuration in which the lower arm **408** and the fore arm **412** are both cascaded along the shoulder-pitch **422** and elbow-pitch **426** axis with respect to the shoulder- roll axis **414** and wrist-roll **438** axis. This configuration allows for a wider range of travel for all the pitch joints when accommodating for the minimum length of the manipulator arm (formed by **408, 412, 424 and 428**) required to enclose the entire actuation unit for each joint given a certain desired linkage length from joint-to-joint.

The exact amount of offset of both the lower arm **408** and upper arm **412** is adjusted by the length of the section **506** (**Figure 18d**) of the shoulder support **439** along the direction of shoulder-pitch axis **422**, and the resulting offset locates the wrist **420** such that the wrist-roll axis **438** is aligned with that of shoulder-roll axis **414**. The reason for this lies in the kinematic consideration which calls for an in-line kinematic chain for more intuitive control and also for simplified kinematics computation. By aligning the wrist-roll **438** and shoulder-roll **414** axes, the in-line kinematic configuration is achieved even though the physical manipulator is in an offset arrangement.

Figures 21fa and 21fb show a block diagram presentation of manipulator **400** of **Figure 16a**, with all the original labeling in two different viewing angles, with the exception of the end-effector **428** which is shown in **Figures 21fa** and **21fb** to have a cover that is not shown in **Figure 16a**. **Figure 21ga** and **21gb** illustrate another embodiment of a surgical manipulator **800** which uses the same components as manipulator **400** in **Figures 21fa** and **21fb** but includes a seventh joint **810** which can be added in between the shoulder-roll joint and the shoulder-pitch joint. The new joint **810**, which includes a right-angle drive mechanism, has a shoulder-yaw joint axis **811** significantly perpendicular to both the said shoulder-roll axis **414** and the shoulder-pitch axis **422** as shown in **Figures 21ga** and **21gb**. The output pulley of this new right-angle drive mechanism **810** is oriented in the plane perpendicular to the output pulley plane of the shoulder-pitch right-angle drive mechanism **406** and is coupled to the right-angle drive **406** responsible for the shoulder-pitch. This additional joint **810** allows the robotic arm to orient the direction of the elbow retraction formed by the junction between the lower arm **408** and forearm **412** in any desired plane with respect to the base **401**. Such a capability allows the manipulator **800** to access patients in a particularly constrained or low volume situation and allows the overall configuration of the manipulator to be adjusted to the task at hand - operating in a primarily vertical plane for minimally invasive neurosurgery, operating in a horizontal plane for stereotaxy or in combination with other equipment and sensors.

Figures 21ha and **21hb** show two different views of another embodiment of a surgical manipulator **820** wherein a seventh joint **830** can be added in between the wrist-pitch joint and the wrist-roll joint. The new joint **830**, which includes a right-angle drive mechanism as described above, has a joint axis wrist-yaw **831** significantly perpendicular to both the the wrist-roll axis **438** and the wrist-pitch axis **432** as shown in **Figure 21ha**. The output pulley of this new right-angle drive mechanism **830** is oriented in the plane perpendicular to the output pulley plane of the wrist-pitch right-angle drive mechanism **416** and is coupled to the supporting structure of the said wrist body **420**. This additional joint **830** allows the manipulator wrist **420** to have an additional degree-of-freedom in the yaw direction when an application requires minimal or no movement of the rest of the manipulator other than the wrist **420,** for instance minimally invasive surgery, or situations where lateral movement of the surgical instrument is desired without rotation.

It will be understood by those skilled in the art that the surgical manipulator **800** may be further configured such that the sequence of joints may be different, including more or less joints than shown in **Figure 21f**. For some tasks, fewer than six (6) joints may be desirable for volume or access reasons, or the order of the joints within the shoulder, elbow and wrist may be reversed for better reach and access in a particular environment.

Referring to **Figure 21i**, surgical manipulator **400** may be configured to be rapidly reconfigurable modular wherein modules of the manipulator can be quickly removed and replaced with a different but similar modules containing a different size, shape, orientation or sequence of joints and end effectors. This permits the manipulator **400** to be reconfigured for the task at hand while at the same time utilizing a common base **401** and controller (not shown). The quick disconnect allows for a mechanical, electrical, video interface between the remaining segment of the manipulator and the segment that is replaced. The various modules including the robotic arm components (upper arm, fore-arm and wrist), all the right angle drives and end effectors may be configured to include mating interfaces **850** comprising quick release mechanical/electrical couplings allowing them to be quickly assembled and disassembled using a minimal number of mechanical hardware parts (bolts, nuts etc.). The electrical wiring is similarly configured so that when two components are assembled the electrical plugs/sockets match to complete the different circuits.

Such interfaces **850** will exist between the base **401** and shoulder cluster **406**, between the shoulder cluster **406** and lower arm cluster 408, between the lower arm cluster **408** and fore arm cluster **412**, between the fore arm cluster **412** and wrist cluster **420**, and between the wrist cluster **420** and end effector **428**. Each of these interfaces **850** may or may not be different from each other among the different joints, but will be identical among the replacements at the same joint. To assembly or disassembly any of these joints, minimal mechanical hardware parts are required, and all electrical connections will be connected or disconnected automatically upon coupling or decoupling of the interface **850**. Software settings will be adjusted at the controller upon reconnection of all clusters forming the manipulator **400** to update the appropriate control parameters reflecting the current configuration of the manipulator **400**, which can be carried out manually or automatically by detecting all components recognized by the controller.

Referring to **Figure 21j**, the modularity of the manipulator joints, in particular that at the wrist **shaft 484** between the end-effector **428** and the wrist **420**, can be used to attach various purpose-specific end-effectors to adapt to different target applications. In the embodiment with the default design of the manipulator **400** shown in **Figure 16a**, all axes **414**, **422**, **426**, **432** and **438** are included and are the same as described earlier. Using the modular quick-disconnect interface 850 described in the previous paragraph, end-effectors **428** with different functions can be attached to the arm to carry out different tasks. In the default embodiment **990**, the end-effector **428** contains the tool-yaw joint **441** as the default design configuration. However, another embodiment **991** demonstrates an end-effector **428** without the sixth degree-of-freedom but instead just a straight instrument (such as a hand-drill). Embodiment **992** illustrates that another much smaller manipulator arm **881** can be attached as the instrument of an end-effector **428**, such that the manipulator arm **400** is responsible for gross motion, whereas fine motion can be carried out by the smaller manipulator arm **881**, such as an endoscope. Additional sensing device **882** can be attached to the end-effector **428** as shown in embodiment **993**, such as a viewing camera or tracking target, as in the case of image-guided surgery.

It will be understood that a manipulator may be constructed in which there is not tool yaw axis 441, so that the entire system has less than six degrees of freedom. For example, if the end-effector is gripping a probe, no rotational axis (rotational degree of freedom) is required by the end-effector.

3) SURGICAL TOOLS

The end effecter **428 (Figure 16a)** connected to the end of the robotic wrist unit **424** holds a surgical tool **430** which can be detached from the end-effector **428** in a manner to be discussed after the discussion of the tools. **Figures 22a** to **22e** show a first embodiment of a surgical tool **430** which can be detachably mounted to end effecter **428** attached to the manipulator **400** (**Figure 16a**). Referring to **Figure 22c** and **22d**, tool **430** includes a main housing **500**, a Teflon bushing **502** seated in the end of housing **500**, a piston **504** sliding in housing **500** through Teflon bushing **502**, a right hand forcep blade **506**, a left hand forcep blade **508**, and a forcep insert **510**. The two forcep blades have a hole through them and a dowel **512** is inserted through the holes and the two blades pivot about this dowel **512** as the piston **504** moves in and out of main housing **500**. Piston **504** includes a head portion

514 located at the outer end of the piston and a narrower neck **516** located between the head portion **514** and the rest of the body of the piston **504**. Piston **504** includes a smaller diameter extension **522** which slides up and down between the end sections of the two forcep blades **506** and **508** which are located inside main housing **500** above the dowel **512**. An O-ring **520** is seated at the end of the larger diameter section of the piston **504**. Tool **430** includes a timing pulley **528**.

Figures 23a and **23b** show another embodiment of a surgical tool shown generally at **560** which includes a main body **562**, a piston **564** having a piston head **566** separated from the body of the piston by a neck **568**. The two forcep blades **570** and **572** pivot about a common pivot point located inside housing **562** and use a spring **574** to return the blades **570** and **572** to its open position. The spring **574** is contained in housing sections **580** and **582** associated with blades **570** and **572** respectively. The tool uses an internal wedge action to close the blades **570** and **572**. The driving piston **564** uses a roller **576** (**Figure 23b**) to separate the upper proximate portion of the blades above the pivot point, which in turn squeezes the distal blade tips together which engage tissue during surgery.

Figures 24a and **24b** show another embodiment of a surgical tool which includes a main body **632**, a central piston **634** having a piston head **636** separated from the body portion by neck **638**. Surgical tool **632** uses a 4-bar linkage, creating a scissor motion, to actuate the forcep blades **640** and **642**.

Figures 25a and **25b** show another embodiment of a surgical tool **700** which again includes a main housing **702**, a center piston **704**, and forcep blades **708** and **710**, made from a single piece. The forcep blades **708** and **710** are either made in a single piece or two pieces welded together so that opening of the blades is carried out by the spring force at the joint of the two blades. To close the blades the piston **704** translates downwards and with a wedge cut into it, it closes the blades **708** and **710** by elastically deforming the material where the blades **708** and **710** joint.

It will be understood that there are numerous types of surgical tools each having a tool portion which may be of different structure and function (eg. Scissors, scalpels, forceps, etc.) that may be mounted to the end-effector **428** and regardless of the structure or function of these different tool portions when the piston **504** is linearly retracted or linearly extended with respect to said end-effector **428** the tool portion of the surgical tool **430** may be activated. The forceps shown is only exemplary and non-limiting.

4) SURGICAL END-EFFECTOR

As mentioned above, with reference to **Figure 16a**, the end effecter **428** connected to the end of the robotic wrist unit **424** with the exchangeable surgical tool **430** held. Microsurgical manipulators preferably require end-effectors that are small and lightweight, use different tools, have 2 degree-of-freedom (DOF) actuation, enable fast and automated tool exchange, have 6 DOF tool tip force sensing, have tool clasp force sensing, maintain a sterile barrier between the robot and the tool and/or patient, and easy to assemble.

The end-effector **428** is comprised of both sterile and non-sterile components. Sterile components are exposed to the working atmosphere of the surgical worksite and are not guarded by a bacteria resistant bag in which the non-sterile components of the end-effector **428**, and subsequent remaining arm, are protected. Therefore, sterile components are required to be contamination free by the auto-claving process, using high pressure and temperature steam, after each surgery. In order to separate components on the end-effector **428** that are in direct contact with the surgical environment (and surgical tool **430**) a sterile barrier needs to be established.

The size requirement of the end-effector **428** is preferably that it be smaller than the typical human hand and as lightweight as possible, thus driving the overall size of the entire arm. **Figure 26a** shows an isometric view of the end-effector **428** assembled holding the surgical tool **430**. Also, the end-effector **428** preferably is sized/orientated accordingly so as to provide maximum visibility at the tool tips and the work site. In order for this to be achieved, the actuator responsible for tool-actuation is preferably located away from the surgical site. This asymmetrical orientation facilitates two end-effectors being positioned closely to allow small workspaces in a dual-manipulator operating configuration to be discussed hereafter.

In a non-limiting embodiment of the surgical manipulator, an overall size of the end-effector **428** (not including the surgical tool) has a length, width and height of: 70mm x 50mm x 80mm respectively and a weight of 240g. These parameters satisfy the size requirements of the end-effector **428**, but are exemplary only and not intended to be limiting.

Presently available surgical systems are known to have numerous sterile sub-components and offer a complex means of assembly, causing long exhaustive set-up times. The end-effector **428** disclosed herein advantageously offers minimal assembly components and a set-up time in minutes.

Referring to Figures **26a, 26b, 26c, 26d, 26e** and particularly **Figure 26b**, end-effector **428** includes a main assembly **436** which constitutes the non-sterile member. This is where a protective bag or hard guarding will encapsulate the end-effector **428**. End-effector **428** also comprises three main sub-components, including a magnetic tool holder **450**, tool actuator **452**, and tool-yaw mechanism **454.** All these subassemblies have a simple interface to the main assembly **436** for ease of set-up by a nurse. The exploded view in **Figure 26b** shows how the sterile components are removed. These three sub-components, magnetic tool holder **450**, tool actuator **452**, and tool-yaw mechanism **454** are located and releasably secured to the main assembly **436** by threaded quick change pins **458**, **460** and **462**.

For a safety requirement, the surgical tool **430** must have the ability to be manually extracted from the workspace from the top during an emergency. This can be achieved by removing both the magnetic tool holder **450** and tool actuator **452** quick pins **458** and **460** respectively, sliding out the tool actuator **452** and then vertically removing the tool holder **450** containing the surgical tool **430**. Another, quicker way would be to manually eject the tool **430** from the tool holder **450** (discussed later) and on a slight angle from vertical, so as to clear the tool flange, extract the tool **430** from the surgical site.

Each of the main assembly **436,** and magnetic tool holder **450**, tool actuator **452,** and tool actuator **452** will be discussed in more detail herebelow.

a) Main assembly 436

Referring to **Figures 27e** and **27f,** the main assembly **436** of the end-effector **428** includes all the electronic components, the tool-yaw motor **600**, the tool-actuation motor **601**, the tool-tip force-moment sensor **608** and the tool-actuation force sensor **604** all mounted on end-effector **428**. This forms the core of the end-effector **428** where these components and their adjacent supporting structures are considered to be non-sterile and thus need to be protected by a drape bag. The drape bag will need to cover from the base of the robot all the way through the entire length of the arm until the front face **611** of the end-effector main assembly **436**, whereas the remaining subassemblies of the end-effector will be attached to the main assembly via their corresponding interfaces pinching through the drape bag.

Referring in particular to **Figure 27f**, the tool-yaw motor **600** is mounted onto the motor-support bracket **602**, which is an inverted C-shape structure clamping onto both ends of the tool-yaw motor **600**. A square drive shaft **609** is attached to the output shaft of the tool-yaw motor **600** which is exposed to the bottom side of the motor-support bracket **602**, at which point the drive timing pulley (discussed in a later paragraph) of the tool-yaw subassembly **454** is connected to the square drive shaft **609** for rotation transmission to the tool-yaw axis **441**.

Referring to **Figures 26e** and **27e**, the tool-actuation motor **601** is attached to the motor-support bracket **602** at a lateral extension, arranging the motor **601** in parallel to the tool-yaw motor **600**. This motor **601** is a linear actuator, in which its output shaft moves up and down along the major axis of the motor itself, and at the end of which the angled actuator bar **603** is connected. The bar **603** can thus transmit the vertical motion to the tool actuator subassembly **452** which is mounted at the other end of the bar **603**. The actuator subassembly **452**, upon engaging with the tool-actuation interface (will be discussed in a later paragraph), provides the tool-actuation axis of motion for the end-effector.

Referring to **Figure 27f**, the tool-tip force-moment sensor **608** is the single mechanical linkage between the motor-support bracket **602** and the base block **605** which interfaces back to the wrist of the robot arm. This is to ensure all of the interactive force and moment at the tool tip is transmitted through the sensor **608** only and back to the base block **605** with no alternative load paths (will be discussed in a later paragraph). This load path is shown by the arrows in **Figure 27a**. The base block **605** has a clearance hole **612** through which the tool-yaw motor **600** is passed through without physically contacting any part of the base block **605**. The tool-holder subassembly **450**, and subsequently the tool **430**, is attached to the front face **611** of the motor-support bracket **602**. Thus it means except for the base block **605**, the remaining components of the entire end-effector are supported at a single interface at the front face of the force-moment sensor **608,** see **Figure 26b**.

Referring again to **Figure 27f**, the tool-actuation force sensor **604** is mounted on the angled actuation bar **603** between the point where the bar **603** is supported by the vertical guide rod **606** and the interface **607** with the tool-actuator subassembly **452**. The sensor **604** takes the form of a strain gauge, at which point on the bar **603** the elastic vertical deflection due to the tool-actuation can be measured (as will be discussed in a later paragraph).

b) Tool-actuation mechanism 452

Referring to **Figure 26d**, the end-effector **428** includes the tool-actuation mechanism **452** that works completely independent from tool yawing mechanism **454** discussed hereinafter. This is achieved using a linear guide support **606** which is coupled to a linear actuator **601** to vertically translate the piston **504** of the surgical tool **430** via the narrow neck section **516** along the tool axis to provide a gripping motion between the two blades **506** and **508** (**Figures 22c** and **22d**). This feature of the end-effector **428** can be utilized whether the tool **430** is rotating about the tool-yaw axis **441** (**Figure 16a**) or static due to the circular neck section **516** of the tool piston **504**. It can also be bypassed when using a surgical tool that doesn't require actuation (e.g. probe, scalpel, cauterizer etc.), with the only requirement being the tool does not possess any mechanical interface to couple with actuation subassembly **452** as does the piston **504** of the forcep tool **430**.

Referring to **Figures 28a** and **28b**, the tool actuator mechanism **452** is coupled to an angled actuation bar **603** by a cross-location pin **460**. The mechanism includes a pair of pivoting fingers **614** that are secured around the piston member **504** of the forcep surgical tool **430.** These fingers **614** are spring loaded by springs **628** to an engaged position, but can be passively opened up for tool removal.

Referring to **Figures 26e** and **27f**, the angled actuation bar **603** is guided by a linear ball bearing **615** to the offset actuator position. Strain gauge **604** located on the angled actuation bar **603** enables the sensing of tool-actuation forces. As the cantilever portion of the bracket exhibits deflection, in either direction caused by the reaction as a result of the up and down motion of the piston **504** of the tool **430**, the strain gauge **604** will generate a voltage signal which will be fed back to the controller for interpretation. With proper calibration of the strain gauge sensor **604**, the vertical force required to actuate the tool can be determined, which can then be translated into a pinching force at the tip of the blades **506** and **508** of the tool **430** (**Figure 22c**) given the geometric profile of the cam section **510** of the blades **506** and **508** that are responsible for the closing of the blades **506** and **508** upon the upward sliding of the extension **522** of the piston **504** in between the blades **506** and **508**. Refer to the arrows in **Figure 26d** for an illustration of how the pinching force at the tips of the blades **506** and **508** is detected by the strain gauge **604**.

c) Magnetic tool holder 450

The purpose of the magnetic tool holder **450** is to hold the tool rigidly, but still allowing the tool to rotate easily. This is accomplished by constraining the tool **430** in a support body **616**, which in a non-limiting exemplary embodiment shown in **Figure 29c** is a generally 'V' shaped block made from ABS plastic having an elongate channel having a size suitable receive therein the cylindrical tool body **500** of surgical tool **430**, which allows the tool **430** to rotate within support body **616** with minimal friction. Referring to **Figures 26b, 29a** and **29b,** the tool body **500** of the surgical tool **430**, preferably made from 400 series stainless steel which is magnetic, is seated in the 'V' block **616** by two rare earth pot magnets **618** imbedded in the 'V' block. The magnetic force and 'V' block reaction forces tangential to the shaft secure the tool **430** radially, whereas flanges **529** on the body **500** of the surgical tool **430** locates and constrains the tool axially **(Figure 22a)**, due to a close axial fit with the 'V' block body **616**. **Figures 29c** to **29e** show more detailed views of the magnetic tool holder.

Another capability of the tool holder **450** is that it can enable passive tool exchange for automatic tool change-out. Referring to **Figures 29c**, **29d** and **29e**, the 'V' block **616** is featured with a tool release mechanism that once compressed can pivot, similar to a scissor action, to strip the tool body **500** away from the magnets **618** and eject the tool **430**. **Figure 29d** shows the tool-engaged configuration, or when the tool-ejection wings **617** are in closed position. **Figure 29e**, on the other hand, shows the tool-ejecting configuration, or when the wings **617** are in opened position. After ejecting the tool, the wings **617** will return to the default closed position by the compression springs **619** located at the back of each wing **617** (best seen in **Figures 29b** and **29d**).

Figure 29f shows the passive tool changer mechanism on a tool tray **911** for auto tool-changing. Static pins **950**, fixed to a tool tray **911** are positioned to engage specific end-effector features to release the tool. These features include the pivoting fingers **614** of the actuator subassembly **452** and the outer idler pulleys **438** of the tool-yaw subassembly **454,** both of which are engaging with the tool **430** and needs to be released. The actual ejecting feature, however, lies in the tool-holder **450,** from which the ejecting wings **617** need to be pressed backward into the opened position so as to eject the tool **430.** This is carried out by the mating ejection latches **951** on the tool tray

911, which line up with the wings **617** and has a spring-loaded pliers-like mechanism to provide a cushioned tool-ejection.

The downward motion of the manipulator **400** is the only active component of this process, in which the end-effector **428** is oriented such that the tool **430** is horizontal when the manipulator **400** pushes down onto the tool tray **911,** forcing the end-effector **428** engaging features **614** and **438** to be opened up by the pins **950** on the tool tray **911,** whereas the wings **617** are actuated by the ejection latches **951**, thus releasing completely the tool **430** onto the tool tray **911.** To pickup a tool, the process is reversed. The manipulator **400** brings the empty-handed end-effector **428** over the top of the tool **430** on the tray **911,** presses down the end-effector **428** to open up the engaging features **614 and 438** as well as the ejection wings **617,** and captures the tool **430** by the magnet **618** on the tool holder **450** of the end-effector **428**. The tool tray **911** has multiple sets of pins **950** for each corresponding surgical tool, and also possesses a tool-identification sensor, which upon reading the tag built-in to each tool, the main controller can register which tool the manipulator **400** has picked up. Identification tags on the tool can be a bar code or infra-red tag, which works with a corresponding IR-sensor on the tool tray **911.**

d) Tool-yaw mechanism 454

The end-effector **428** includes a tool-yaw DOF that is actuated by a servo motor integrated with an anti-backlash spur gearhead and an incremental encoder. Referring to **Figure 26b**, bonded to the output shaft of the motor-gear-encoder combo **600** is the previously described square pin

609 that drives a timing pulley **736** from the tool-yaw subassembly **454**. Since the tool-yaw mechanism **454** is a removable sterile component, a quick-disconnect coupling from the non-sterile servo actuator main assembly **436** is required. The square pin **609** matched precisely to a square bore on the drive pulley **736** enables torque to be transmitted to the tool yaw mechanism **454**, but allows easy de-coupling for auto-claving.

Referring to **Figure 27a** and **27b**, tool yaw mechanism **454** includes a frame **442**, and through a pair of idler pulleys **438** mounted thereon, a disposable toothed belt **540** engages a complementarily toothed pulley **528** on the surgical tool **430**, (see **Figure 26b**) on two opposite ends of the pulley diameter. The toothed belt **540** routing is completed by the middle idler pulley **620** mounted on frame **442** which has the same pitch diameter as the outer idler pulleys **438**. The bi-directional rotation of the belt **540,** driven by the drive pulley **736**, converts tangential forces to rotary motion on the surgical tool **430**. One of the main attributes that the tool yaw mechanism **454** exhibits is the passive removal and replacement of different surgical tools **430**. The open front-framed architecture and belt configuration allows the tool **430** to be ejected/replaced from the front of the tool yaw mechanism **454**, avoiding it being tangled around the belt **540**. The tool ejection process is further aided by the outer idler pulleys **438**, supported by sheet metal flexures **621**, which can be passively spread out enough to completely disengage the tool, eliminating any frictional effects. When engaged with the tool **430**, the metal flexures **621** allow a constant preload to the timing belt **540** during tool yawing but can also manually collapse, when no tool is present, for easy timing belt replacement. **Figures 27c** and **27d** show further details of components making up the end-effector.

It will be appreciated by those skilled in the art that the end-effector **428** disclosed herein may be retrofitted onto any robotic arm assembly and is not restricted to being mounted on manipulator **400** disclosed herein.

Similarly, it will be appreciated by those skilled in the art that the right-angle drive unit 10 disclosed herein may be used in any application requiring conversion of rotational motion along one axis to rotational motion along another axis and is not restricted to being mounted on manipulator **400** disclosed herein.

Haptic Feedback

In order for the surgeon to retain the sense of touch at the hand-controller during a telerobotic operation, haptics is required which means the end-effector must be capable of providing realistic external force and torque sensing at the tool tips and reflecting back to the hand-controller. To obtain accurate haptic feedback, the end-effector is advantageously designed so that forces and torques (moments) at the tool tips are directly registered by the force-moment sensor **608**, which measures force and moment through elastic deflection in the direction of interest. The sensor **608** needs to measure the force and moment in all six directions, so that a full 6DOF haptic feedback can be achieved. It needs to have sensing precision within the range of soft tissue interaction, which is roughly 1 to 200g. The size of the sensor **608** is preferably compact enough to be incorporated into the end-effector design without enlarging the overall end-effector size to an undesirable scale. Given these parameters, the smallest force-moment sensor preferred in the present manipulator is the Nano17 of ATI Industrial Automation, having an overall size of just ø17mm x 14.5mm long.

The location of the force-moment sensor **608** within the end-effector **428** is important as it determines the eventual precision of the haptic feedback. Ideally, the sensor **608** should be right at the tool tip where the external forces and moments are exerting when the tool is in contact with a foreign object. In practice this is difficult to achieve as it will mean having a delicate electronic component build-in to the surgical tool, which needs to go through auto-claving cycles for sterilization. Also, various tools need to be fitted onto the end-effector **428**, thus electronic interfacing is required upon changing of tools which add to the complexity of the end-effector design. Furthermore, sensors on each tool will significantly increase the cost of tool production and subsequently the investment on the overall system by the customers.

Therefore, it is beneficial to keep the miniature force-moment sensor within the end-effector but close to the surgical tool. This will minimize the amount of weight on the free end of the sensor so as to avoid saturating the sensing capacity of the sensor. Also by reducing the physical distance between the tool tips and the point of sensing, signal distortion throughout the load path due to mechanical imperfections, such as backlash, compliance and vibration, can be minimized. The load path is analogous to the current path in an electrical circuit. Optimum force and moment sensing can be achieved when all the forces and moments originating from the tool tips are transmitted through the sensor only and back to the supporting structure at the other end of the sensor, or the “ground”, therefore ensuring all tool-tips loads are gathered by the sensor before sending back the force and moment signals back to the controller for interpretation.

Figure 26e shows a cross-section through the load path of the end-effector **428**. The grounded portion consists of the base block **605** that supports the backend of the force-moment sensor **608** only. All of the actuators **600** and **601**, the tool-actuation sensor **604**, and their corresponding supporting structure are mounted to the front face of the sensor **608** free end. This excess weight read by the sensor **608** can be offset by zeroing out the signal at the controller with the known weights and center-of-gravity distances of each part contributing to the weight measured by the sensor **608**, including those of the tool **430**. This active gravity compensation technique can be completed by computing the expected dead weight of all parts at the sensor location with the dynamic equations of the manipulator, minus which the filtered signal from the sensor is the pure external forces and moments acting at the tool tips.

Besides tool-tips forces and moments, haptic feedback also includes the tool-actuation force feedback. Referring to **Figure 26d**, the closing and opening of the blades **506** and **508** of the tool **430** is achieved by the vertical motion of the piston **504**. The piston **504** is carried by the actuator subassembly **452**, which is connected back to the tool-actuation motor **601** via the actuation bar **603**. The pinch force at the tool tips of the blades **506** and **508**, therefore, is transmitted vertically through the above mentioned path. Thus a strain-gauge type sensor **604** is located at middle of the cantilever section of the actuation bar **603** to measure the elastic deformation of the bar **603** to provide tool-actuation force feedback to the controller. The voltage signal generated can be used in force regulation for tool-actuation, or can be reproduced at the hand-controller for tool-actuation haptic feedback via an appropriate human-machine interface.

Referring to **Figure16a**, surgical manipulator **400** (and all others) is designed to be used for surgical operations in a telerobotic system under the direct control of a surgeon **960**. In a telerobotic system, a robot and a hand-controller form a master-slave relationship as the operator moves the hand-controller, or the master, to perform the action, and the robot, or the slave, carries out the actual operation as the output by following the hand motions of the operator. Referring to **Figure 30**, the telerobotic system is comprised of two portions, the slave which is a mobile platform **906** containing two manipulators **900** and **901**, and the master in the form of a workstation **908** including one or more computer monitor, and two haptic devices **903**, **904** as hand-controllers, with each manipulator-hand-controller pair mimicking the left and right arm of a surgeon **960** such that dual-hand operation is possible.

The two manipulators **900** and **901** have mirrored configurations to each other, with all components being identical. Thus the surgical manipulator system includes at least two surgical manipulators **900** and **901** configured to be structural mirror images of each other, with one of the surgical manipulator being configured for left handed operation and the other being configured for right handed operation. This configuration is advantageous in that it allows the surgical tools attached to respective end-effectors to be brought into closest proximity with each other in a surgical site on a patient.

There is a communication system coupling the left and right hand-controllers to their respective surgical manipulators for translating movement of the left and right hand-controllers to scaled movement of the first and second surgical manipulators. This scaled motion may be predetermined in software and may be 1:1 in which the move of the surgeons hand on the controller is translated into exactly the same movement of the end-effector. However the ratio need not be 1:1 depending on the surgical procedure involved.

For each of the manipulators **900** and **901**, there is a tool tray **911** located near the base of each manipulator. The tool tray **911** holds a number of surgical tools which may or may not be identical to the tools shown in **Figures 22a** to **25b**, but are required for the planned surgical procedures. The manipulators **900** and **901** are programmed to change tools automatically at the tool tray **911** upon a single command from the surgeon **960**. Both manipulators **900** and **901** are mounted on the mobile platform **906** which can easily be transported to dock with the operating table **907** and undock and remove when the operation is completed. A microscope and/or stereo camera **909**, which can be mounted either on the mobile platform **906** or as a fixture in the operating room, provides visual display of the surgical site and/or the overview of the manipulators plus their tools with respect to the patient **962**.

A single cable connection using regular network protocol may be used for communication of signals between the manipulators mobile platform **906** and the workstation **908** at which the surgeon **960** is at. The left hand-controller **903** by default controls the left manipulator **900**, and the right hand-controller controls the right manipulator **901**, although through software selection the surgeon **960** can switch over the communication linkage between the pair if it is required during the operation.

Each of the haptic devices **903** and **904** is a 6DOF hand-controller that can measure a surgeon's hand motion in all six directions of translation and rotation in 3D space. The motion signals are then sent to the intended manipulator through the motion controller, at which the surgeon's input will be reproduced. These signals can also be scaled, such that the surgeon **960** can fully utilize the best resolution of the manipulators motion by having their hand motions at the hand-controllers **903** and **904** scaled down before being carried out by the manipulators. At the hand-controllers **903** and **904**, switches are available for the surgeon **960** to control other functions of the manipulators, such as tool-actuation, dead-man switch, and automatic tool changing.

The hand-controllers **903** and **904** also have three to six powered joints to provide haptic feedback to the surgeon **960**. The base positions of the hand-controllers **903** and **904** on the workstation **908** can be adjusted to the comfort of the surgeon **960**, and with the addition of arm rests the only motion required from the surgeon **960** is at the wrists. Since there is no absolute referencing of the hand-controller motion with respect to that of the manipulators, the surgeon **960** can hold the handles of the hand-controllers **903** and **904** at a comfortable posture, again to minimize fatigue, while the manipulators **900** and **901** are holding the surgical tools in the appropriate positions. Also on the workstation **908**, there is one or more computer monitor **905** displaying system status and also providing touch-screen interface to the surgeon **960** and/or nurses for adjusting critical system parameters.

One of the most important settings the surgeon **960** needs to make is the virtual boundaries for the manipulators. Using a preoperative image with registration back to the manipulator, or with a real-time intraoperative image taken by the camera **909**, the surgeon **960** can specify on-screen the region at the surgical site where the manipulator with the surgical tool **430** can operate within. If the surgeon 960 commanded the manipulator via the hand-controllers to move near these boundaries, the motion controller will automatically stop the manipulators from moving any further unless the surgeon **960** reverse the motion. This will set a prohibited area where the manipulators cannot move the surgical tools to, such that the surgeon **960** can ensure critical areas in the patient's anatomy is protected. The monitor **905** also displays the real-time video taken by the microscope and/or camera **909**.

Alternatively, the microscope/camera **909** video signal can be displayed via a digital eyepiece **910** which mimics that of a conventional microscope if the surgeon **960** prefers. The surgeon **960** together with the workstation **908** can be immediately next to the operating table **907** for telepresence operation, where the surgeon **960** will directly observe the surgical site on the patient **962** without any visual aid. In the case of remote operation, the surgeon **960** and the workstation **908** is at a physical distance from the operating table **907** limited only by the network connection infrastructure available. Visual feedback via the monitor **905** and haptic feedback via the hand-controllers **903** and **904** retain the senses of vision and touch of the surgeon **960** over the physical distance, which makes remote teleoperation possible with the additional benefits of finer and more consistent hand motion, more ergonomic user-interfaces to reduce surgeon **960** fatigue, less intrusive to the surgical theatre, and built-in fail-safe features to protect the patient **962** and the surgeon **960**.

Besides teleoperation, the manipulators can also be operated using pre-planned image-guided trajectories. Pre-operative images of the patient's surgical site are taken with an external imager, such as fluoroscope or CT-scanner. The surgeon **960** can then use those images to define where the problem exists, which area the manipulator needs to go to and with which surgical tool. The surgeon **960** can then take an intra-operative image with registration to the manipulator coordinate system, and map it to the pre-operative image with the planned targets. The control software will then interpret the targets into workspace coordinates of the manipulators, thereby allowing the surgeon **960** to specify the complete trajectories of the surgical tool held by the manipulator with respect to the surgical site of the patient **962**. Upon execution of the pre-planned trajectories, the surgeon **960** can either start the autonomous motion of the manipulator and pause or rewind at any time at the workstation monitor, or use the hand-controller to control the motion along the prescribed trajectories.

Comparing to the other devices available in the current market, the surgical manipulator described herein has several advantages in the field of microsurgeries, including brain, spine and eye surgery. First of all, this surgical manipulator is smaller than a regular human arm thanks to the right-angle transmission modules and the compactness of the other actuation components, which allows easy access to the surgical site and minimizes intrusion to the operating room. Although being compact in size, this manipulator has broad enough motion range and reach to accomplish tasks requiring bigger manipulator workspace such as suturing. The 6DOF available means dexterous motion is capable in any given direction. With high-power brushless servo motors deployed at each joint, relatively heavier-duty tasks such as tissue-retraction and bone-drilling for pedicle screw is made possible. The smallest step size achievable at the tool tip, due to the use of the right-angle transmission modules as well as high resolution sensors, amplifiers and motion controllers, matches the finger motion resolution of the best brain surgeons. The auto tool-changing capability as a result of the end-effector design reduces the tool-changing time and also human-error. The end-effector structure forces the load-path to go through the force-moment, and the consequent high fidelity of haptic feedback retains the sense of touch of the surgeon, without which the surgeon would lose a significant amount of surgical techniques and know-how.

As used herein, the terms "comprises", "comprising", "including" and "includes" are to be construed as being inclusive and open ended, and not exclusive. Specifically, when used in this specification including claims, the terms "comprises", "comprising", "including" and "includes" and variations thereof mean the specified features, steps or components are included. These terms are not to be interpreted to exclude the presence of other features, steps or components.

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THEREFORE WHAT IS CLAIMED IS:

1. A surgical manipulator, comprising:

a) a base and a first right angle drive mechanism mounted on said base, a shoulder-roll drive mechanism located in said base for rotating said first right-angle drive mechanism about a shoulder-roll axis,

said first right-angle drive mechanism including a first input pulley and a first output pulley and a first bi-directional coupling mechanism,

a first drive mechanism, having a first rotational drive axis, coupled to said first input pulley for rotating said first input pulley about a first input axis, said first input axis being coincident with said first rotational drive axis, wherein rotation of said first input pulley is translated into rotation of said first output pulley by said first bi-directional coupling mechanism about a shoulder-yaw axis which is perpendicular to, and intersecting with, said first input axis;

b) a second right-angle drive mechanism coupled to said first right-angle drive mechanism including a second input pulley and a second output pulley and second bi-directional coupling mechanism,

a second drive mechanism, having a second rotational drive axis, coupled to said second input pulley for rotating said second input pulley about a second input axis, said second input axis being coincident with said second rotational drive axis, wherein rotation of said second input pulley is translated into rotation of said second output pulley by said bi-directional coupling mechanism about a shoulder-pitch axis which is perpendicular to, and intersecting with, said second input axis;

c) a robotic lower arm being mounted at one end thereof to said second output pulley so that when said second output pulley is rotated, said robotic lower arm rotates about said shoulder-pitch axis,

a third right-angle drive mechanism mounted in said robotic lower arm, said third right-angle drive mechanism including a third input pulley and a third output pulley and a third bi-directional coupling mechanism,

a third drive mechanism, having a third rotational drive axis, coupled to said third input pulley for rotating said third input pulley about a third input axis, said third input axis being coincident with said third rotational drive axis, wherein rotation of said third input pulley about said third input axis is translated into rotation of said third output pulley by said bi-directional coupling mechanism about an elbow-pitch axis perpendicular to, and intersecting with, said third input axis;

d) a robotic fore arm mounted on said third output pulley of said third right-angle drive mechanism so that when said third output pulley is rotated, said robotic fore arm rotates about said elbow-pitch axis, a fourth right-angle drive mechanism mounted in said robotic fore arm, said fourth right-angle drive mechanism including a fourth input pulley and a fourth output pulley, and a fourth bi-directional coupling mechanism,

a fourth drive mechanism, having a fourth rotational drive axis, coupled to said fourth input pulley for rotating the fourth input pulley about a fourth input axis, said fourth input axis being coincident with said fourth rotational drive axis, wherein rotation of said fourth input pulley about said fourth input axis is translated into rotation of said fourth output pulley by said bi-directional coupling mechanism about a wrist-pitch axis perpendicular to, and intersecting with, said fourth input axis;

e) a robotic wrist mounted on said fourth output pulley of said fourth right-angle drive mechanism so that when said fourth output pulley is rotated, said robotic wrist rotates about said wrist-pitch axis,

said robotic wrist including an actuation mechanism coupled to a wrist output shaft for rotating said robotic wrist output shaft about a wrist-roll axis; and

f) an end-effector mounted to said wrist output shaft, said end-effector including gripping means for releasibly gripping a surgical tool wherein, when said actuation mechanism is engaged, said end-effector is rotated about said wrist-roll axis.

2. The surgical manipulator according to claim 1 wherein components of said surgical manipulator including said base, said first, second, third and fourth right-angle drive mechanisms, said robotic lower arm, said robotic forearm, said robotic wrist, and said end effector include mechanical quick release mechanisms for quick assembly and disassembly of said surgical manipulator and include quick electrical connections so that when said components are assembled said components are electrically connected.

3. The surgical manipulator according to claim 2 wherein said components of said manipulator are modular components and configured to be quickly removed and replaced with different but similar modular components which are any one or combination of a different size, shape, orientation or sequence of said modular components.

4. The surgical manipulator according to claim 1 wherein said shoulder-roll drive mechanism includes a spur-gear mechanism mounted in said base and including a pinion anti-backlash gear meshed with a driven gear, a motor for rotating said pinion gear which in turn rotates said driven gear and therefore the first right angle drive mechanism about a shoulder-roll axis, and including a motor brake.

5. The surgical manipulator according to claim 1 wherein said end-effector includes

a main body portion including a frame having an interface configured to be attached to said robotic wrist, a tool-yaw motor mounted on said frame, a tool-actuation motor mounted on said frame,

a tool holder mounted on said frame and being detachable therefrom, said tool holder being configured to hold said surgical tool,

a tool-actuation mechanism mounted on said frame and being detachable therefrom, said tool-actuation mechanism being configured to engage a piston on said surgical tool, said tool-actuation mechanism being coupled to said tool-actuation motor,

and a tool-yaw drive mechanism mounted on said frame and being detachable therefrom, said tool-yaw drive mechanism being coupled to said tool-yaw motor, wherein upon activation of said tool-yaw drive mechanism said surgical tool rotates about said tool-yaw axis and wherein upon activation of said tool-actuation mechanism said piston is linearly retracted or linearly extended with respect to said end-effector thereby activating a tool portion of said surgical tool.

6. The surgical manipulator according to claim 5 wherein said interface includes a base block which interfaces to said robotic wrist, and wherein

said end-effector includes a tool-tip force-moment sensor which is a single mechanical linkage between said frame and said base block, and wherein said tool-tip force-moment sensor mounted to said end-effector is configured to sense tool forces and moments at a tip of the surgical tool, and wherein said end-effector includes a tool-actuation force sensor mounted thereon configured to measure actuation forces on a tip of the surgical tool, said surgical manipulator including hand controller means being configured to be operated by a surgeon, and including a communication system coupling said hand controller means to said surgical manipulator for translating movement of said hand controller means to scaled movement of said surgical manipulator, and wherein said communication system coupling said hand controller means to said surgical manipulator is configured to communicate said forces and moments to said hand controller means providing haptic feedback to a surgeon.

7. The surgical manipulator according to claim 6 wherein said tool-actuation motor is a linear actuator having an output shaft which moves up and down along a major axis of the linear actuator and at a distal end portion of said output shaft an actuator bar is connected at a first end portion thereof, said actuator bar having a second end portion supported by a vertical guide rod and including an interface which couples to said tool-actuation mechanism, wherein said actuator bar transmits vertical motion of

the output shaft to the tool-actuation mechanism which is mounted at the second end of the bar such that said vertical motion provides a tool-actuation axis of motion for the end-effector, and wherein said tool-actuation mechanism includes a pair of pivoting fingers pivotally mounted to a support member with matched end portions configured to engage and hold a portion of a piston on the surgical tool.

8. The surgical manipulator according to claim 5 wherein said tool-yaw mechanism includes a frame on which is mounted a pair of outer idler pulleys, a middle idler pulley and a drive pulley, including a toothed belt being routed on said outer idler pulleys, said middle idler pulley and said drive pulley, said toothed belt being configured to engage a toothed pulley on said surgical tool, on two opposite ends of a diameter of said toothed pulley, and wherein bi-directional rotation of said toothed belt driven by said drive pulley, converts tangential forces to rotary motion of said surgical tool, and wherein said frame has an open front-framed architecture and a toothed belt routing configuration on said outer idler pulleys and said middle idler pulley configured to allow the surgical tool to be ejected/replaced from the open front of the end-effector, and wherein said frame includes sheet metal flexures supporting said outer idler pulleys so that said outer idler pulleys can be passively spread out enough to completely disengage the surgical tool thereby eliminating any frictional

effects, and wherein when engaged with said surgical tool, the metal flexures allow a constant preload to the toothed belt during tool yawing but also manually collapse, when no surgical tool is present, for facilitating toothed belt replacement.

9. The surgical manipulator according to claim 8 wherein said tool holder includes a support body having an elongate channel having a size suitable to receive therein a cylindrical tool body of said surgical tool, and wherein said cylindrical tool body is made of a magnetic material, and wherein said support body includes at least one magnet embedded therein adjacent to said elongate channel for magnetically restraining said magnetic cylindrical tool body, wherein said support body is made of a material which allows the surgical tool to rotate with minimal friction within said support body when rotated by said tool-yaw mechanism, wherein said surgical tool includes flanges on the body of the surgical tool for locating and constraining the surgical tool axially within said channel in said support body due to a close axial fit with the support body; wherein said tool holder includes a tool release mechanism including a pair of tool-ejection wings pivotally mounted on said support body with a portion of each wing located in said channel behind said tool body and configured such that once said tool-ejection wings are compressed on outer surfaces thereof, said tool-ejection wings pivot in a scissor action, to strip the tool body away from

said at least one magnet responsively ejecting said tool from said tool holder.

10. The surgical manipulator according to claim 9 including a tool changer mechanism comprising a tool storage and tool change tray, said tool change tray including a support structure for holding the surgical tools and including engaging features arrayed on said tool change tray configured to simultaneously spread said pulleys apart, engage the pivoting fingers located on said tool-actuation mechanism, and engage said ejection-wings located on said tool holder thereby releasing said surgical tool from said end-effector, wherein said support structure for holding the surgical tools and said engaging features arrayed on said tool change tray include first and second pair of pins fixed in vertical arrangement to said tool tray being positioned and spaced apart such that they engage said pulleys on said tool-yaw mechanism and spread said pulleys apart when said end-effector engages said passive tool changer when picking up a surgical tool or releasing a surgical tool, and including a third pair of pins positioned on said tool change tray with respect to said first and second pairs of pins such that the third pair of pins engage pivoting fingers located on said tool-actuation mechanism responsively pivoting said fingers out of engagement with said piston on said surgical tool, said tool change tray including mating ejection latches mounted on the tool tray which line up

with said ejection-wings located on said tool holder, which mating ejection latches include a spring-loaded pliers-like mechanism to provide a cushioned tool-ejection; wherein each surgical tool includes identifying means mounted thereon, and wherein said tool changer includes a tool-identification sensor for said identifying means, wherein said identifying means includes a radio frequency (rf) tag and, and wherein said reading means includes an rf receiver, wherein said identifying means includes a bar code, and wherein said reading means includes a bar code reader.

11. The surgical manipulator according to claim 1 wherein said surgical manipulator is a first surgical manipulator, including at least a second surgical manipulator and configured to be a structural mirror image of said first surgical manipulator, said first surgical manipulator being configured for left handed operation and said at least a second surgical manipulator being configured for right handed operation to allow the surgical tools attached to respective end-effectors to be brought into close proximity with each other in a surgical site on a patient.

12. The surgical manipulator according to claim 1 wherein each right-angle drive mechanism includes

a housing and wherein said drive mechanism includes a harmonic drive mounted on said housing and connected to said input pulley for rotation about said input axis;

an output shaft being connected to said output pulley, said output pulley being mounted in said housing for rotation about an output axis, said input and output pulleys being mounted in said housing and positioned with respect to each other such that said input and output axes are perpendicular to, and intersecting with each other;

each bi-directional coupling mechanism for coupling said input pulleys and said output pulleys comprising a cable drive mounted in said housing, said cable drive including,

at least one flexible cable, said input and output pulleys each including at least one cable guide for receiving therein said at least one flexible cable,

idler means for guiding said at least one flexible cable between said input and output pulleys,

wherein when the input pulley rotates in one direction about said input axis, said at least one flexible cable pulls the output pulley and output shaft to rotate in one direction about said output axis, and when the input pulley rotates in the other direction about said input axis, said at least one flexible cable pulls the output pulley and output shaft to rotate in an opposite direction about said output axis.

13. A surgical manipulator, comprising:

a) a base and a first right-angle drive mechanism mounted on said base, a shoulder-roll drive mechanism located in said base for rotating said first right-angle drive mechanism about a shoulder-roll axis,

said first right-angle drive mechanism including a first input pulley and a first output pulley and a first bi-directional coupling mechanism,

a first drive mechanism, having a first rotational drive axis, coupled to said first input pulley for rotating said first input pulley about a first input axis, said first input axis being coincident with said first rotational drive axis, wherein rotation of said first input pulley is translated into rotation of said first output pulley by said first bi-directional coupling mechanism about a shoulder-pitch axis which is perpendicular to, and intersecting with, said first input axis;

b) a robotic lower arm being mounted at one end thereof to said first output pulley so that when said first output pulley is rotated, said robotic lower arm rotates about said shoulder-pitch axis,

a second right-angle drive mechanism mounted in said robotic lower arm, said second right-angle drive mechanism including a second input pulley and a second output pulley and a second bi-directional coupling mechanism,

a second drive mechanism, having a second rotational drive axis, coupled to said second input pulley for rotating said second input pulley about a second input axis, said second input axis being coincident with said second rotational drive axis, wherein rotation of said second input pulley is translated into rotation of said second output pulley by said second bi-directional coupling mechanism about an elbow-pitch axis which is perpendicular to, and intersecting with, said second input axis;

c) a robotic fore arm mounted on said second output pulley of said second right-angle drive mechanism so that when said second output pulley is rotated, said robotic fore arm rotates about said elbow-pitch axis,

a third right-angle drive mechanism mounted in said robotic fore arm, said third right-angle drive mechanism including a third input pulley and a third output pulley and a third bi-directional coupling mechanism,

a third drive mechanism, having a third rotational drive axis, coupled to said third input pulley for rotating said third input pulley about a third input axis, said third input axis being coincident with said third rotational drive axis, wherein rotation of said third input pulley is translated into rotation of said third output pulley by said third bi-directional coupling mechanism about an wrist-pitch axis perpendicular to, and intersecting with, said third input axis;

d) a fourth right-angle drive mechanism mounted on said third output pulley of said third right-angle drive mechanism, said fourth right-angle drive mechanism including a fourth input pulley and a fourth output pulley and a fourth bi-directional coupling mechanism,

a fourth drive mechanism, having a fourth rotational drive axis, coupled to said fourth input pulley for rotating said fourth input pulley about a fourth input axis, said fourth input axis being coincident with said fourth rotational drive axis, wherein rotation of said fourth input pulley is translated into rotation of said fourth output pulley by said fourth bi-directional coupling mechanism about a wrist-yaw axis perpendicular to, and intersecting with, said fourth input axis;

e) a robotic wrist mounted on said fourth output pulley of said fourth right-angle drive mechanism so that when said fourth output pulley is rotated, said robotic wrist rotates about said wrist-yaw axis,

said robotic wrist including an actuation mechanism coupled to a wrist output shaft for rotating said robotic wrist output shaft about a wrist-roll axis; and

f) an end-effector mounted to said wrist output shaft, said end-effector including gripping means for releasibly gripping a surgical tool wherein, when said actuation mechanism is engaged, said end-effector is rotated about said wrist-roll axis.

14. The surgical manipulator according to claim 13 wherein components of said surgical manipulator including said base, said first, second, third and fourth right-angle drive mechanisms, said robotic lower arm, said robotic forearm, said robotic wrist, and said end effector include mechanical quick release mechanisms for quick assembly and disassembly of said surgical manipulator and include quick electrical connections so that when said components are assembled said components are electrically connected.

15. The surgical manipulator according to claim 14 wherein said components of said manipulator are modular components and configured to be quickly removed and replaced with different but similar modular components which are any one or combination of a different size, shape, orientation or sequence of said modular components.

16. The surgical manipulator according to claim 14 wherein said shoulder-roll drive mechanism includes a spur-gear mechanism mounted in said base and including a pinion anti-backlash gear meshed with a driven gear, a motor for rotating said pinion gear which in turn rotates said driven

gear and therefore the first right angle drive mechanism about a shoulder-roll axis, and including a motor brake.

17. The surgical manipulator according to claim 13 wherein said end-effector includes

a main body portion including a frame having an interface configured to be attached to said robotic wrist, a tool-yaw motor mounted on said frame, a tool-actuation motor mounted on said frame,

a tool holder mounted on said frame and being detachable therefrom, said tool holder being configured to hold said surgical tool,

a tool-actuation mechanism mounted on said frame and being detachable therefrom, said tool-actuation mechanism being configured to engage a piston on said surgical tool, said tool-actuation mechanism being coupled to said tool-actuation motor,

and a tool-yaw drive mechanism mounted on said frame and being detachable therefrom, said tool-yaw drive mechanism being coupled to said tool-yaw motor, wherein upon activation of said tool-yaw drive mechanism said surgical tool rotates about said tool-yaw axis and wherein upon activation of said tool-actuation mechanism said piston is linearly retracted or linearly extended with respect to said end-effector thereby activating a tool portion of said surgical tool.

18. The surgical manipulator according to claim 17 wherein said interface includes a base block which interfaces to said robotic wrist, and wherein said end-effector includes a tool-tip force-moment sensor which is a single mechanical linkage between said frame and said base block, and wherein said tool-tip force-moment sensor mounted to said end-effector is configured to sense tool forces and moments at a tip of the surgical tool, and wherein said end-effector includes a tool-actuation force sensor mounted thereon configured to measure actuation forces on a tip of the surgical tool, said surgical manipulator including hand controller means being configured to be operated by a surgeon, and including a communication system coupling said hand controller means to said surgical manipulator for translating movement of said hand controller means to scaled movement of said surgical manipulator, and wherein said communication system coupling said hand controller means to said surgical manipulator is configured to communicate said forces and moments to said hand controller means providing haptic feedback to a surgeon.

19. The surgical manipulator according to claim 18 wherein said tool-actuation motor is a linear actuator having an output shaft which moves up and down along a major axis of the linear actuator and at a distal end portion of said output shaft an actuator bar is connected at a first end

portion thereof, said actuator bar having a second end portion supported by a vertical guide rod and including an interface which couples to said tool-actuation mechanism, wherein said actuator bar transmits vertical motion of the output shaft to the tool-actuation mechanism which is mounted at the second end of the bar such that said vertical motion provides a tool-actuation axis of motion for the end-effector, and wherein said tool-actuation mechanism includes a pair of pivoting fingers pivotally mounted to a support member with matched end portions configured to engage and hold a portion of a piston on the surgical tool.

20. The surgical manipulator according to claim 17 wherein said tool-yaw mechanism includes a frame on which is mounted a pair of outer idler pulleys, a middle idler pulley and a drive pulley, including a toothed belt being routed on said outer idler pulleys, said middle idler pulley and said drive pulley, said toothed belt being configured to engage a toothed pulley on said surgical tool, on two opposite ends of a diameter of said toothed pulley, and wherein bi-directional rotation of the toothed belt driven by the drive pulley, converts tangential forces to rotary motion of said surgical tool, and wherein said frame has an open front-framed architecture and a toothed belt routing configuration on said outer idler pulleys and said middle idler pulley configured to allow the surgical tool to be ejected/replaced from the open front of the end-effector, and wherein said

frame includes sheet metal flexures supporting said outer idler pulleys so that said outer idler pulleys can be passively spread out enough to completely disengage the surgical tool thereby eliminating any frictional effects, and wherein when engaged with said surgical tool, the metal flexures allow a constant preload to the toothed belt during tool yawing but also manually collapse, when no surgical tool is present, for facilitating toothed belt replacement.

21. The surgical manipulator according to claim 20 wherein said tool holder includes a support body having an elongate channel having a size suitable to receive therein a cylindrical tool body of said surgical tool, and wherein said cylindrical tool body is made of a magnetic material, and wherein said support body includes at least one magnet embedded therein adjacent to said elongate channel for magnetically restraining said magnetic cylindrical tool body, wherein said support body is made of a material which allows the surgical tool to rotate with minimal friction within said support body when rotated by said tool-yaw mechanism, wherein said surgical tool includes flanges on the body of the surgical tool for locating and constraining the surgical tool axially within said channel in said support body due to a close axial fit with the support body; wherein said tool holder includes a tool release mechanism including a pair of tool-ejection wings pivotally mounted on said support body with a portion of each wing located

in said channel behind said tool body and configured such that once said tool-ejection wings are compressed on outer surfaces thereof, said tool-ejection wings pivot in a scissor action, to strip the tool body away from said at least one magnet responsively ejecting said tool from said tool holder.

22. The surgical manipulator according to claim 21 including a tool changer mechanism comprising a tool storage and tool change tray, said tool change tray including a support structure for holding the surgical tools and including engaging features arrayed on said tool change tray configured to simultaneously spread said outer pulleys apart, engage the pivoting fingers located on said tool-actuation mechanism, and engage said ejection-wings located on said tool holder thereby releasing said surgical tool from said end-effector, wherein said support structure for holding the surgical tools and said engaging features arrayed on said tool change tray include first and second pair of pins fixed in vertical arrangement to said tool tray being positioned and spaced apart such that they engage said outer pulleys on said tool-yaw mechanism and spread said outer pulleys apart when said end-effector engages said passive tool changer when picking up a surgical tool or releasing a surgical tool, and including a third pair of pins positioned on said tool change tray with respect to said first and second pairs of pins such that the third pair of pins engage pivoting fingers

located on said tool-actuation mechanism responsively pivoting said fingers out of engagement with said piston on said surgical tool, said tool change tray including mating ejection latches mounted on the tool tray which line up with said ejection-wings located on said tool holder, which mating ejection latches include a spring-loaded pliers-like mechanism to provide a cushioned tool-ejection; wherein each surgical tool includes identifying means mounted thereon, and wherein said tool changer includes a tool-identification sensor for said identifying means, wherein said identifying means includes a radio frequency (rf) tag and, and wherein said reading means includes an rf receiver, wherein said identifying means includes a bar code, and wherein said reading means includes a bar code reader.

23. The surgical manipulator according to claim 13 wherein said surgical manipulator is a first surgical manipulator, including at least a second surgical manipulators and configured to be structural mirror images of each other, said first surgical manipulator being configured for left handed operation and said at least a second surgical manipulator being configured for right handed operation to allow the surgical tools attached to respective end-effectors to be brought into close proximity with each other in a surgical site on a patient.

24. The surgical manipulator according to claim 13 wherein each right-angle drive mechanism includes

a housing and wherein said drive mechanism includes a harmonic drive mounted on said housing and connected to said input pulley for rotation about said input axis;

an output shaft being connected to said output pulley, said output pulley being mounted in said housing for rotation about an output axis, said input and output pulleys being mounted in said housing and positioned with respect to each other such that said input and output axes are perpendicular to, and intersecting with each other;

each bi-directional coupling mechanism for coupling said input pulleys and said output pulleys including

a cable drive mounted in said housing, said cable drive including,

at least one flexible cable, said input and output pulleys each including at least one cable guide for receiving therein said at least one flexible cable,

idler means for guiding said at least one flexible cable between said input and output pulleys,

wherein when the input pulley rotates in one direction about said input axis, said at least one flexible cable pulls the output pulley and output shaft to rotate in one direction about said output axis, and when the input pulley rotates in an opposite direction about said input axis, said at least one flexible cable pulls the output pulley and output shaft to rotate in an opposite direction about said output axis.

25. A surgical manipulator system, comprising;

a) at least first and second surgical manipulators according to claim 11; b) left and right hand controllers with the right hand controller being associated with the first surgical manipulator and the left hand controller being associated with the second surgical manipulator, said at least first and second hand controllers being configured to be operated by a surgeon;

c) communication system coupling said left and right hand controllers to said at least first and second surgical manipulators for translating movement of said left and right hand controllers to scaled movement of said at least first and second surgical manipulators; and

d) a vision system focused on a work area including an area of a patient to be operated on and focused on the end-effectors and associated surgical tools attached to said at least two surgical manipulators, said vision system including display means for displaying images of said work area to a surgeon.

26. The surgical system according to claim 25 configured for teleoperation wherein said surgeon is located remotely from a patient.

27. The surgical system according to claim 26 wherein said end-effector includes a tool-tip force-moment sensor mounted to said end-effector and configured to sense tool forces and moments at a tip of the surgical tool, and wherein said end-effector includes a tool-actuation force sensor mounted thereon configured to measure actuation forces on a tip of the surgical tool, and wherein said communication system coupling said left and right hand controllers to said at least first and second surgical manipulators is configured to communicate said forces and moments to said left and right handed controllers providing haptic feedback to a surgeon.

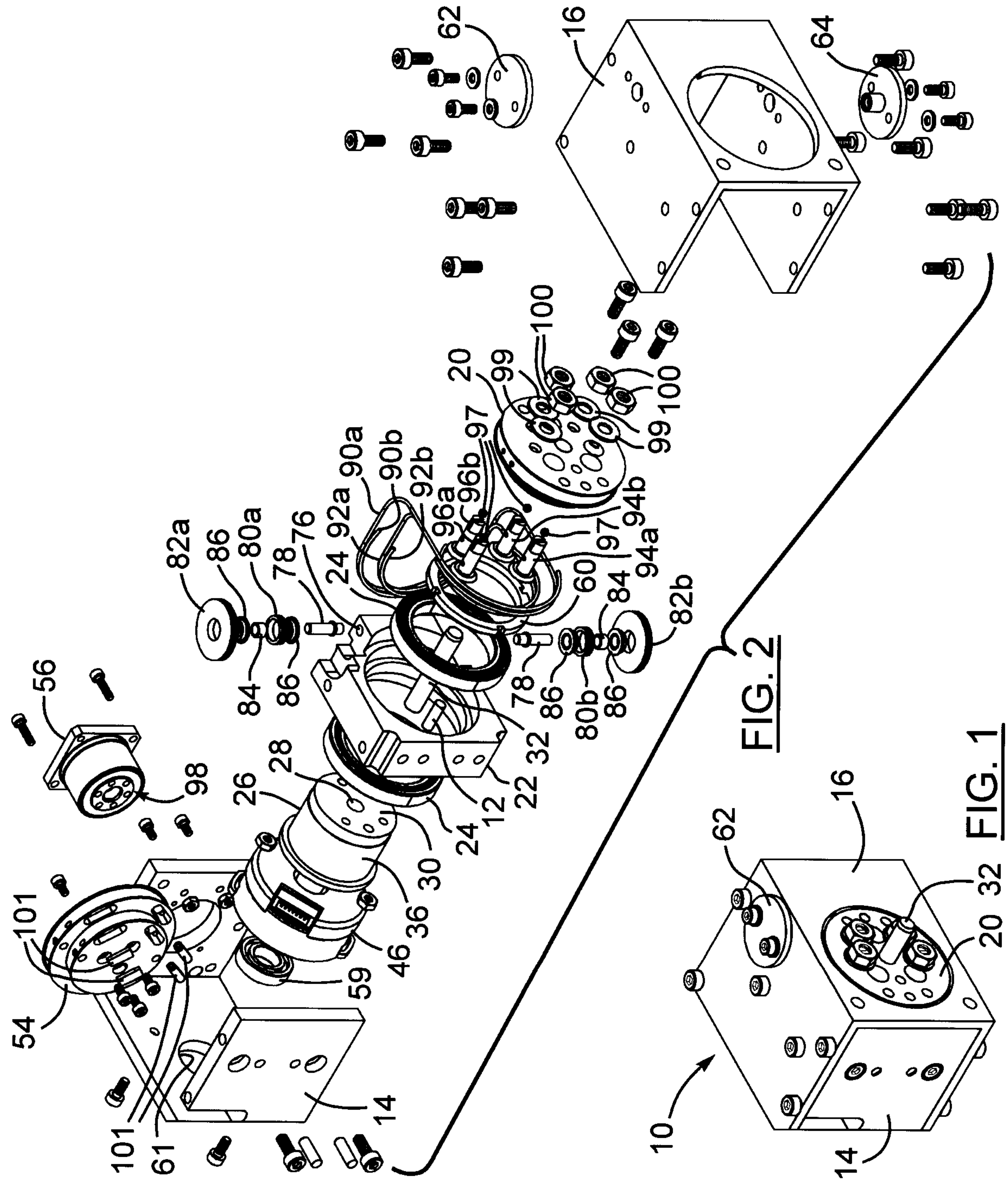
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FIG. 2

FIG. 1

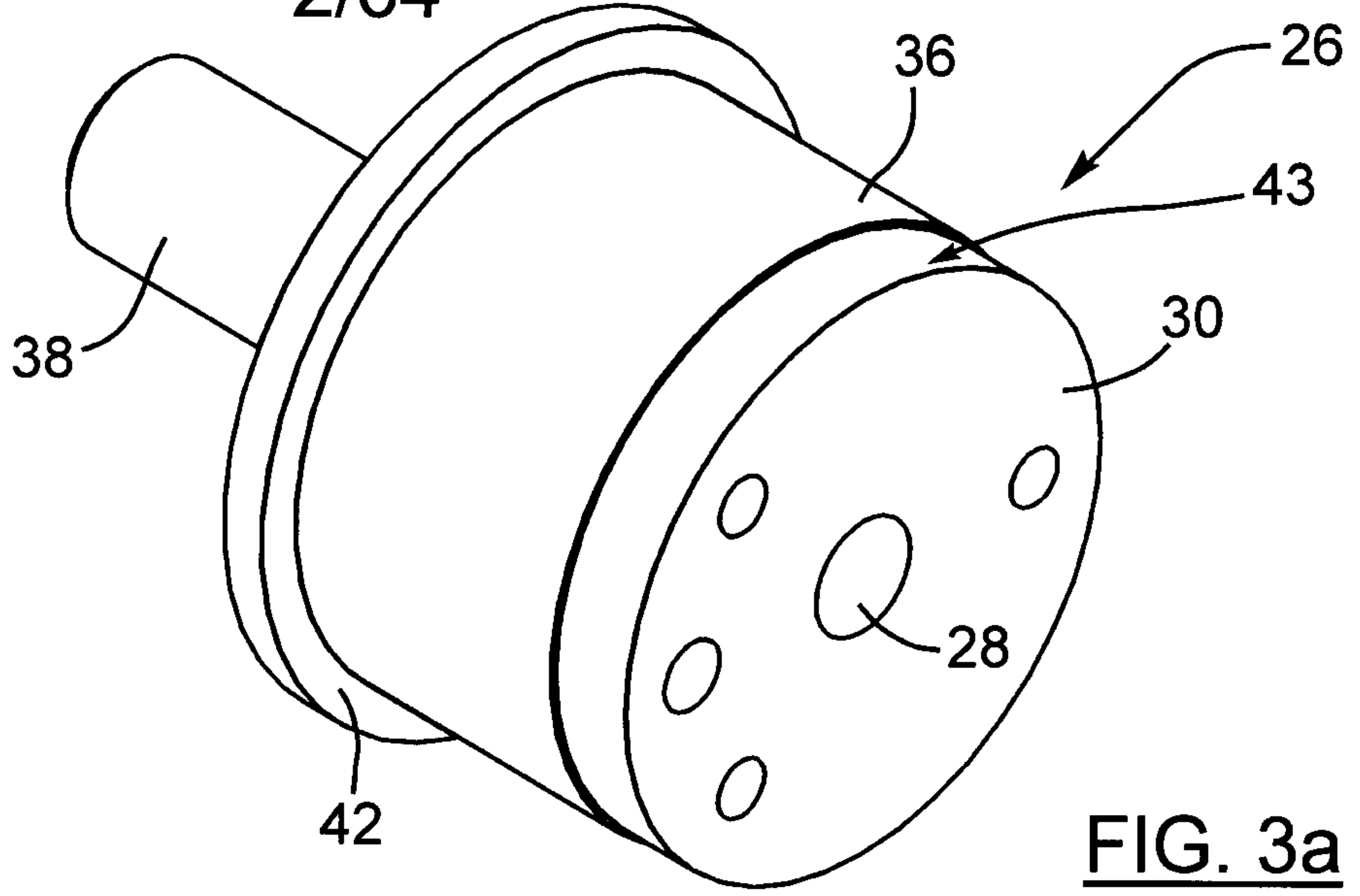

FIG. 3a

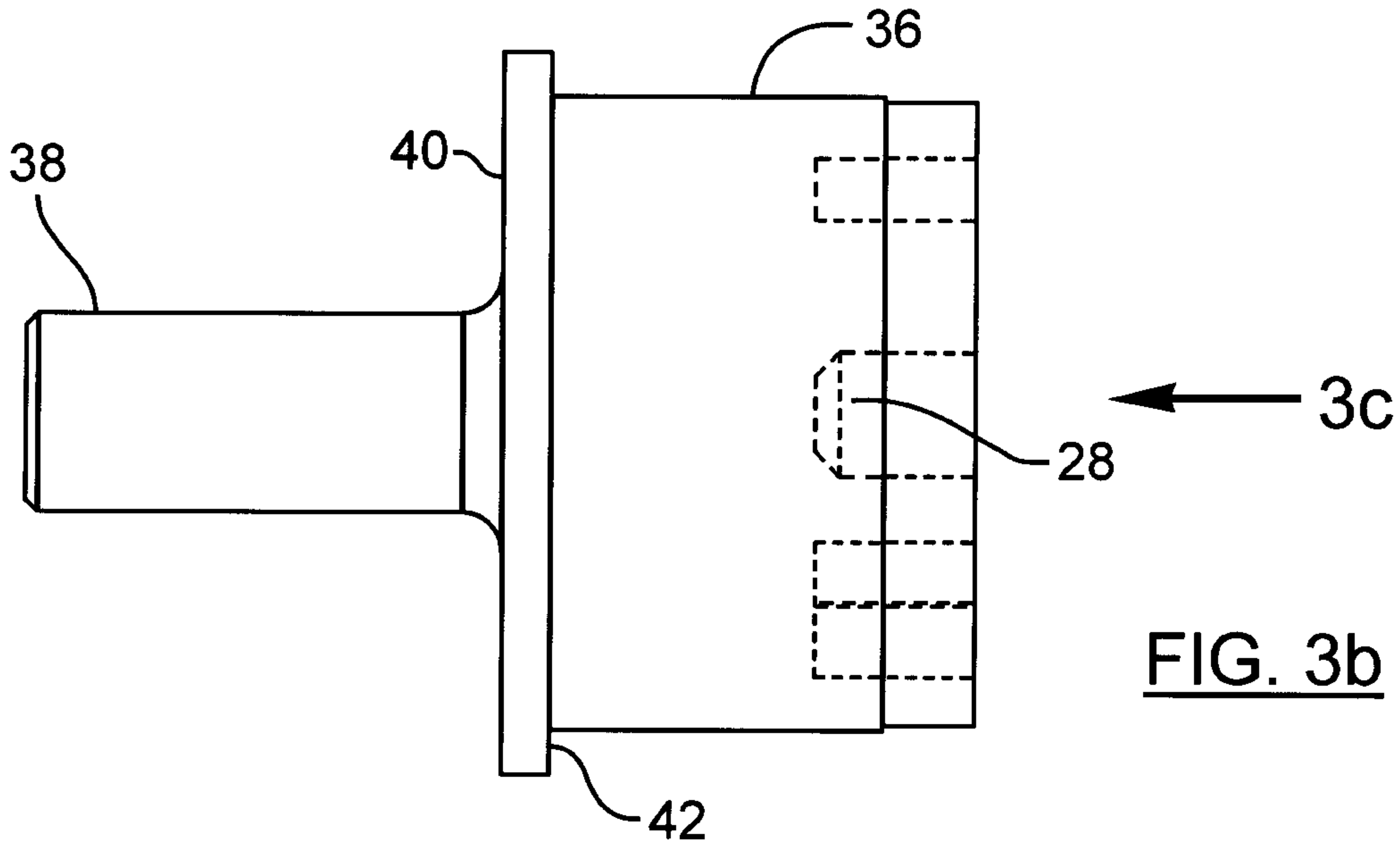

FIG. 3b

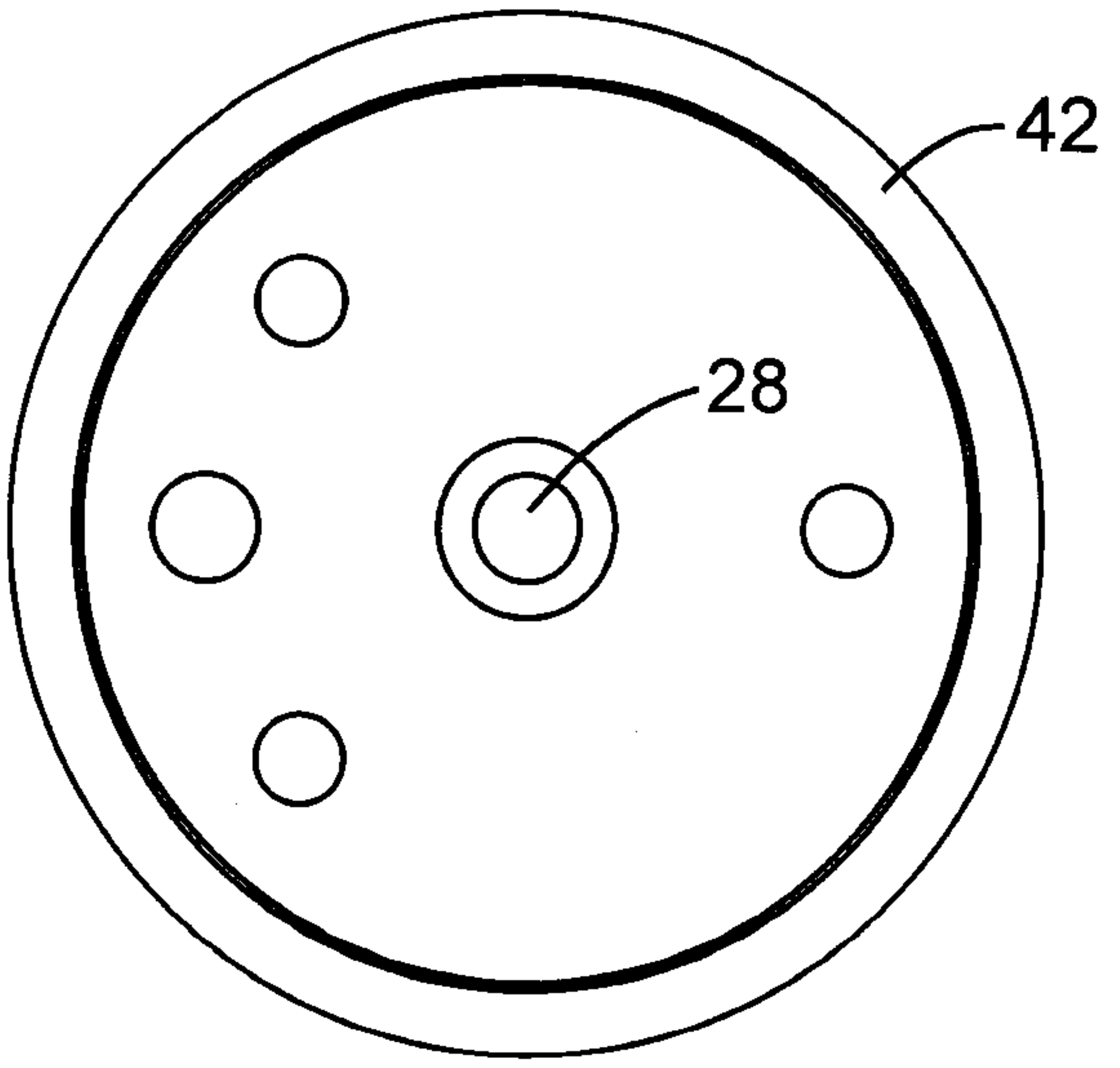

FIG. 3c

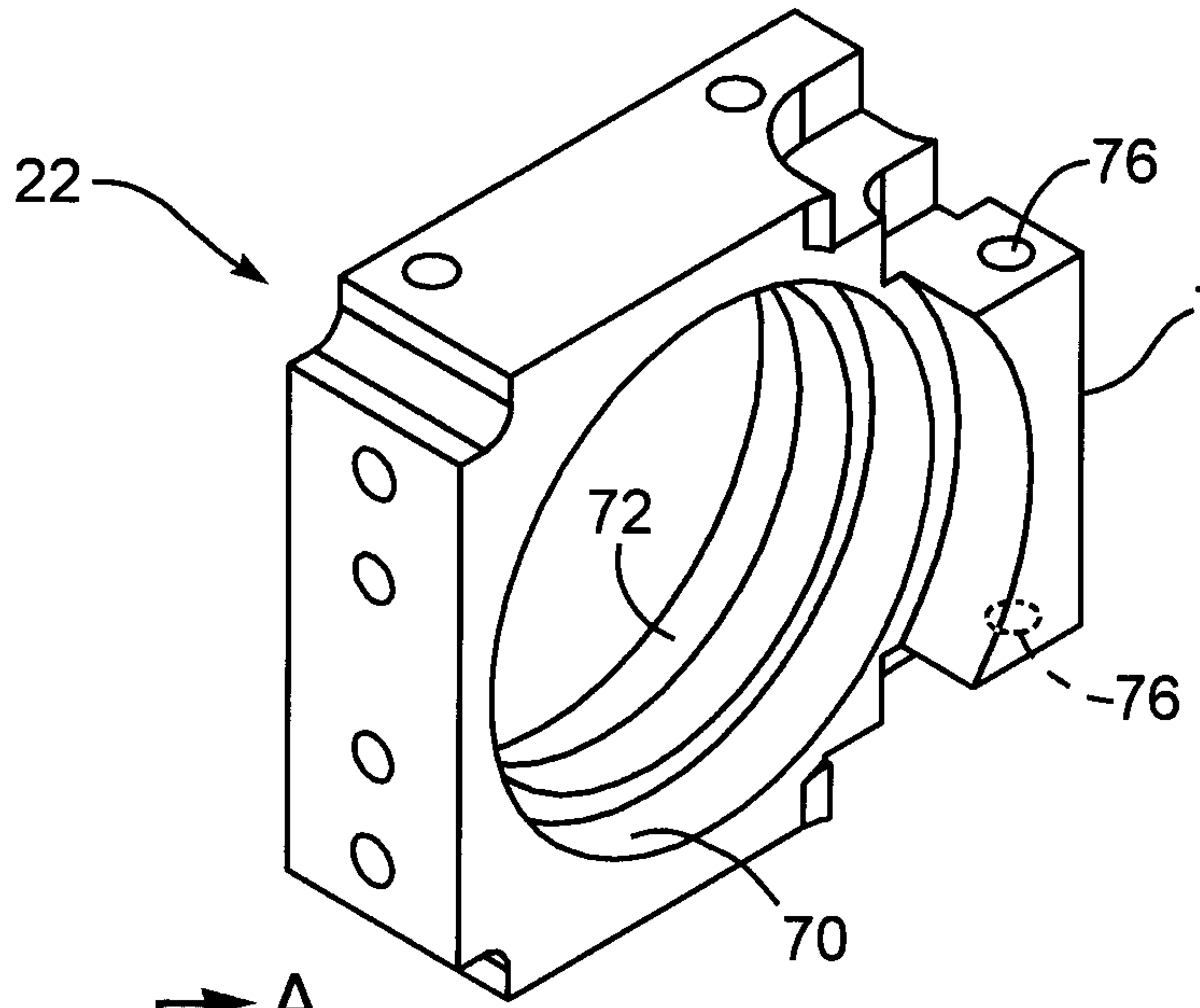

FIG. 4a

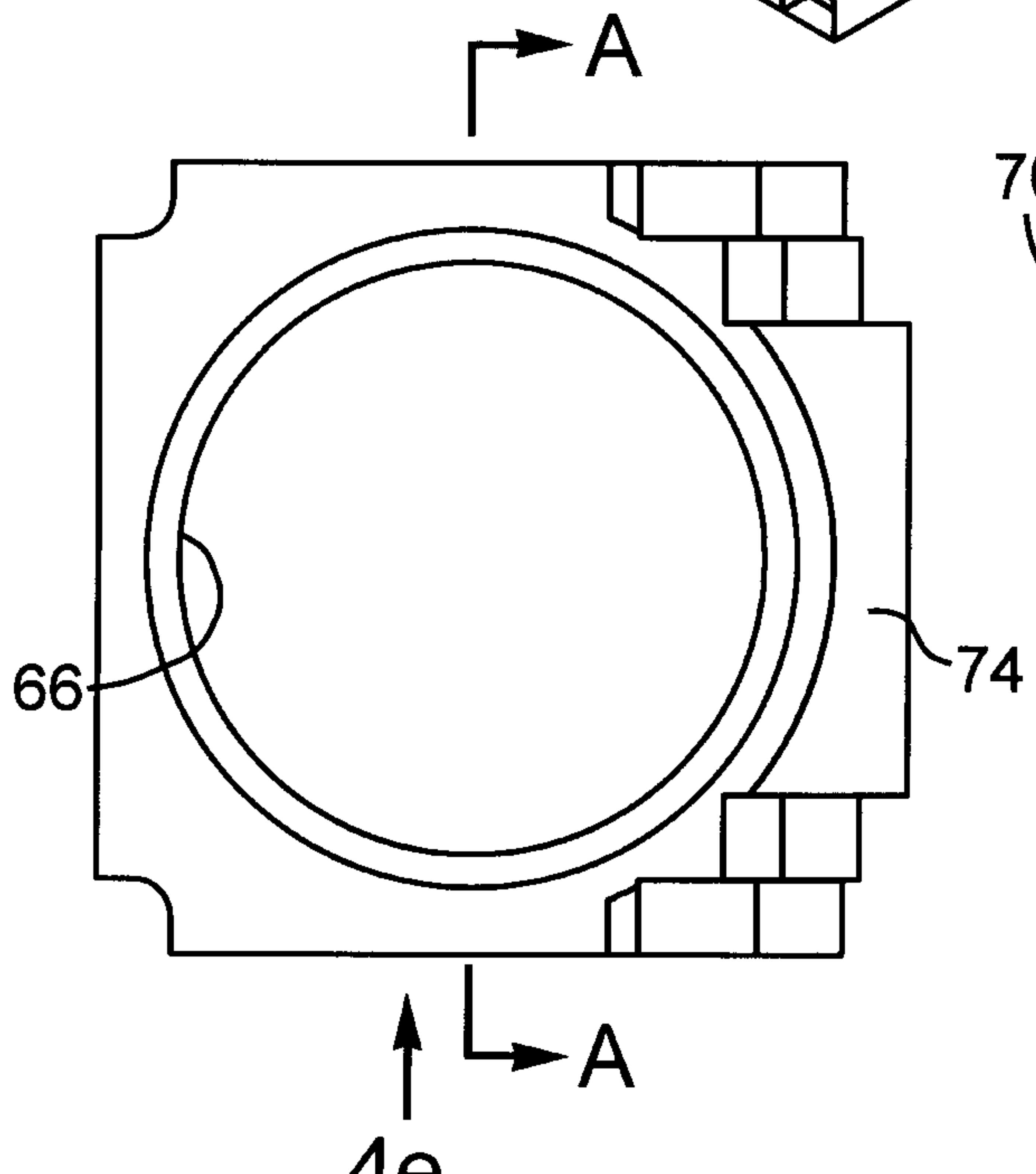

FIG. 4b

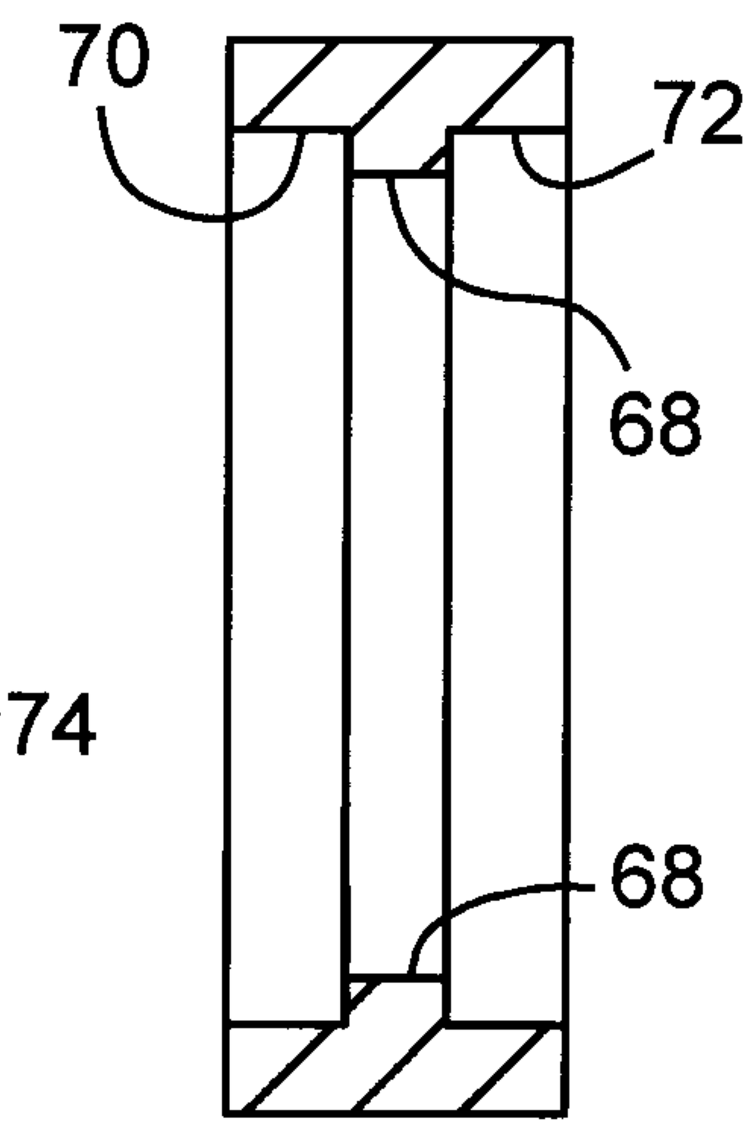

FIG. 4c

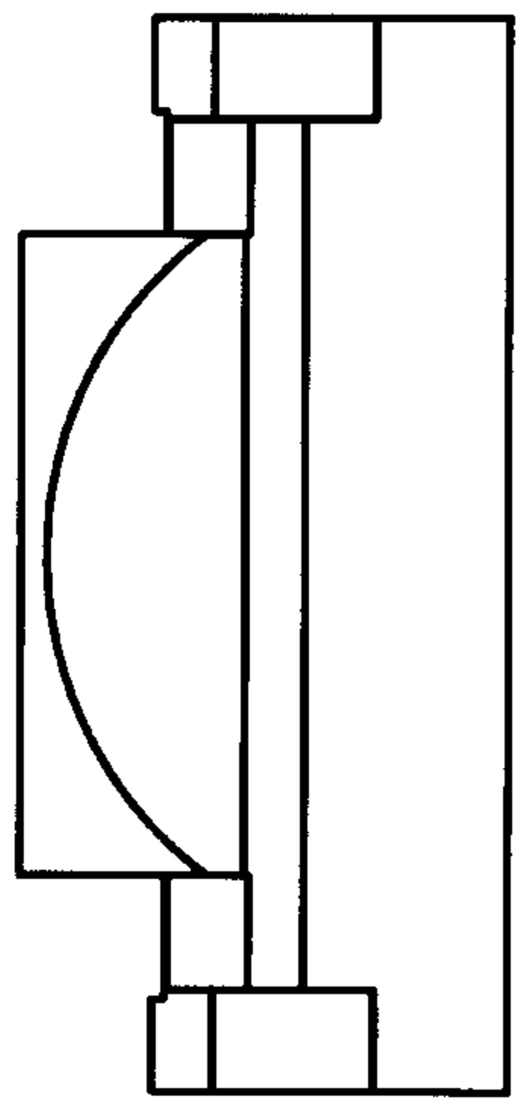

FIG. 4d

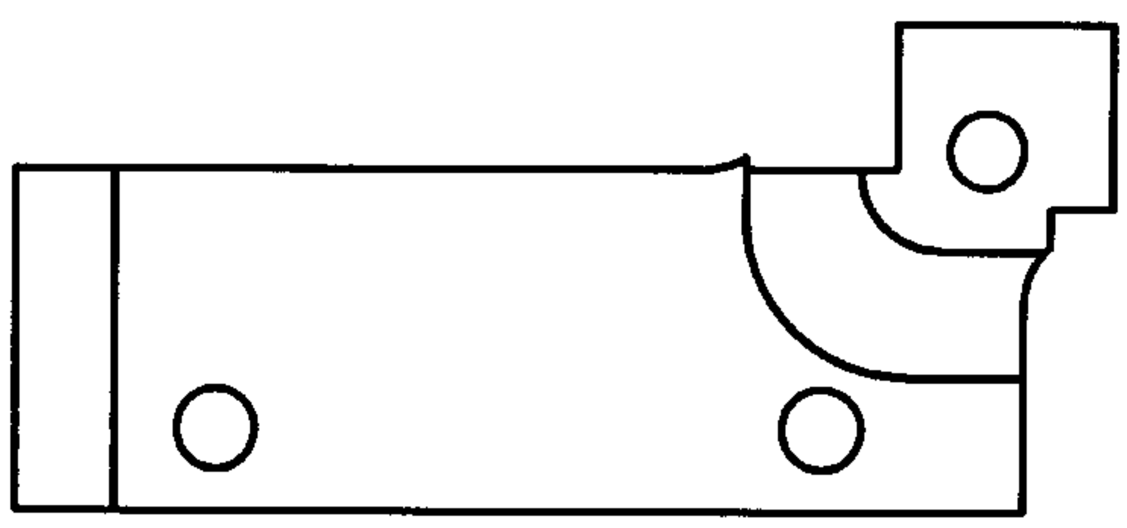

FIG. 4e

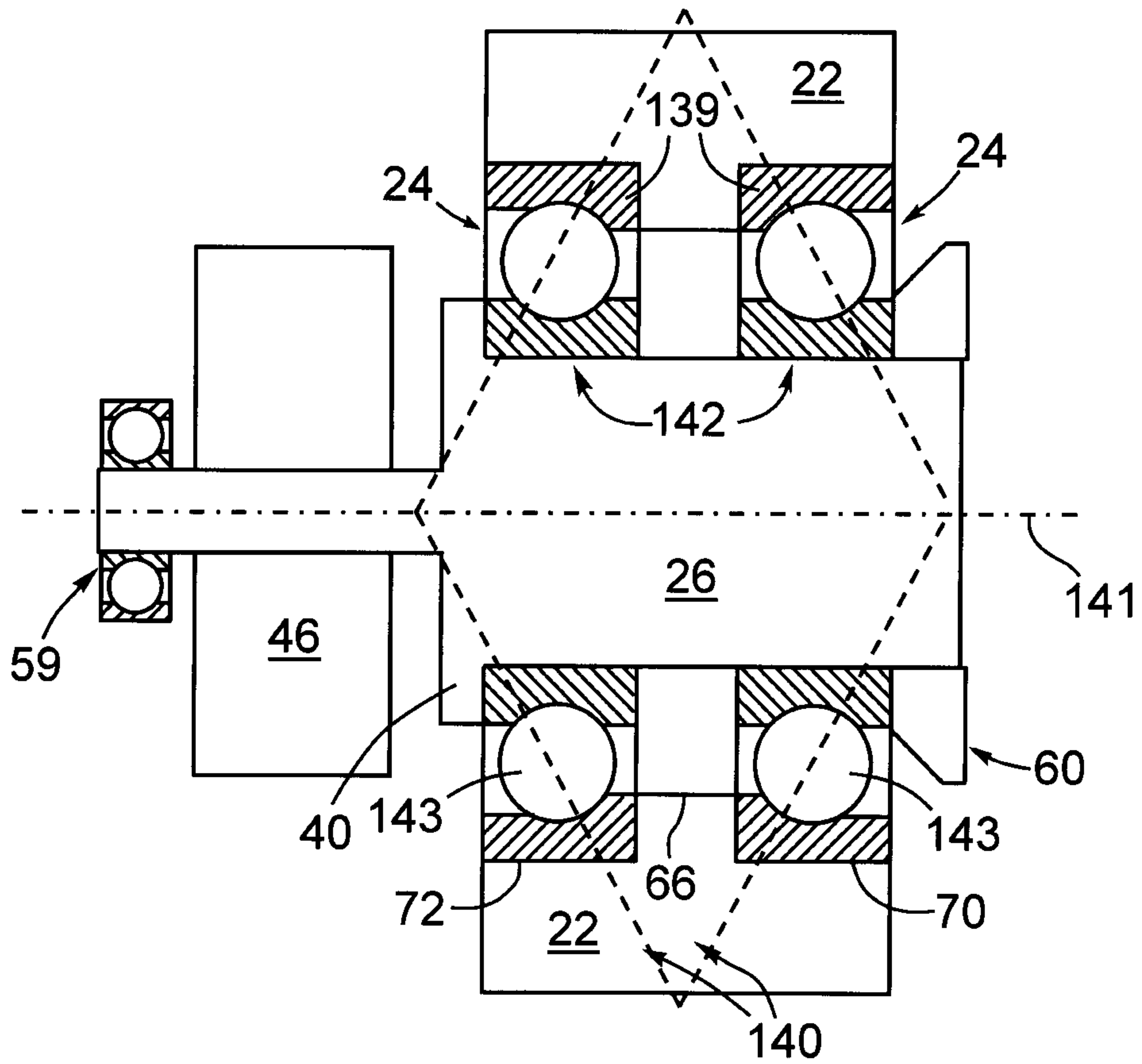

FIG. 4f

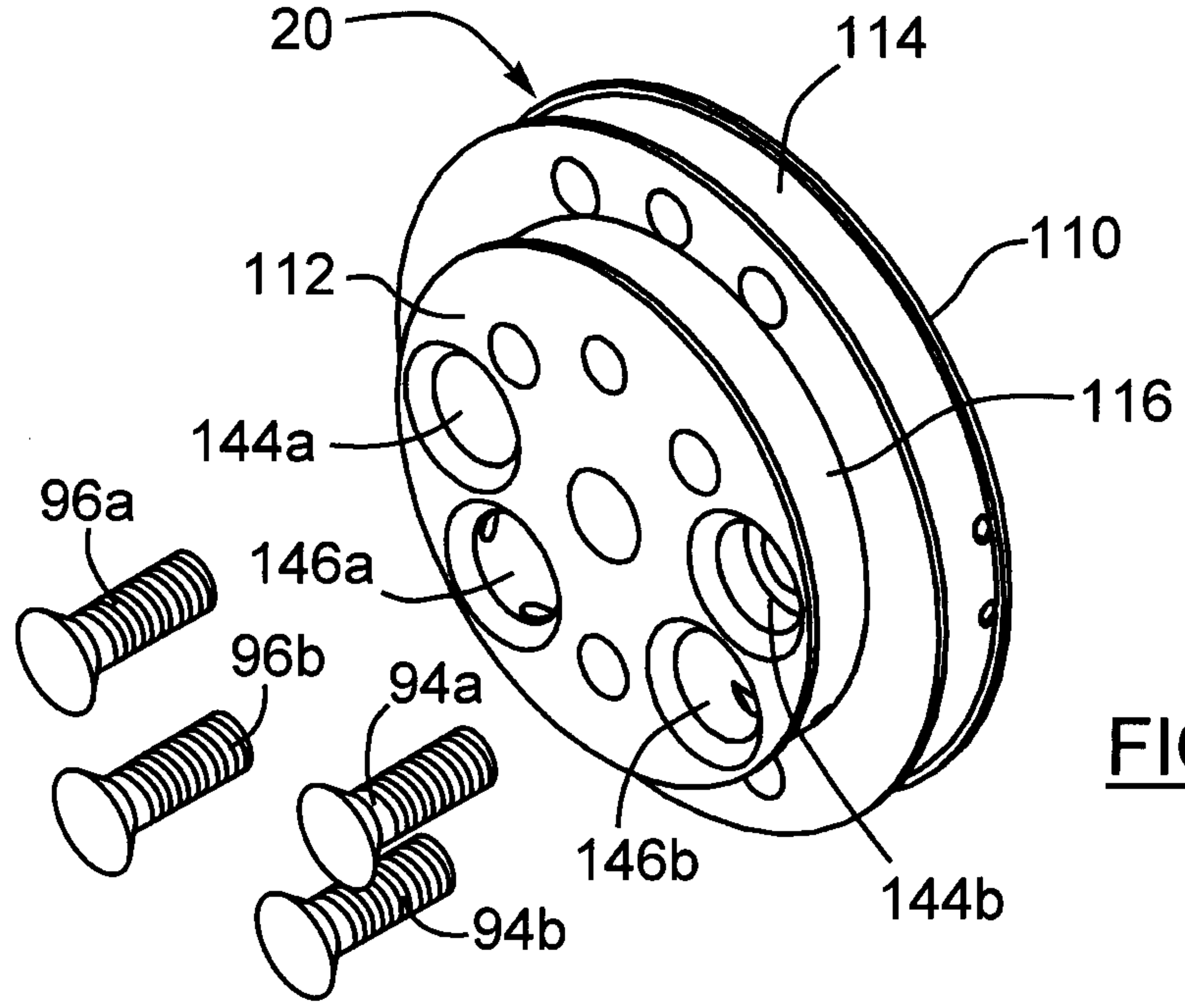

FIG. 5a

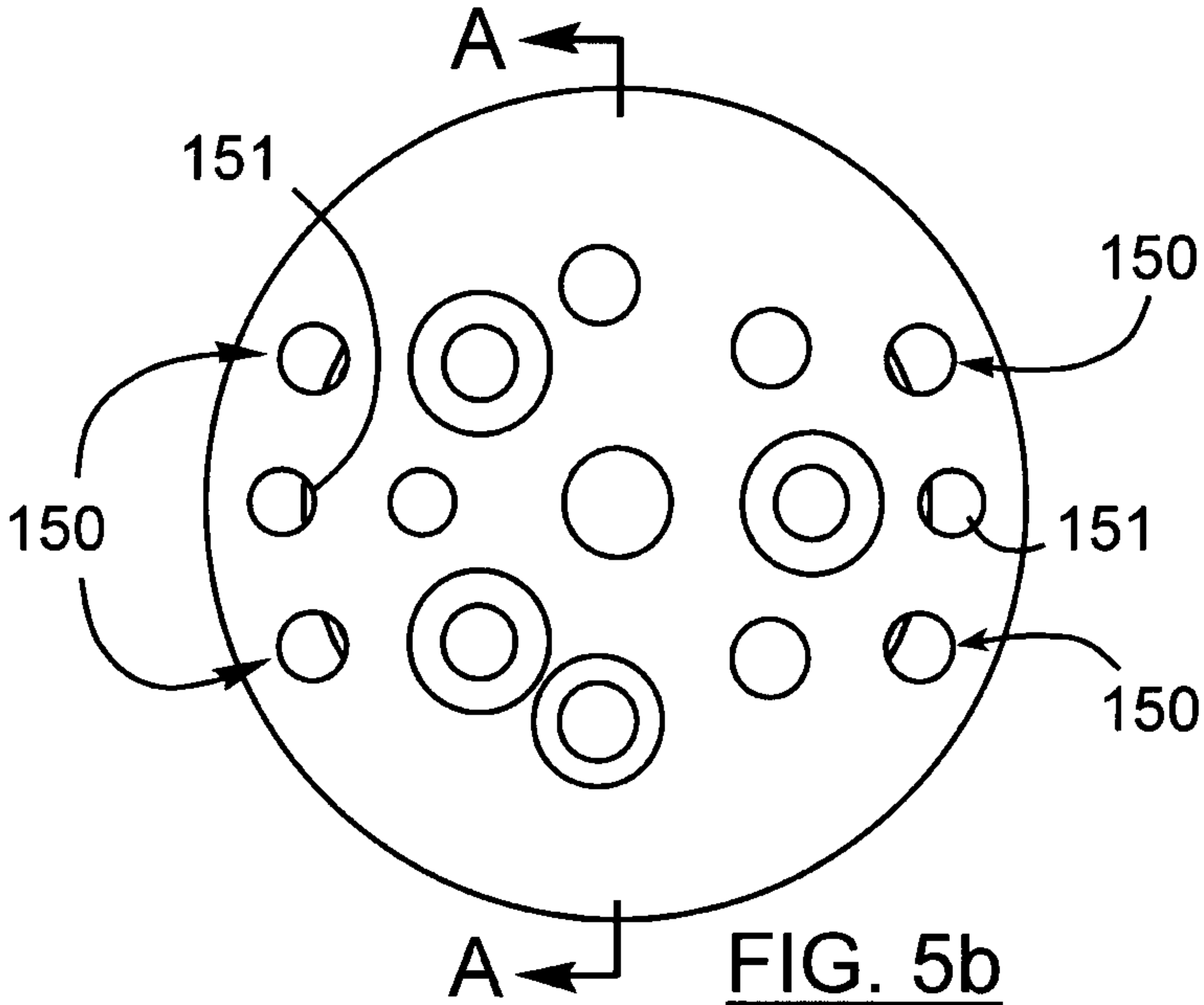

FIG. 5b

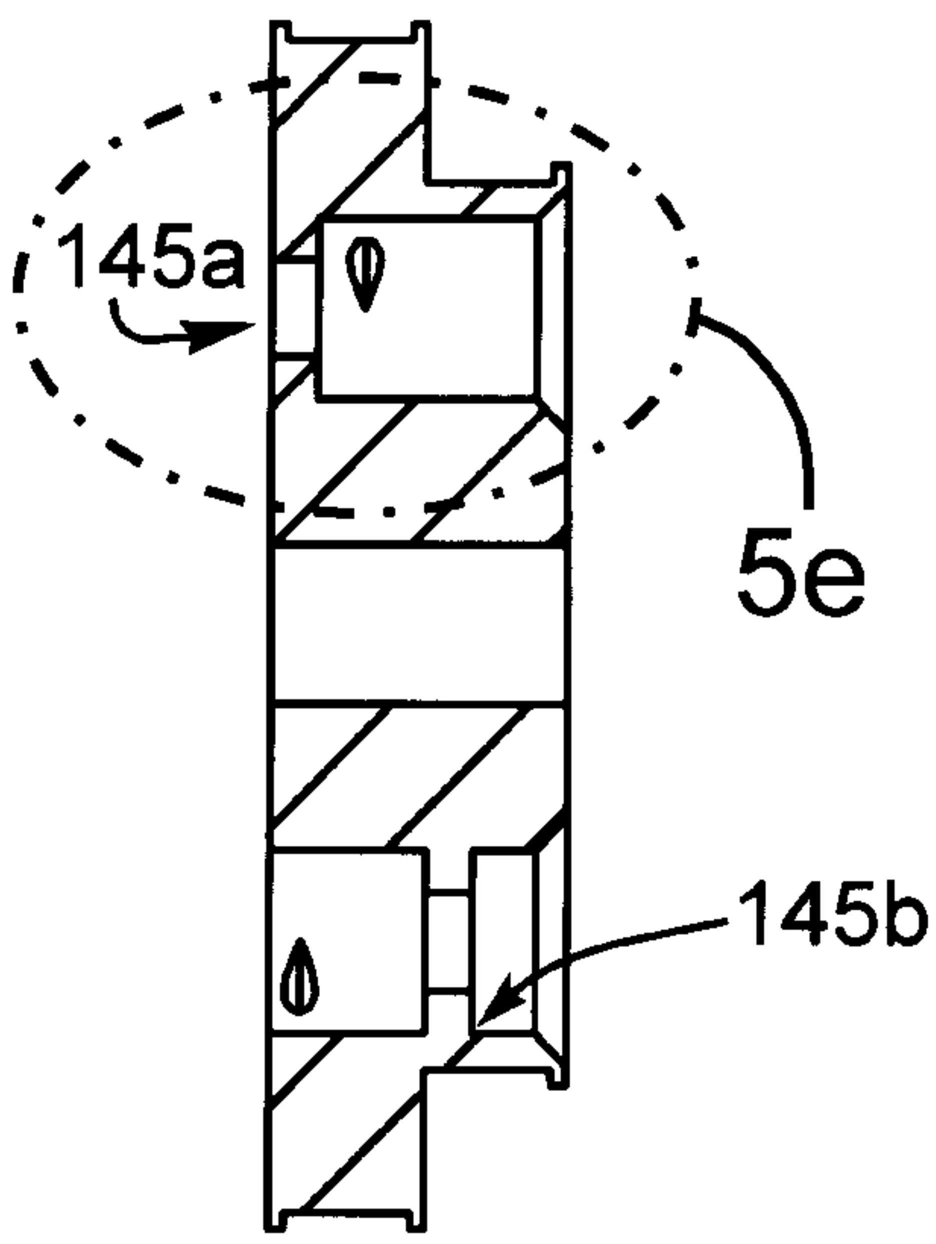

FIG. 5d

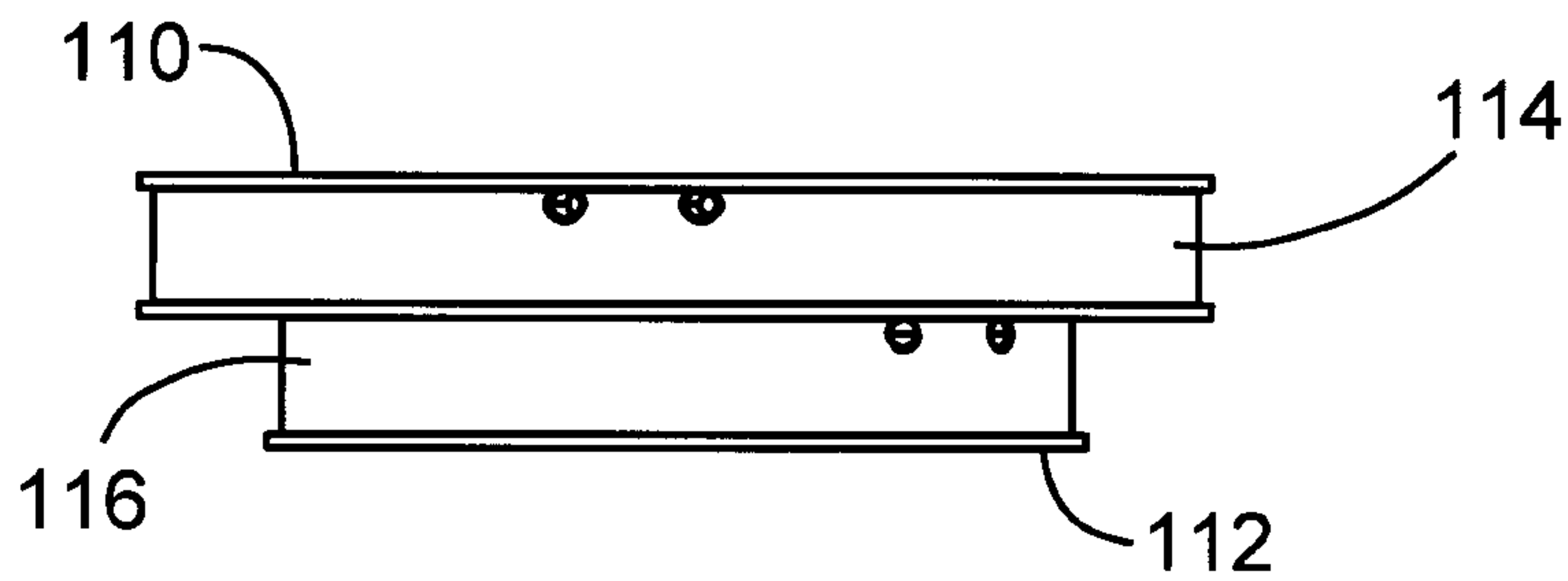

FIG. 5c

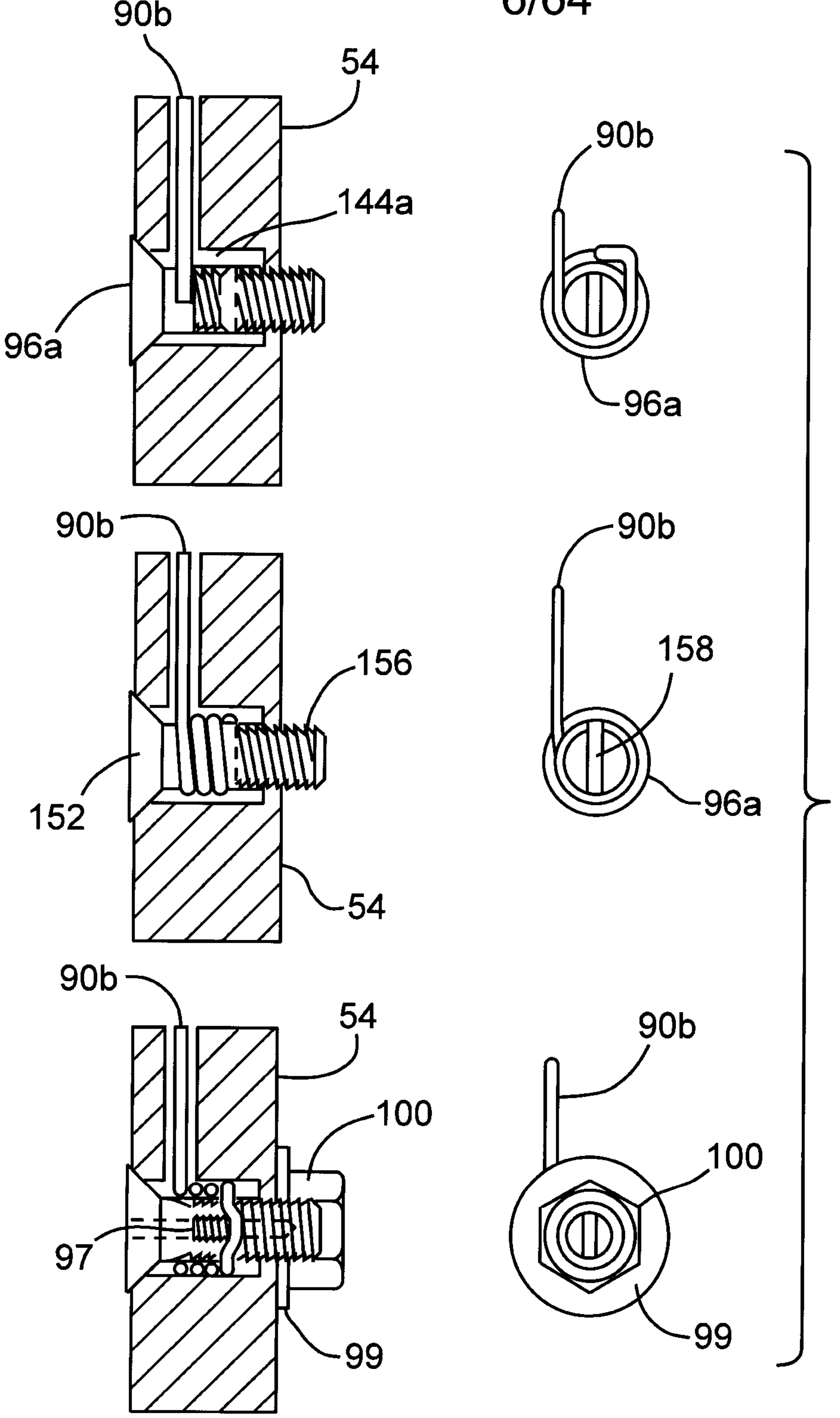
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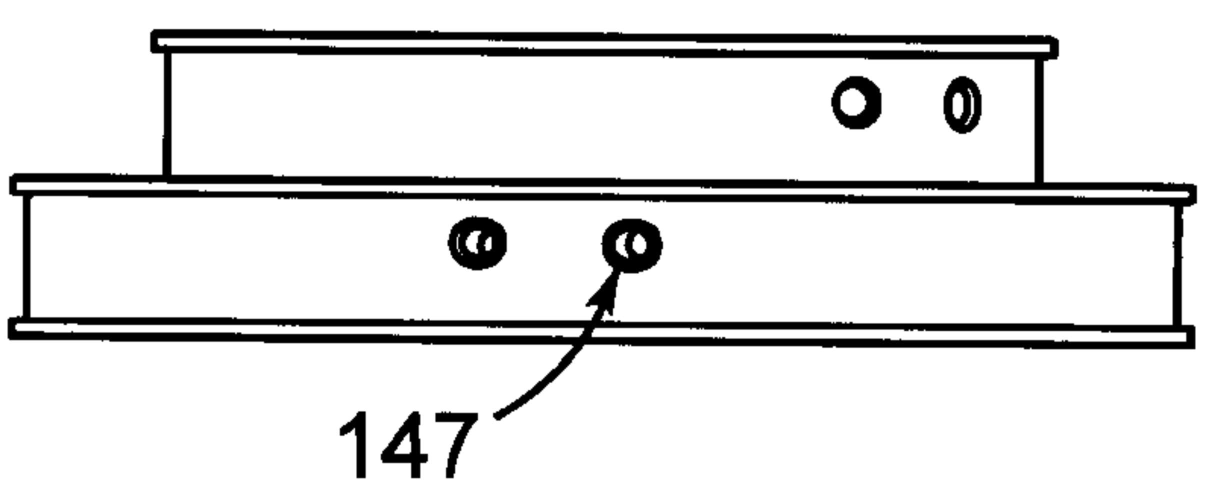
FIG. 5e

FIG. 5f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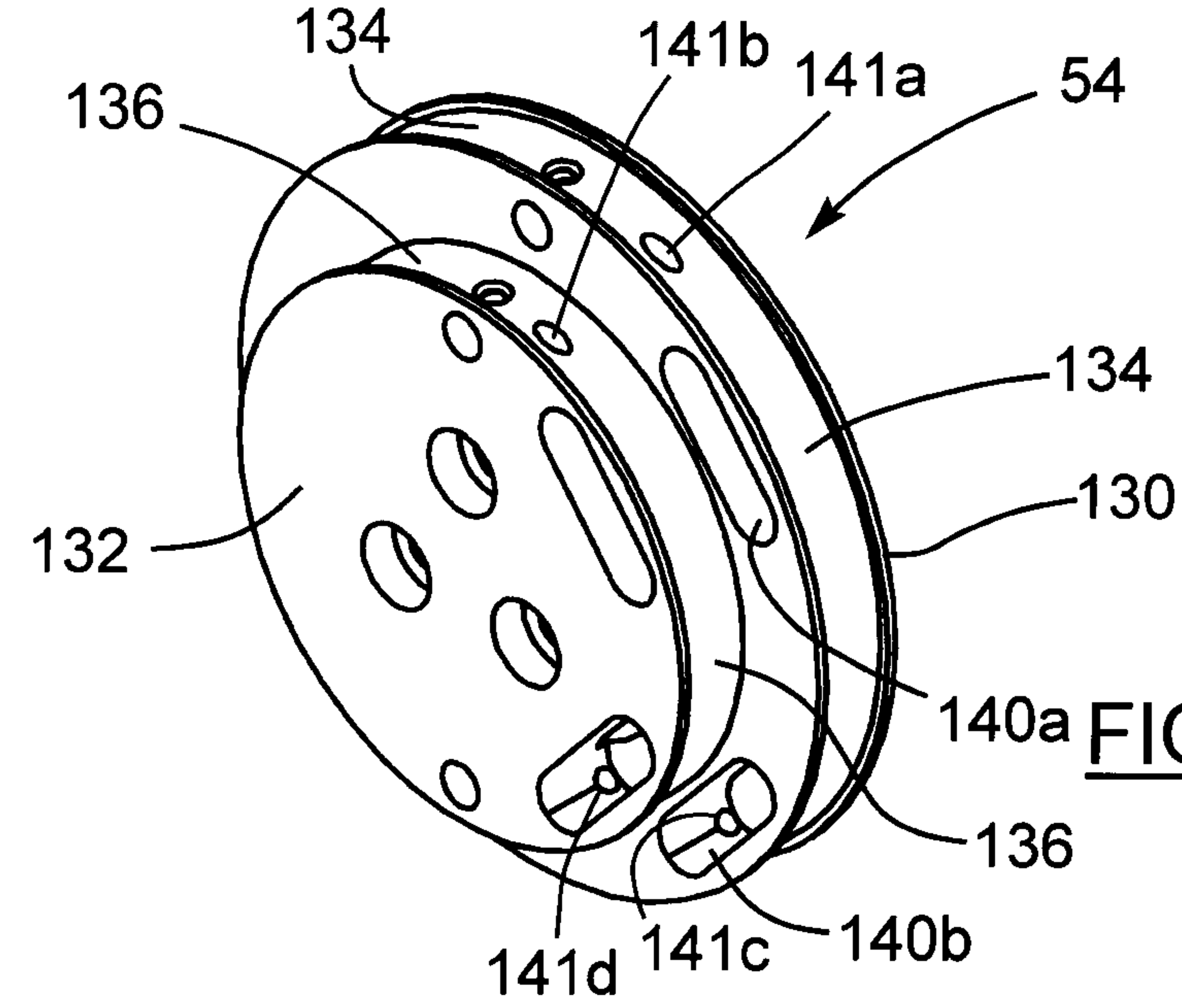

FIG. 6a

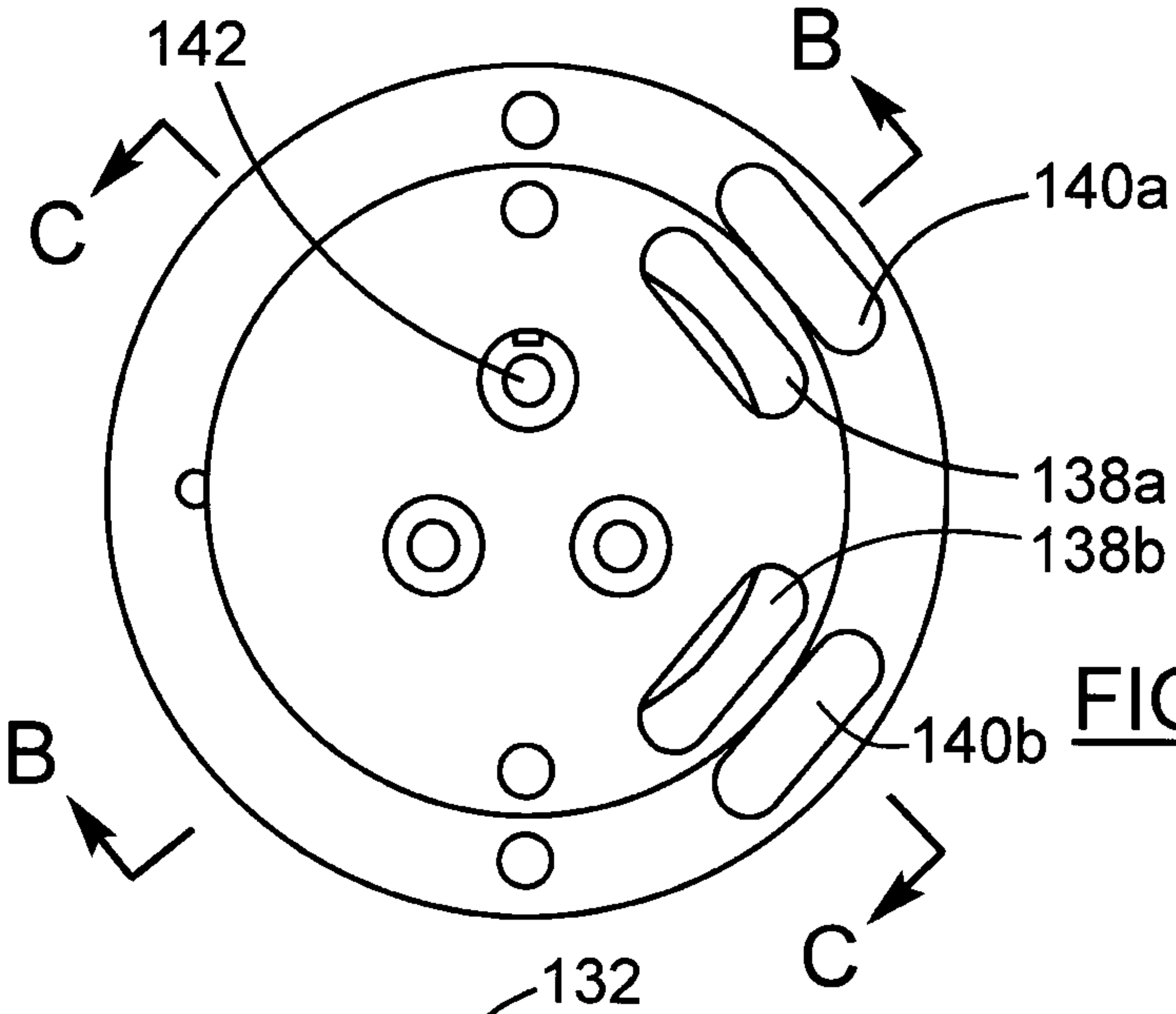

FIG. 6b

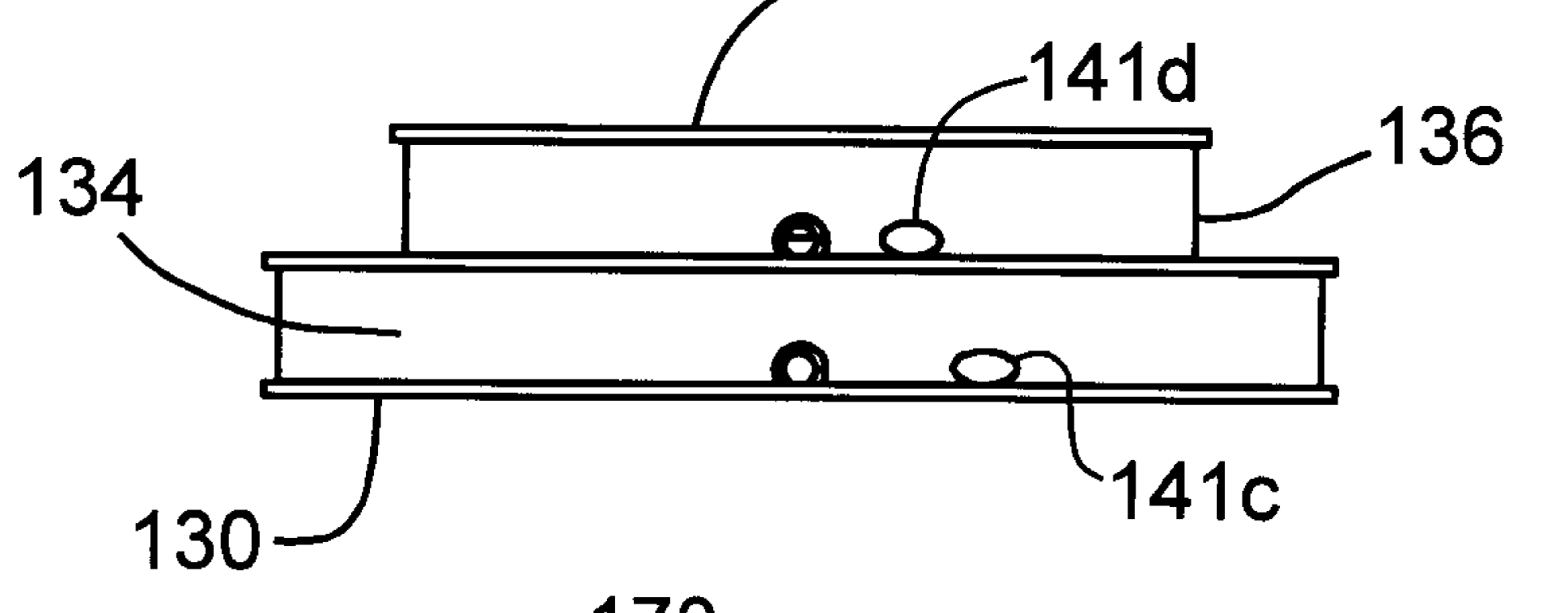

FIG. 6c

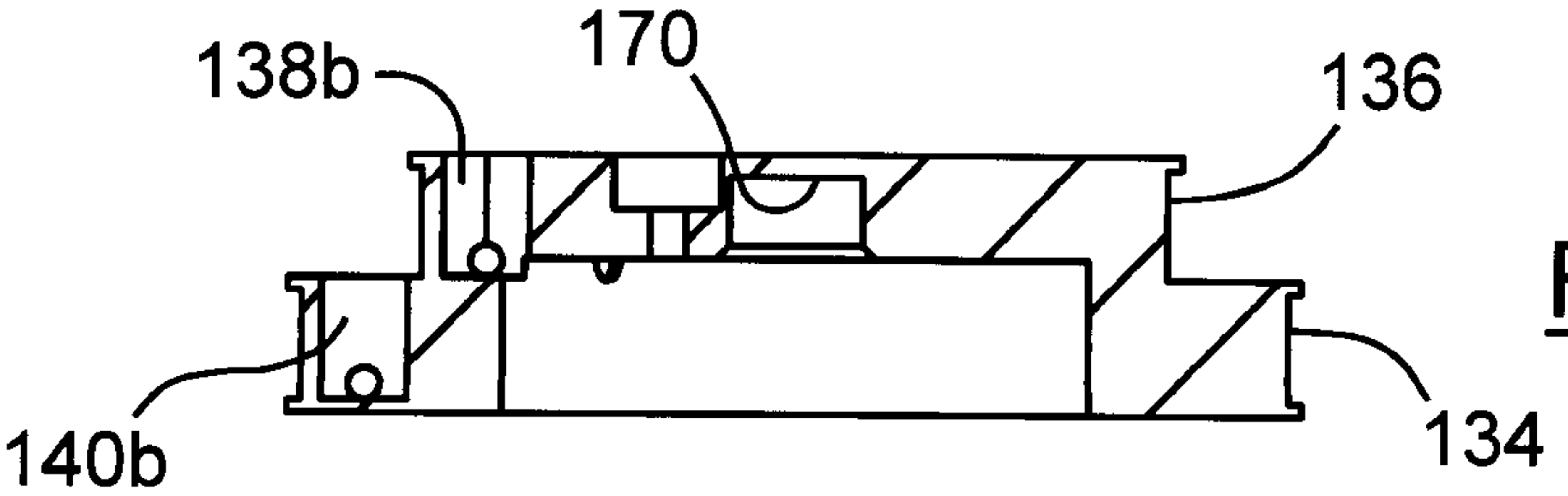

FIG. 6d

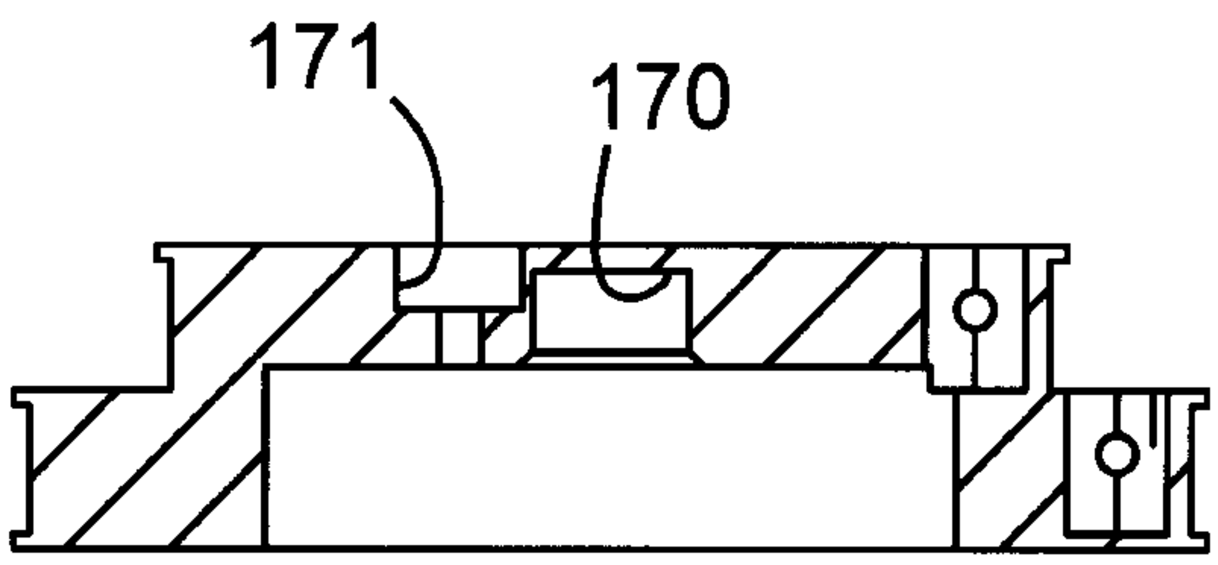

FIG. 6e

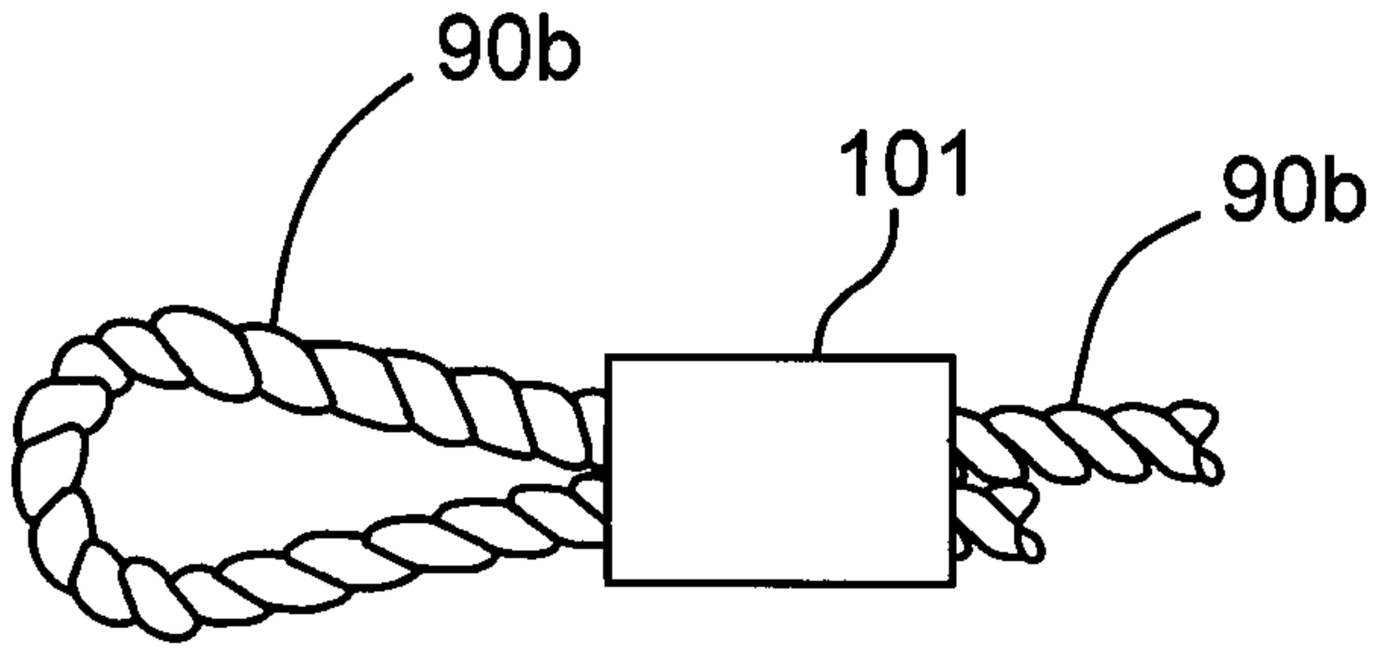

FIG. 6f

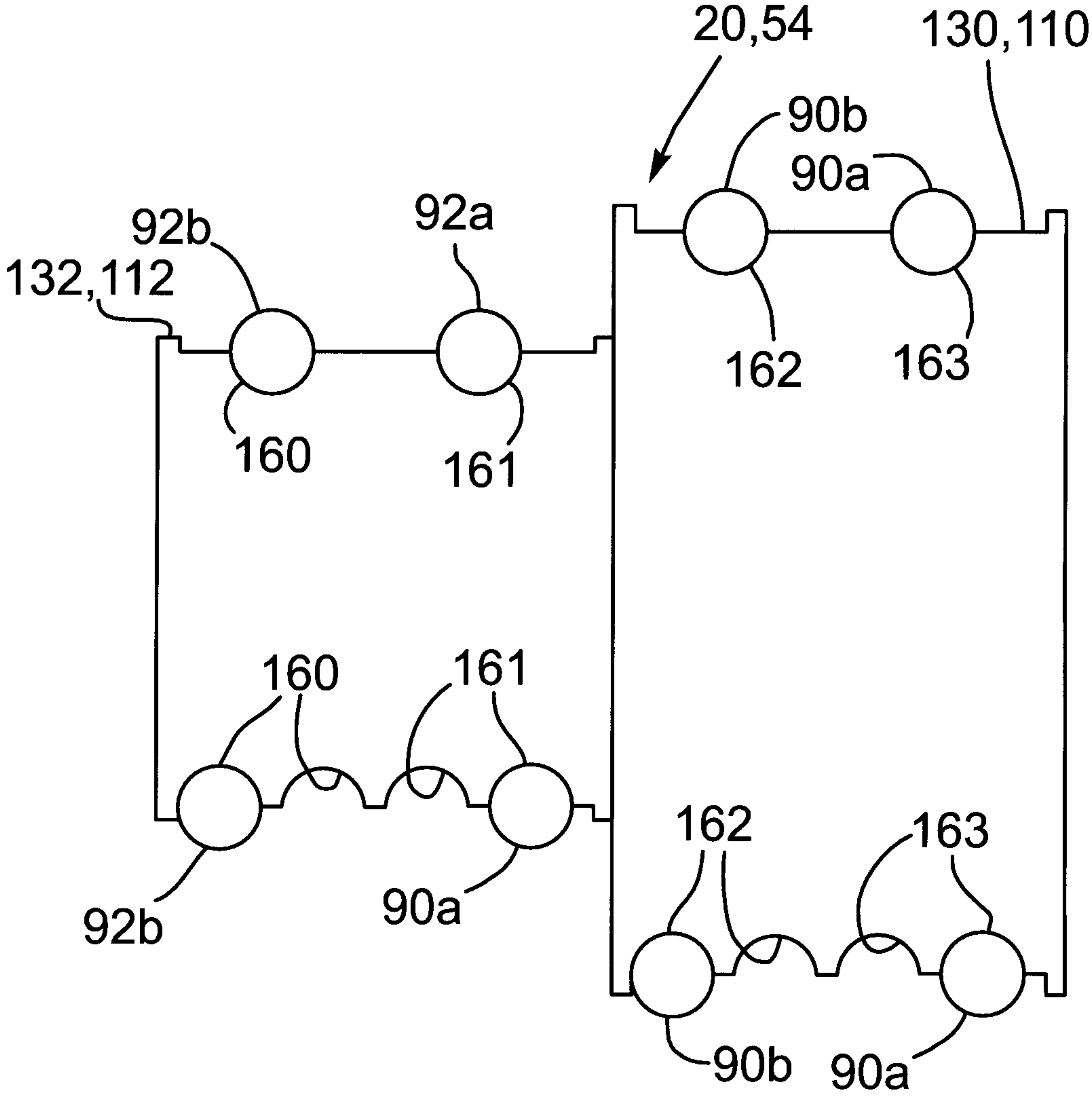
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FIG. 6g

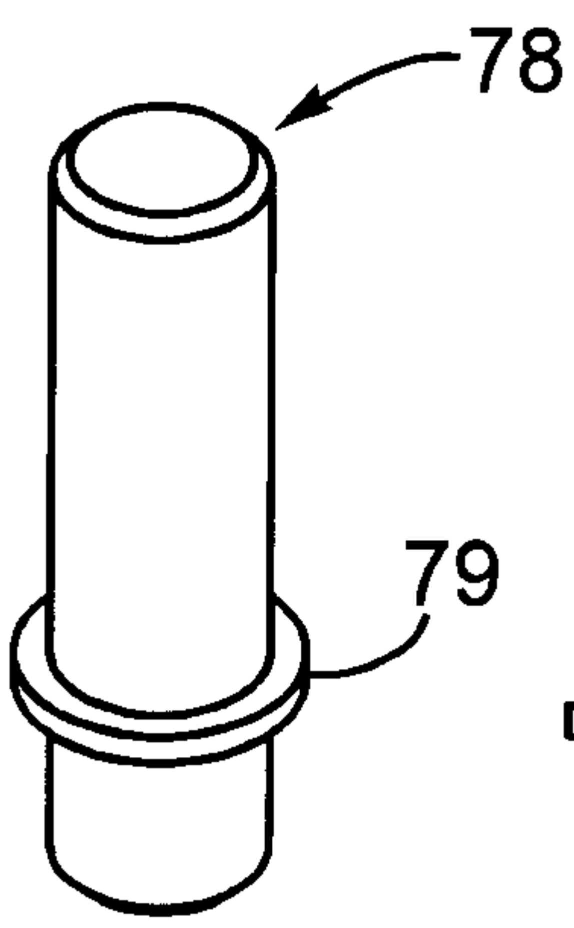


FIG. 7a

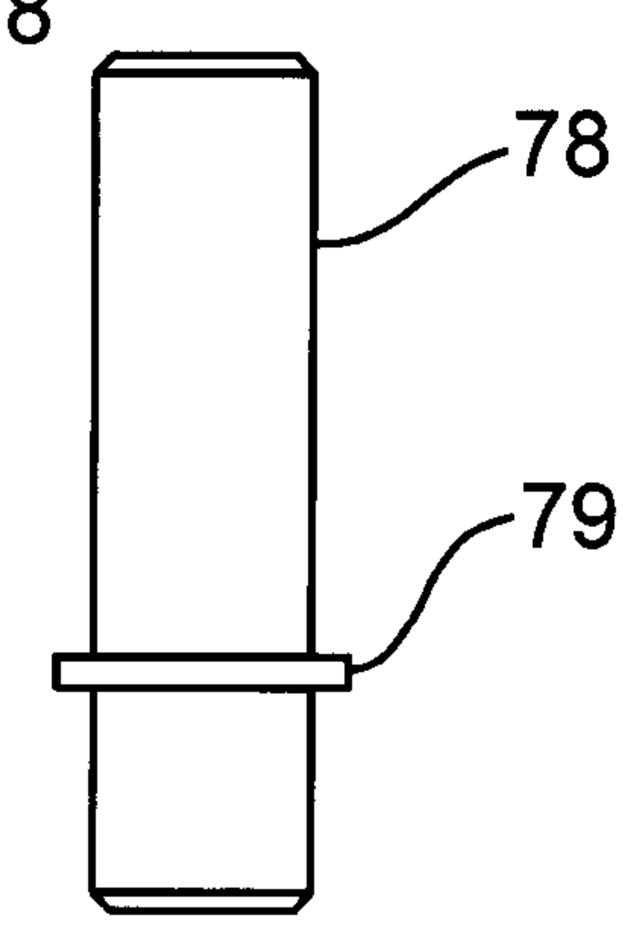


FIG. 7b

DIRECTION OF MOTION		INPUT TERMINATION	CABLE	IDLER	OUTPUT TERMINATION
AUX	CW	140b	90a	82a	94a
MAIN		138b	92a	80a	94b
AUX	CCW	140a	90b	82b	96a
MAIN		138a	92b	80b	96b

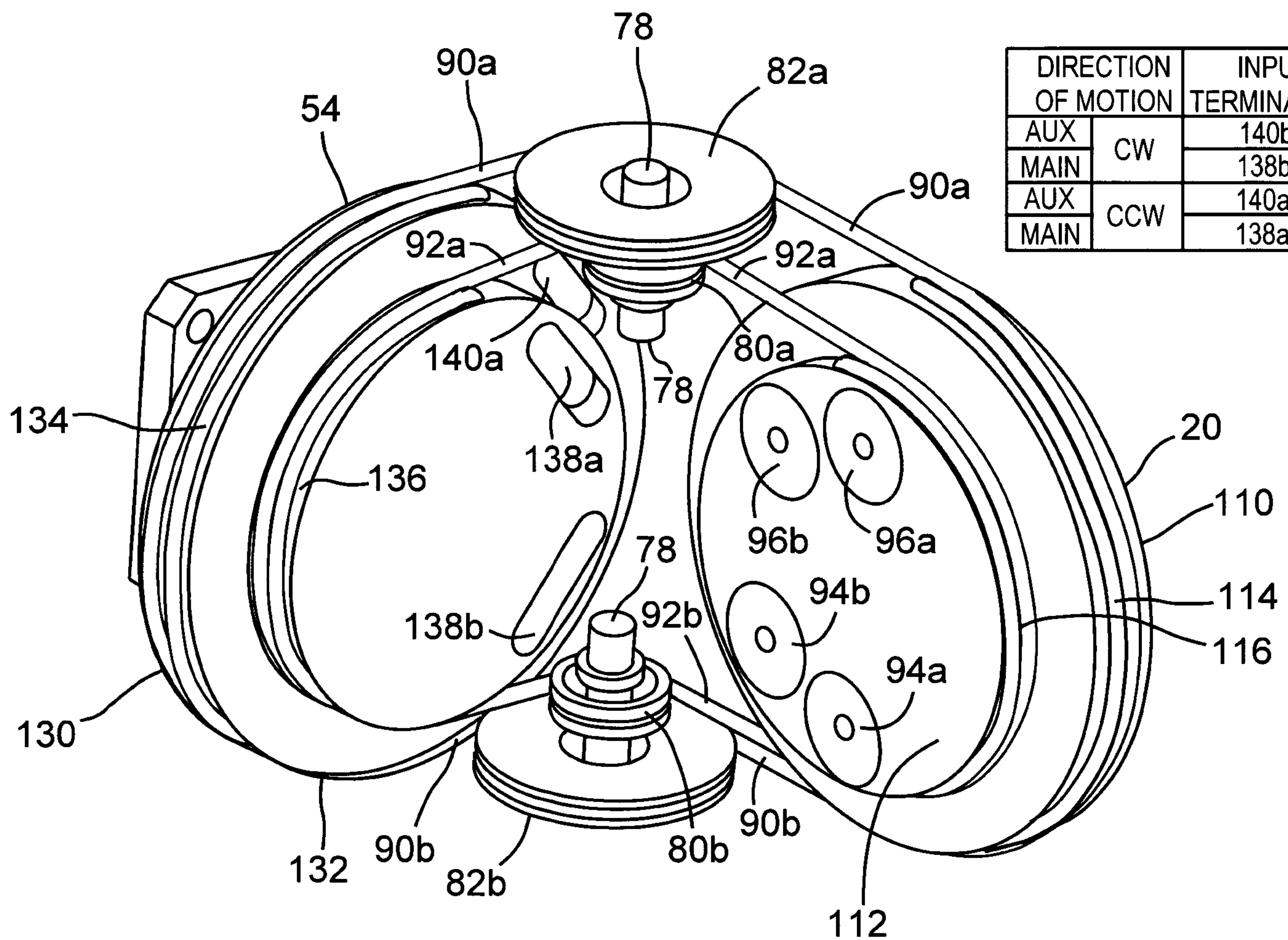


FIG. 8

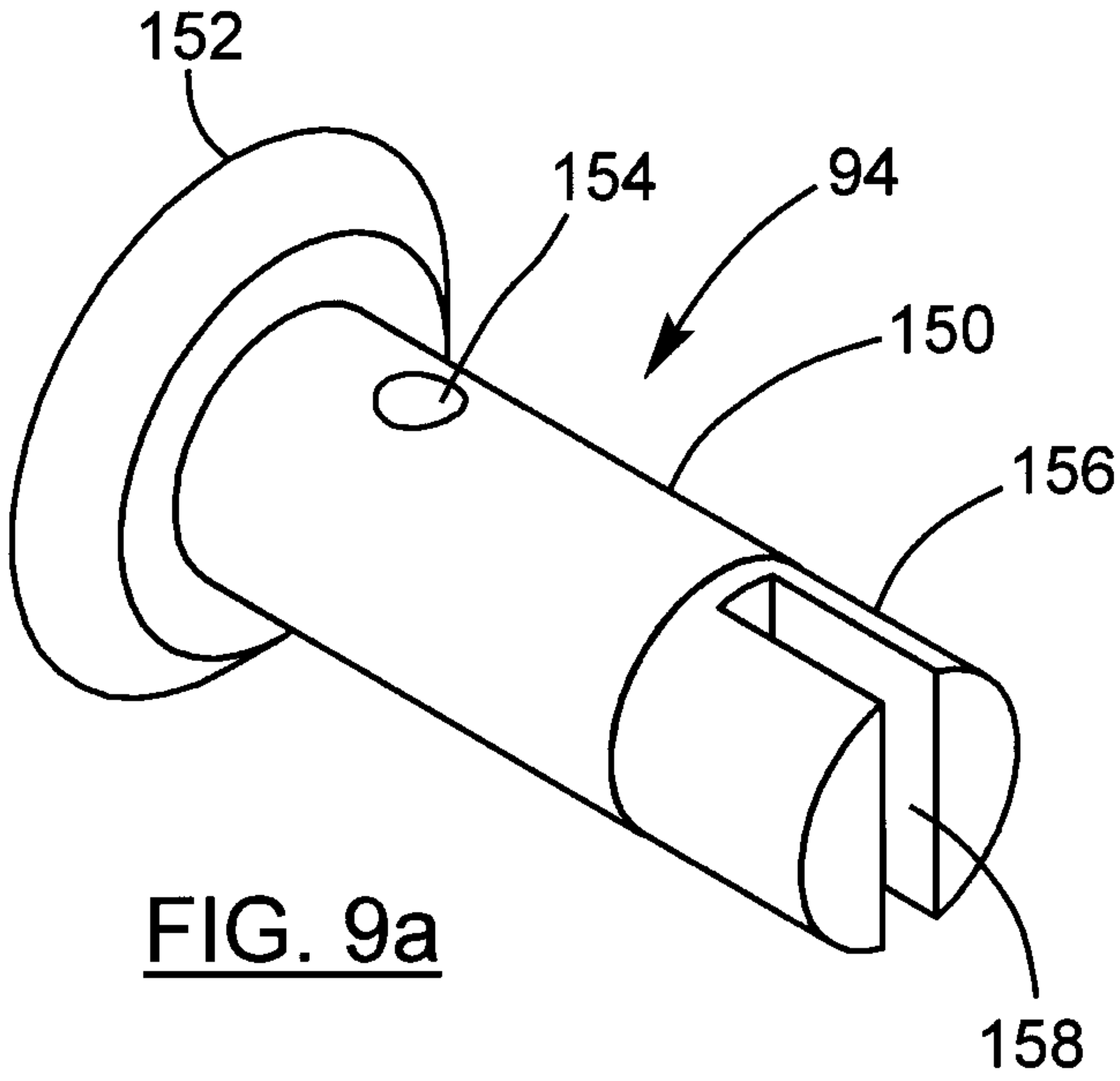


FIG. 9a

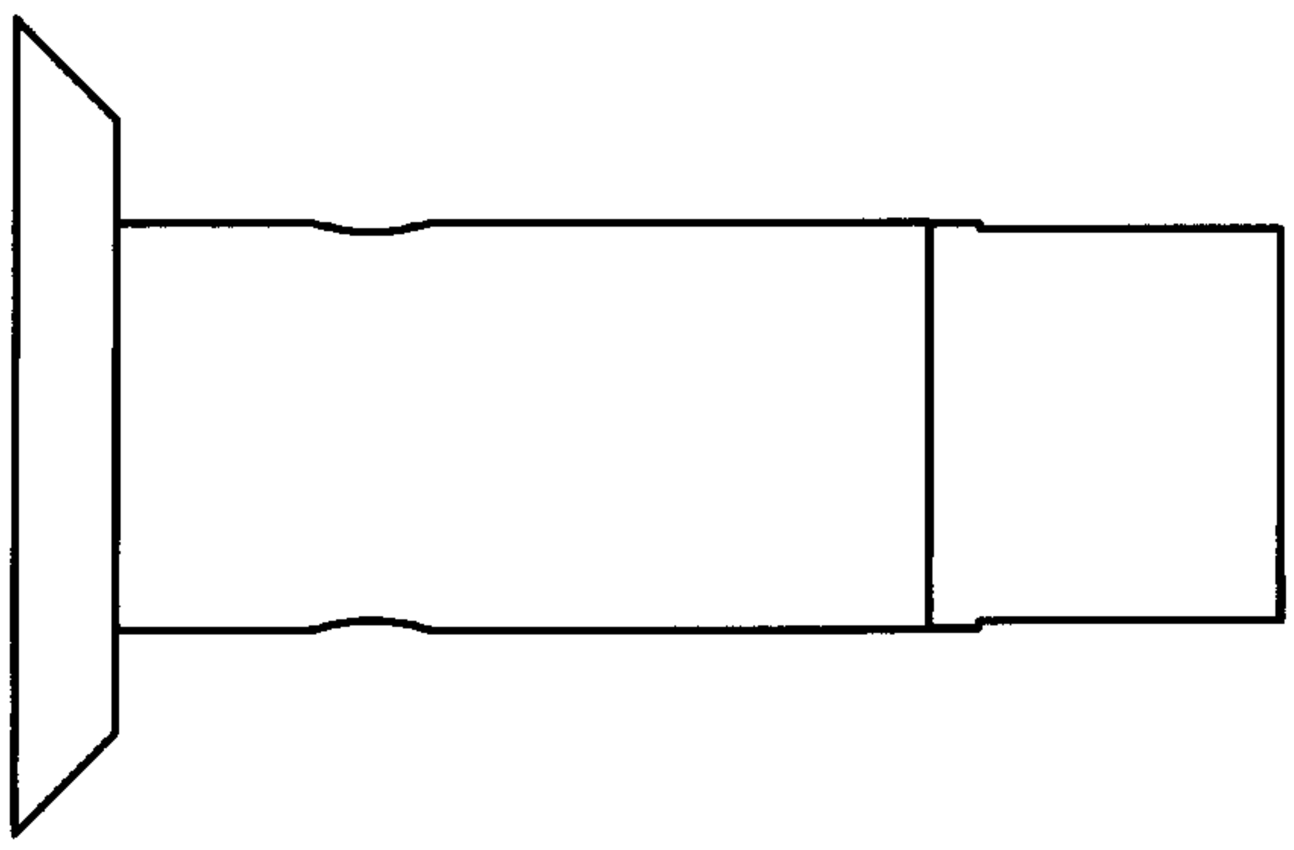


FIG. 9c

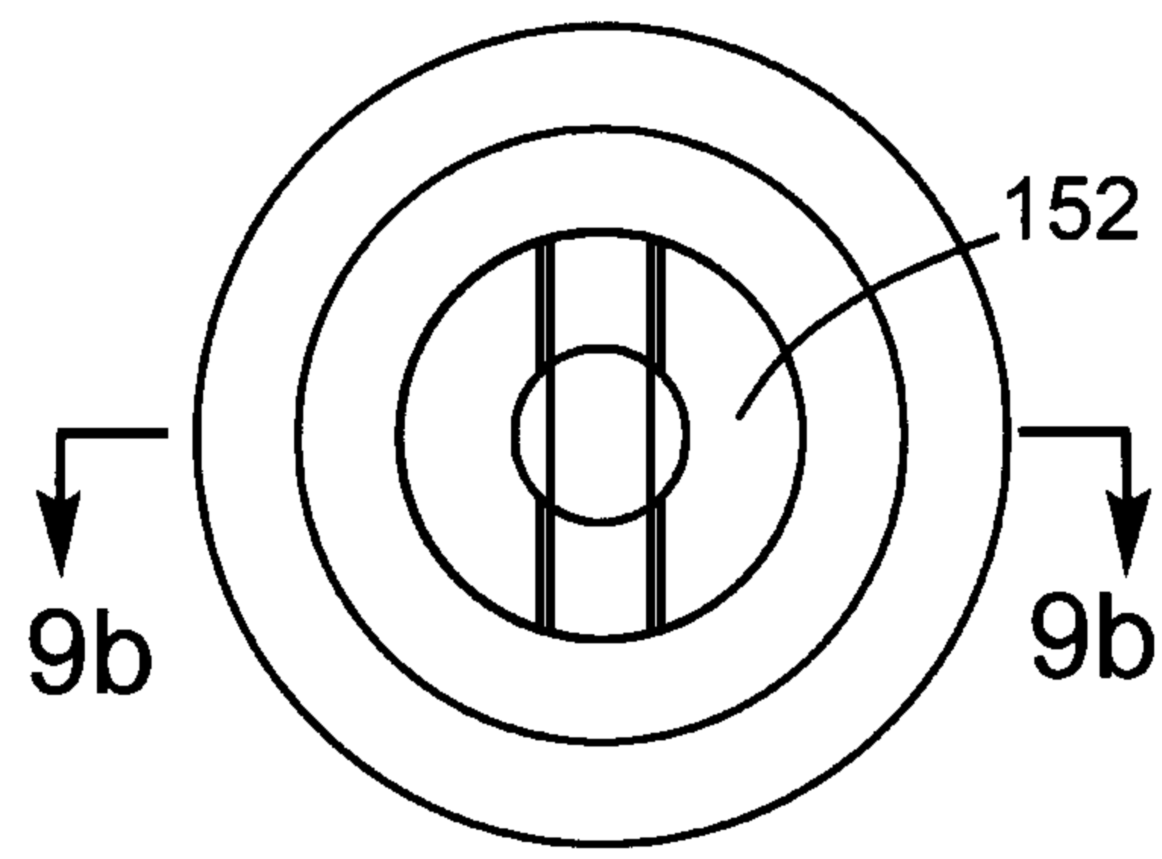


FIG. 9d

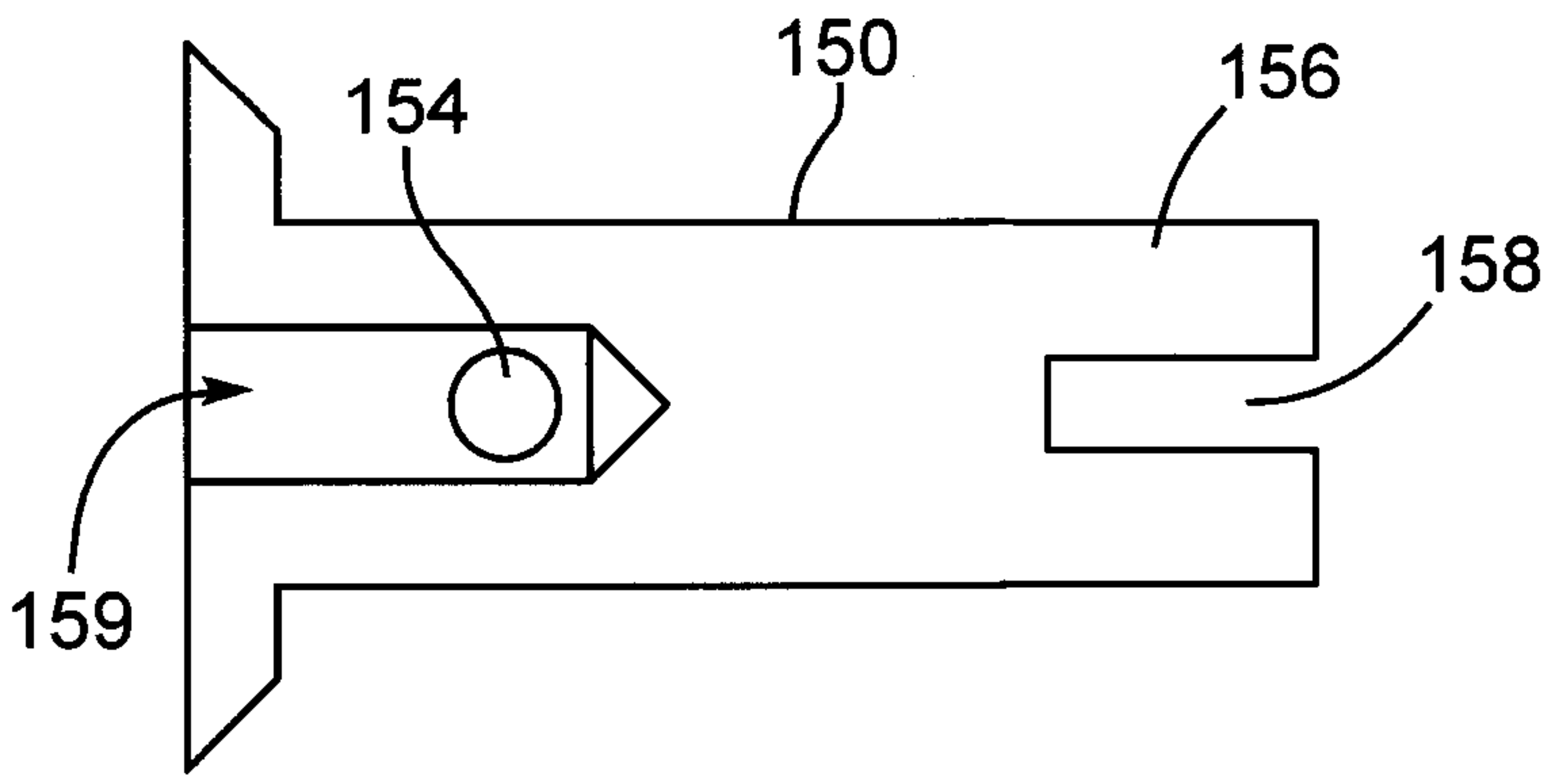


FIG. 9b

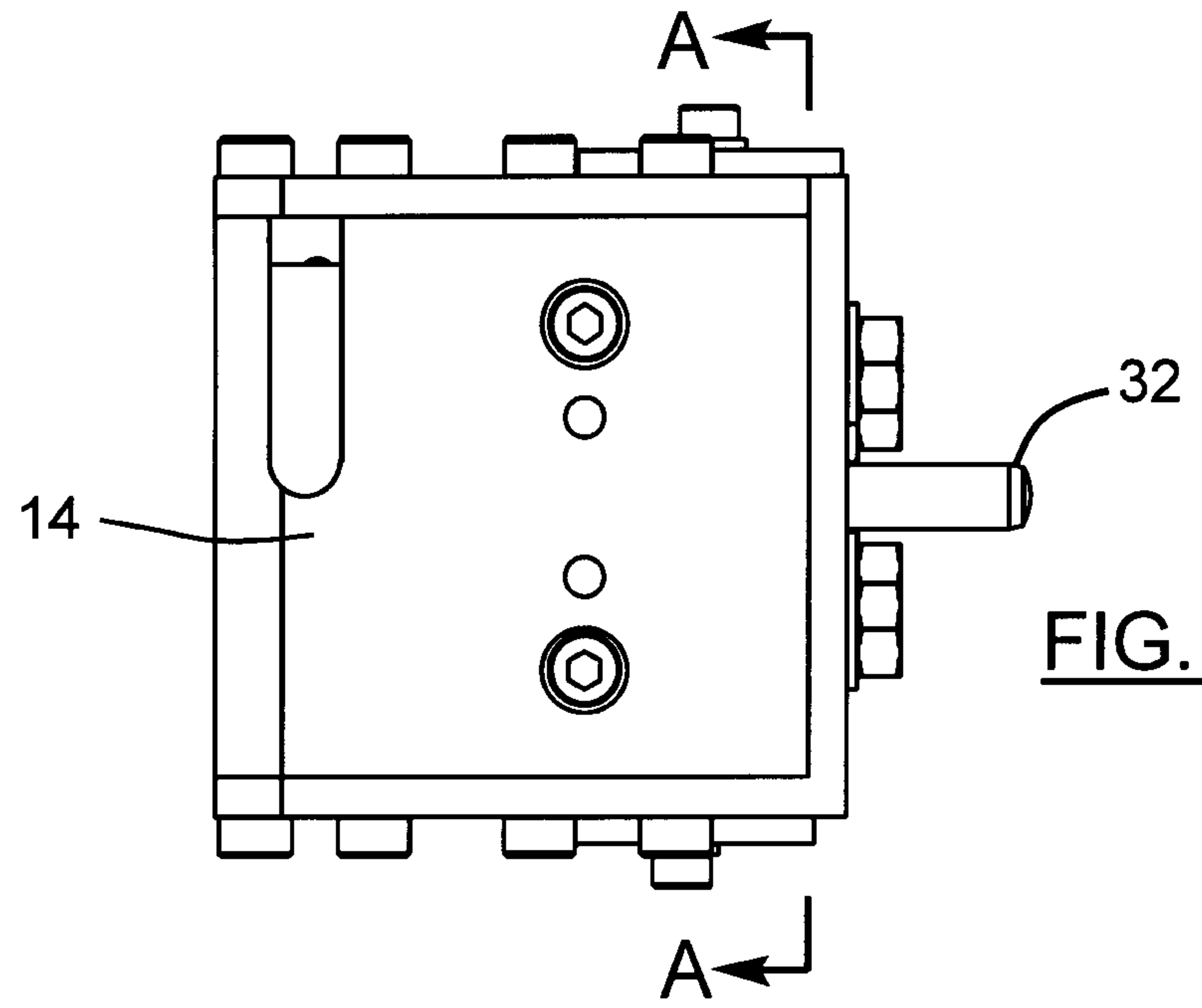


FIG. 10a

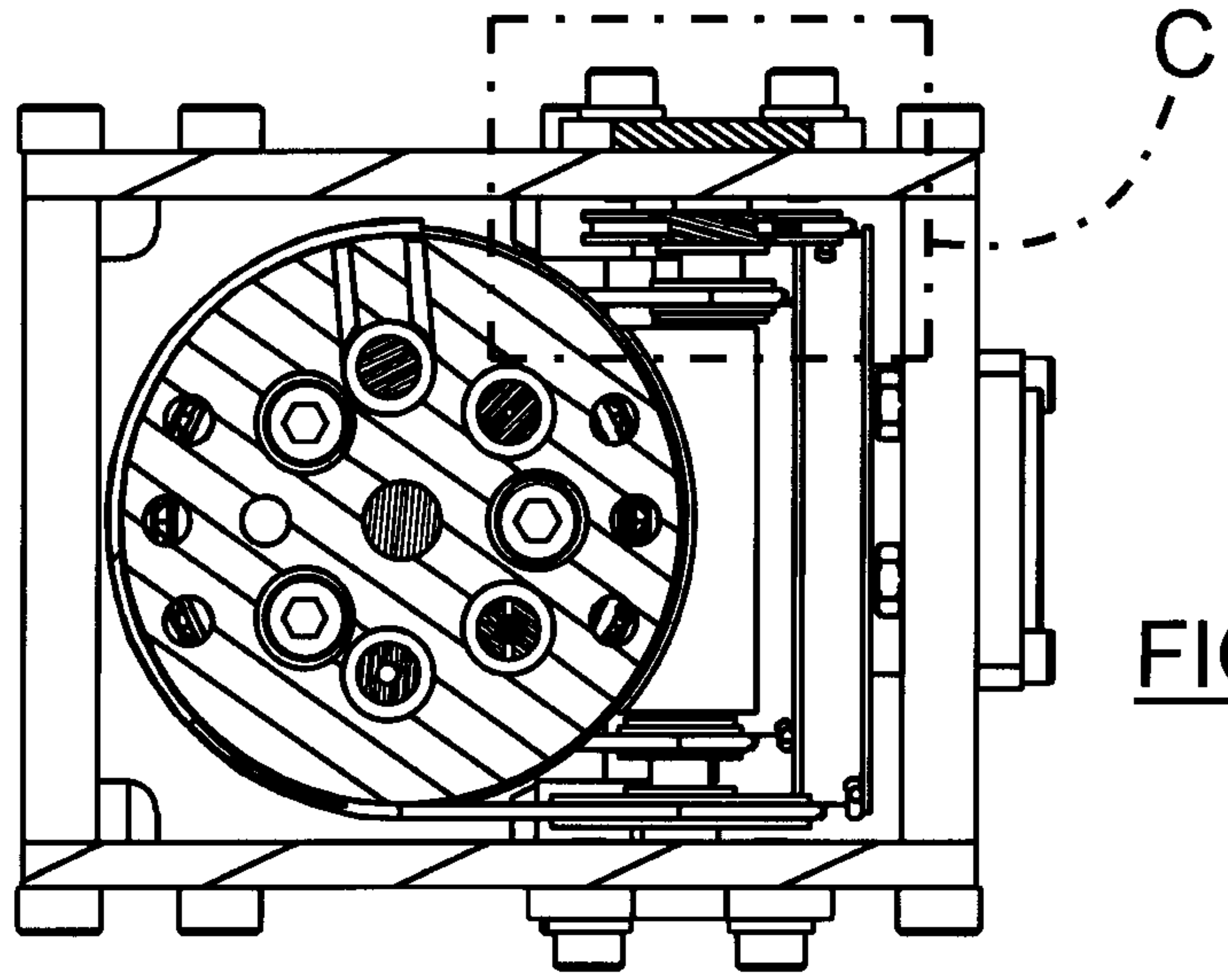


FIG. 10b

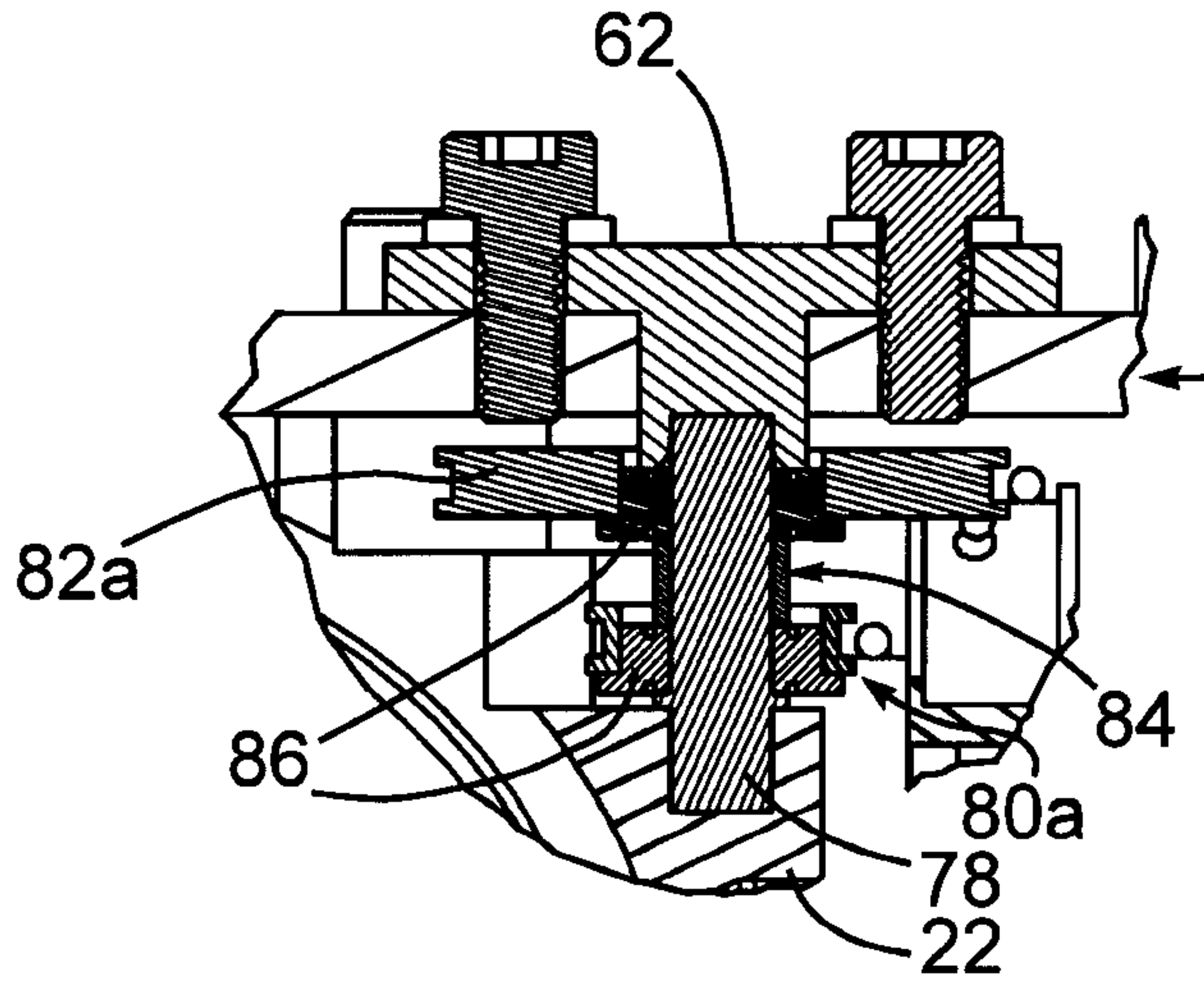


FIG. 10c

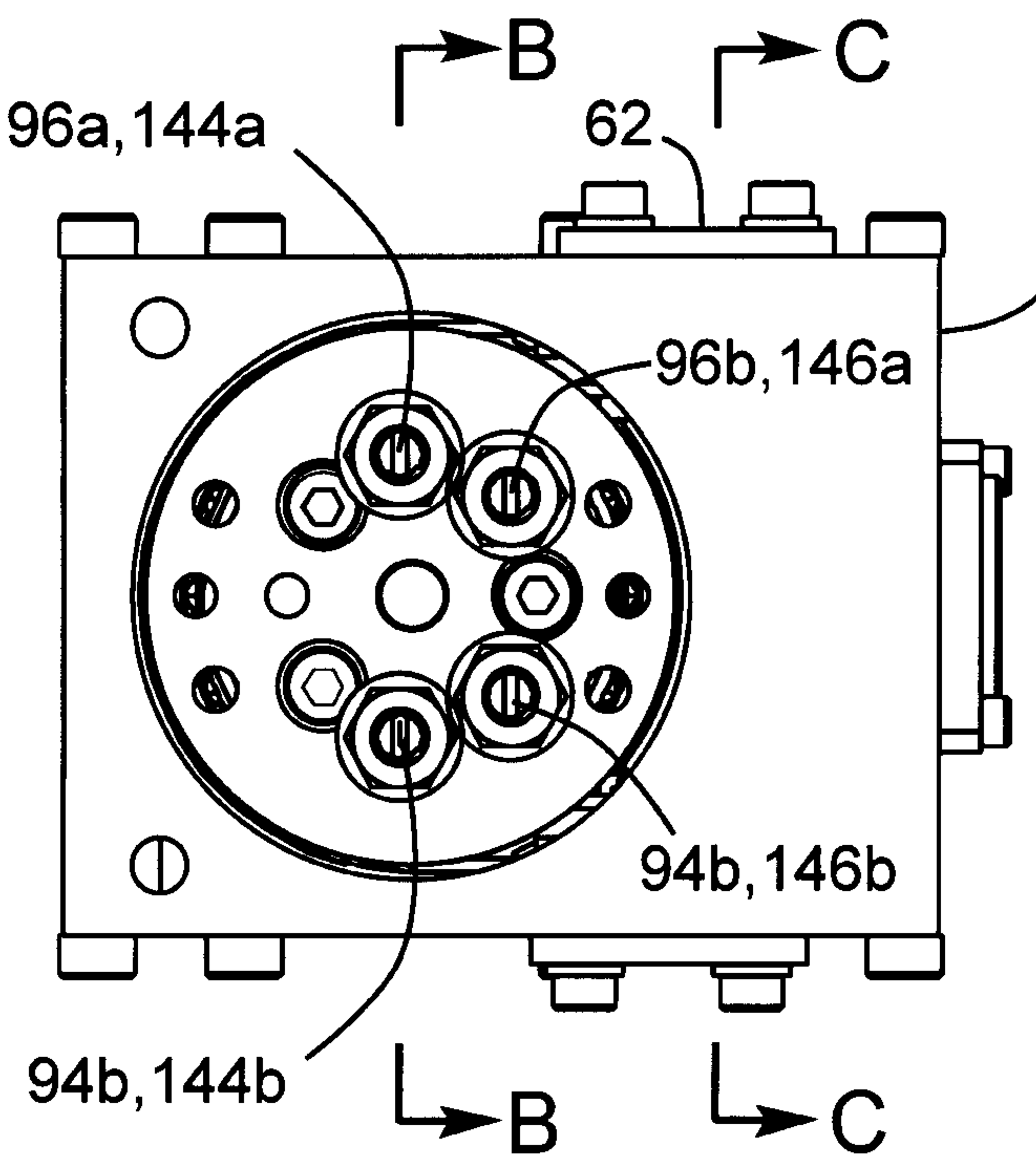


FIG. 11a

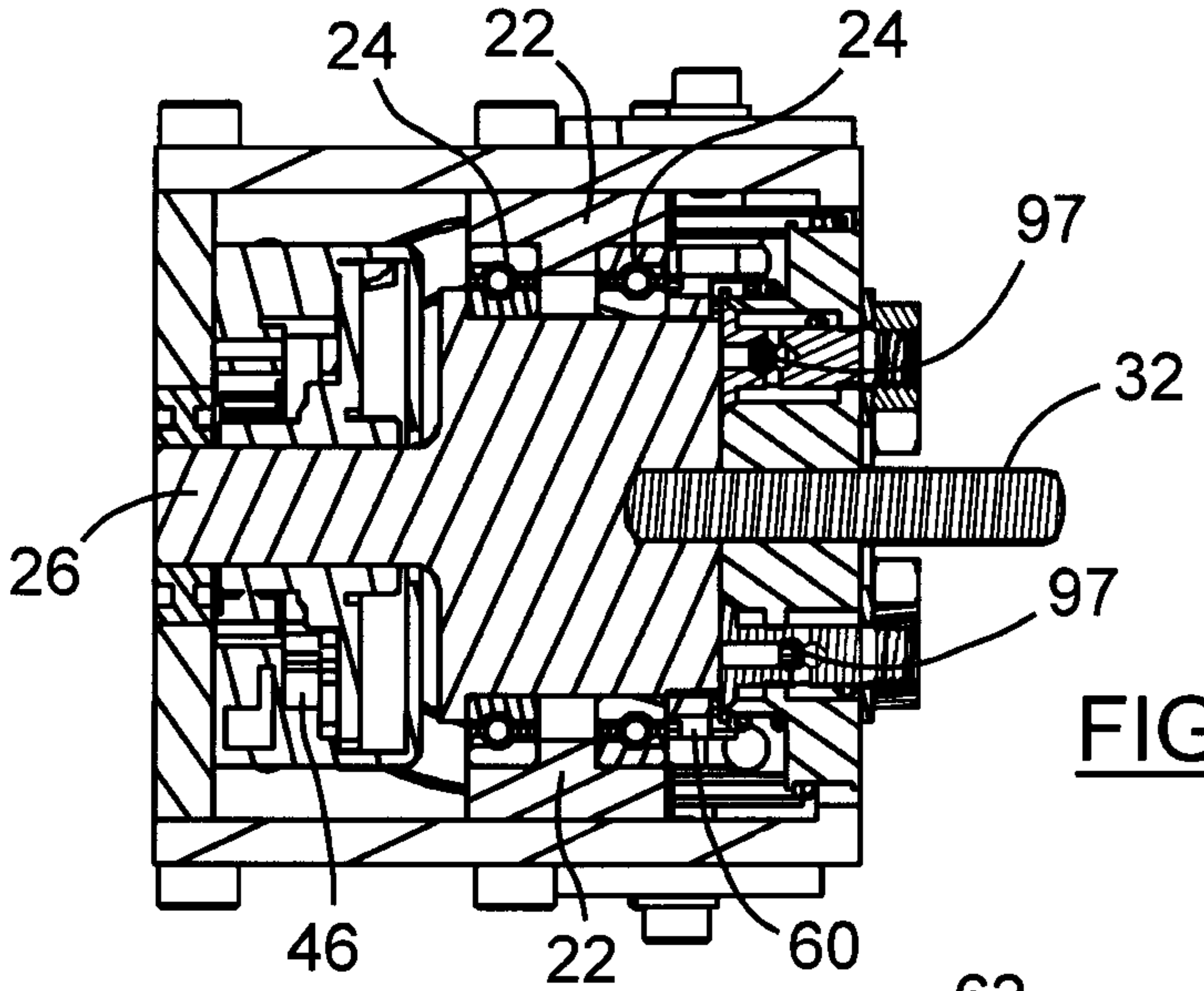


FIG. 11b

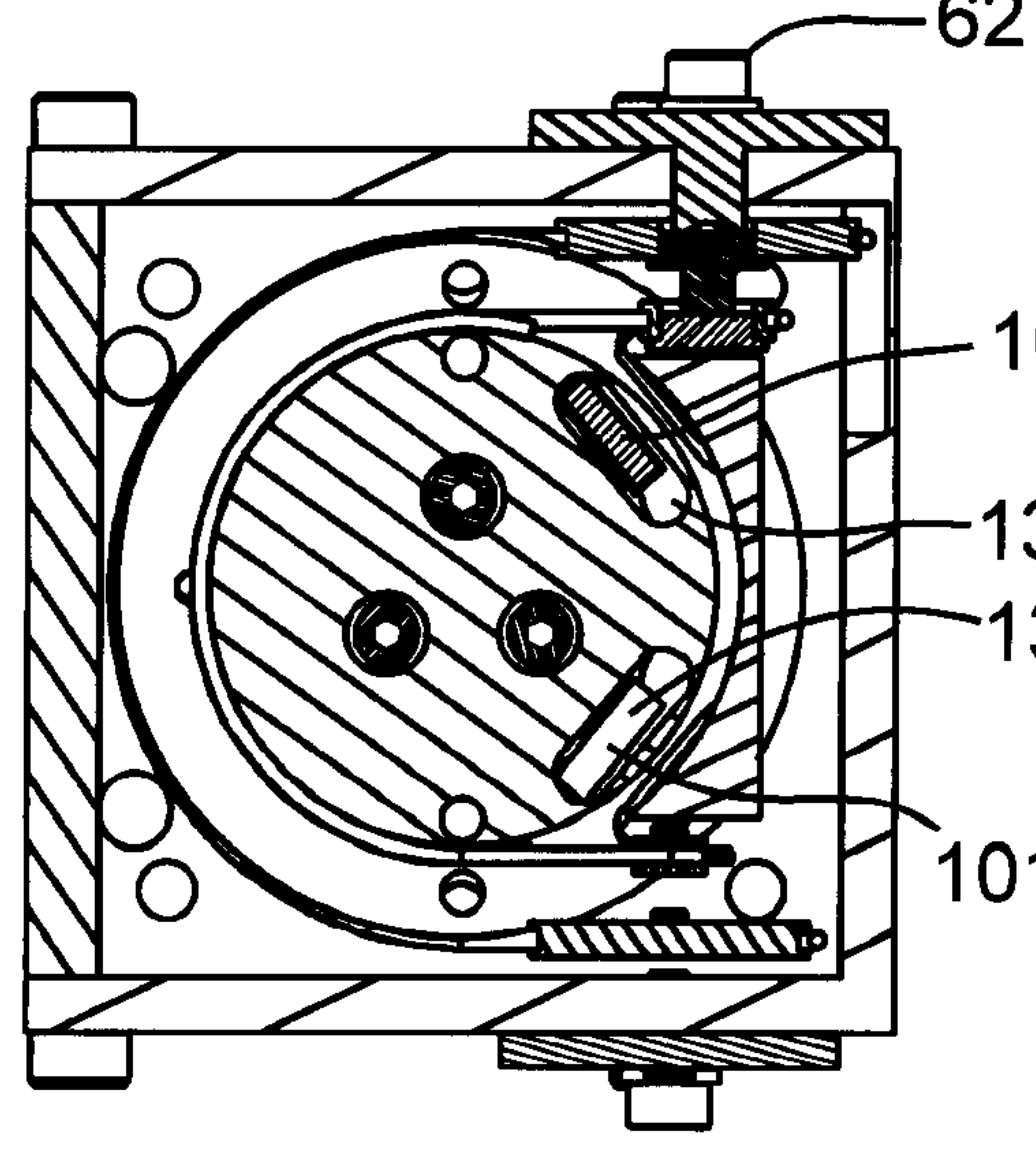


FIG. 11c

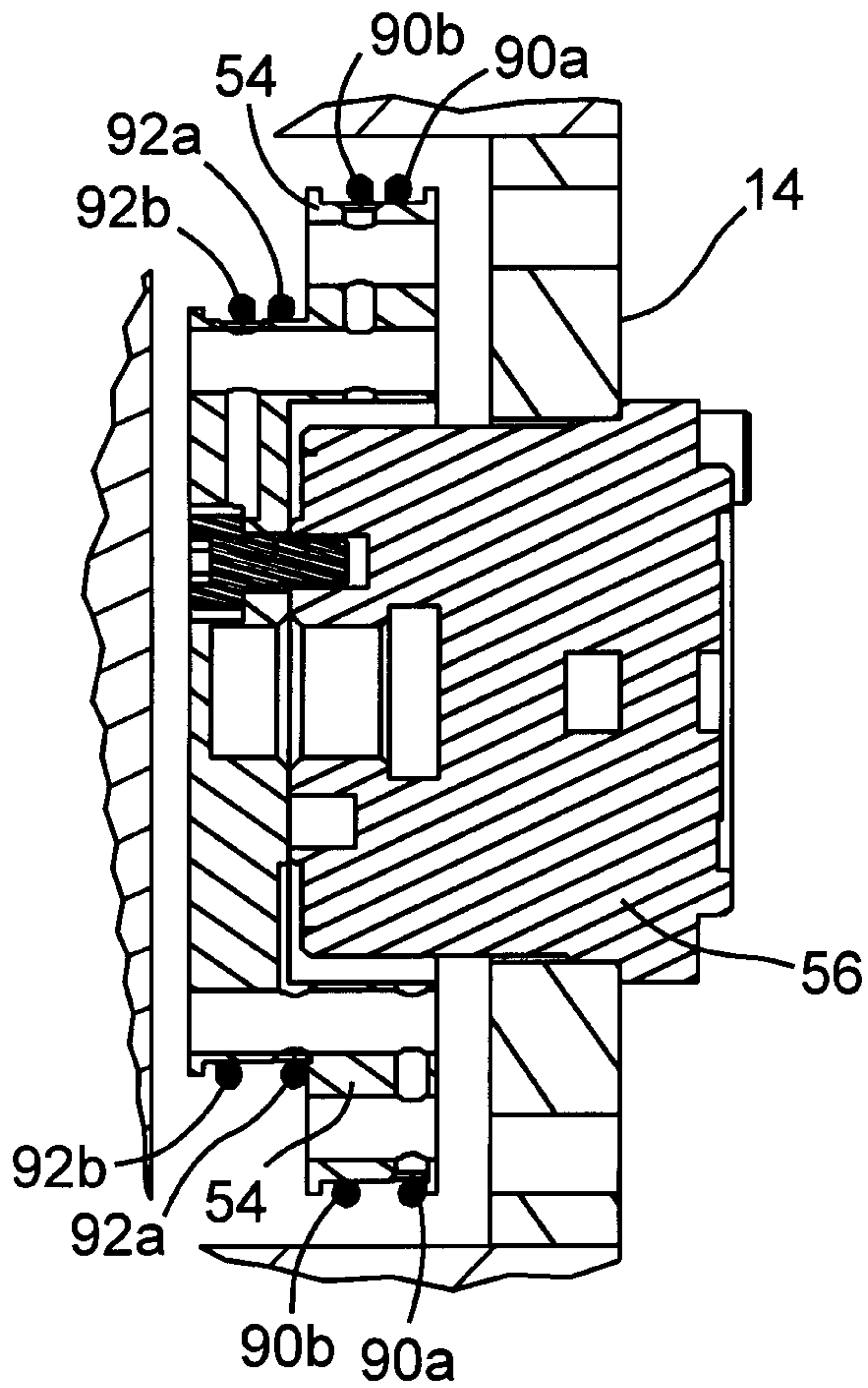


FIG. 12

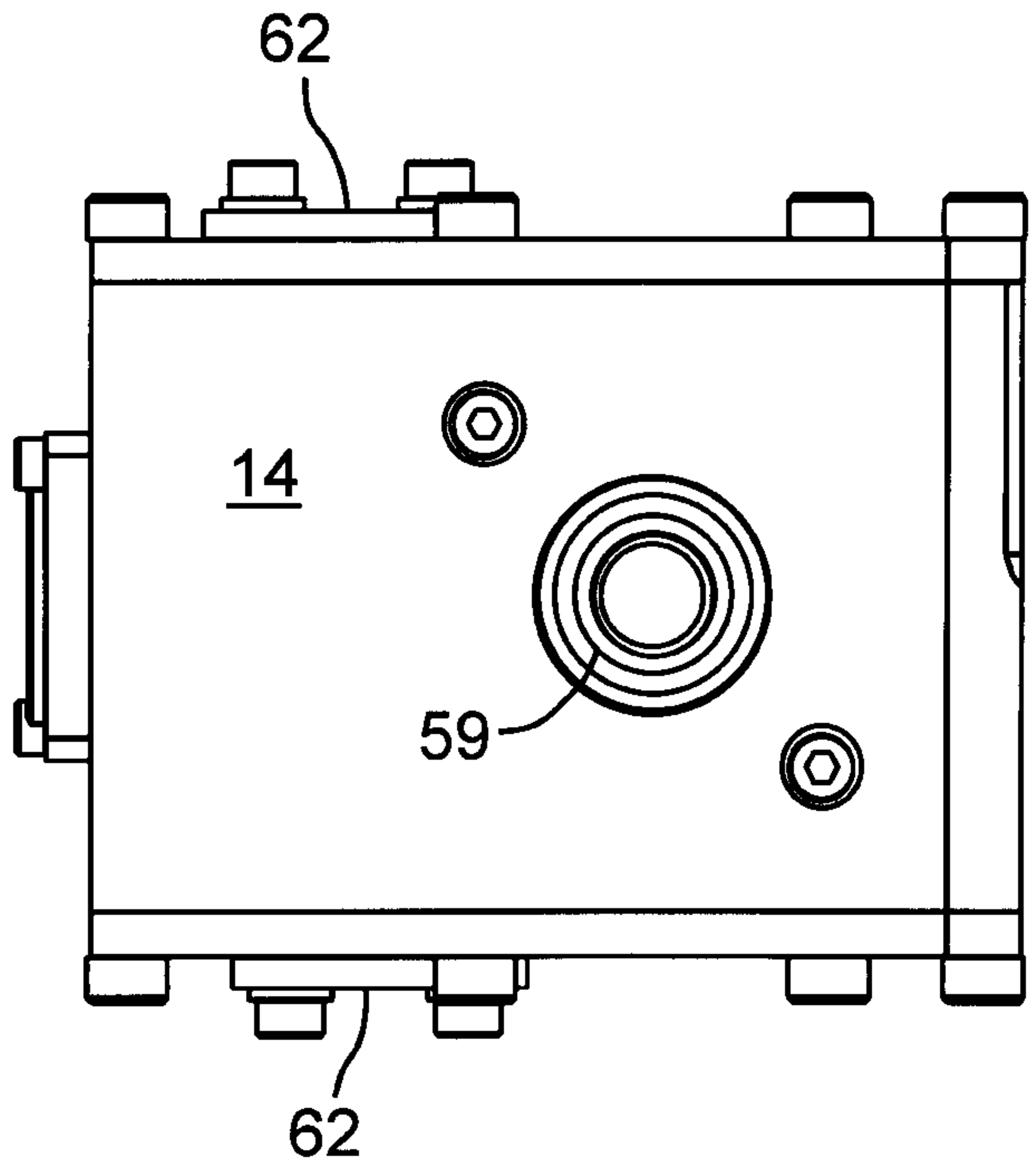


FIG. 13

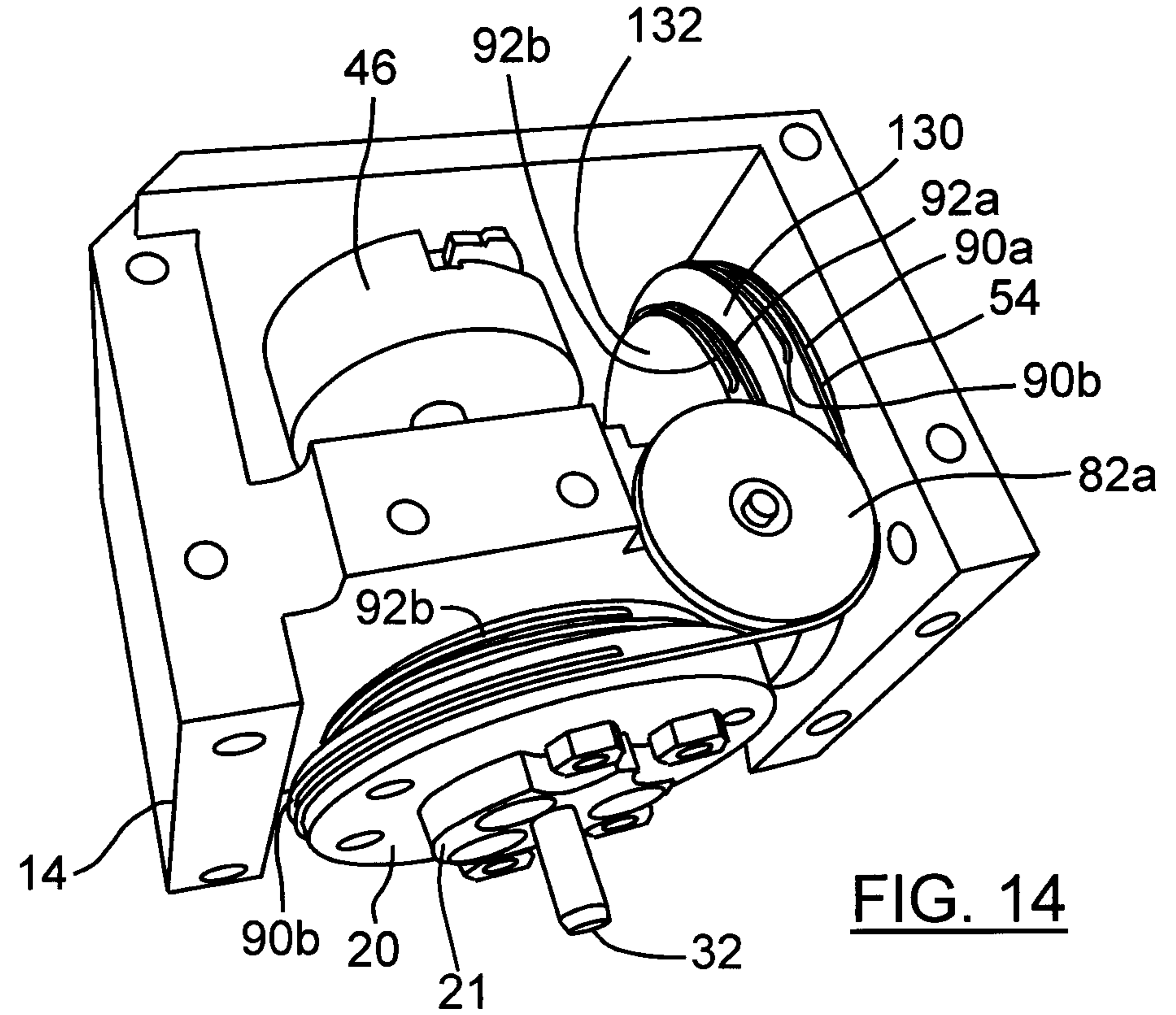

46
92b
132
130
92a
90a
54
90b
82a
92b
14
90b
20
21
32

FIG. 14

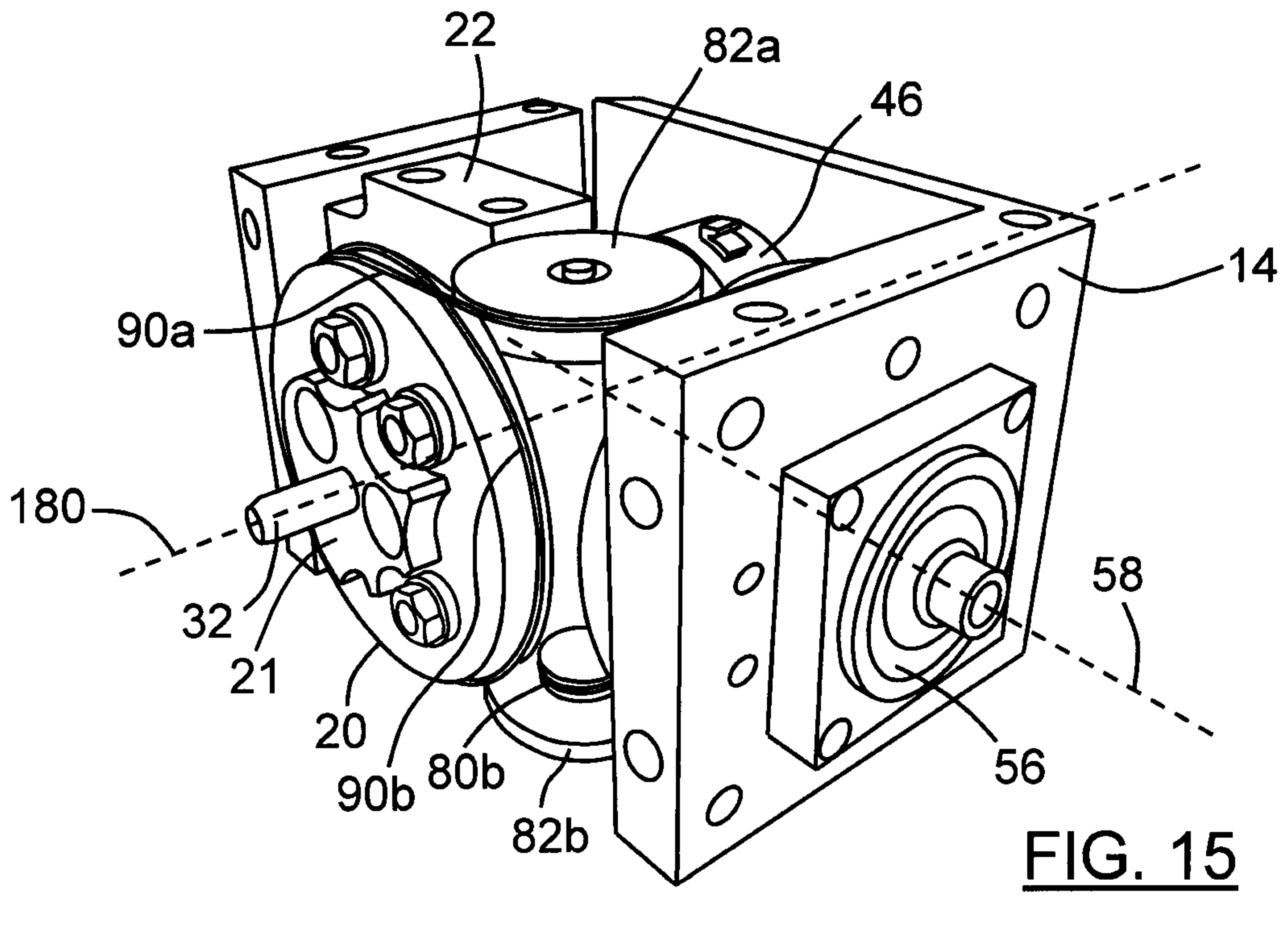

22
82a
46
14
90a
180
32
21
20
90b
80b
82b
58
56

FIG. 15

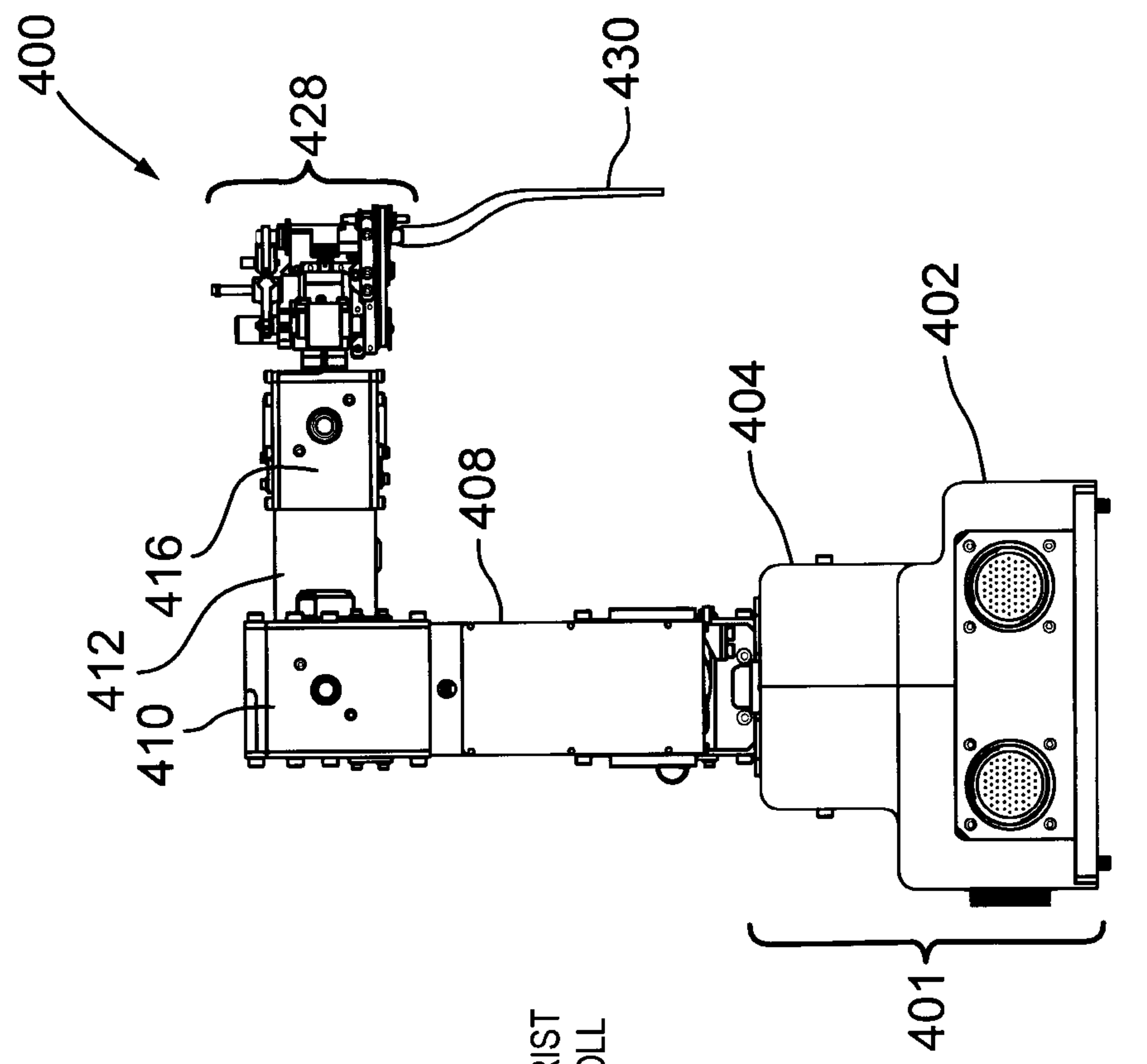


FIG. 16b

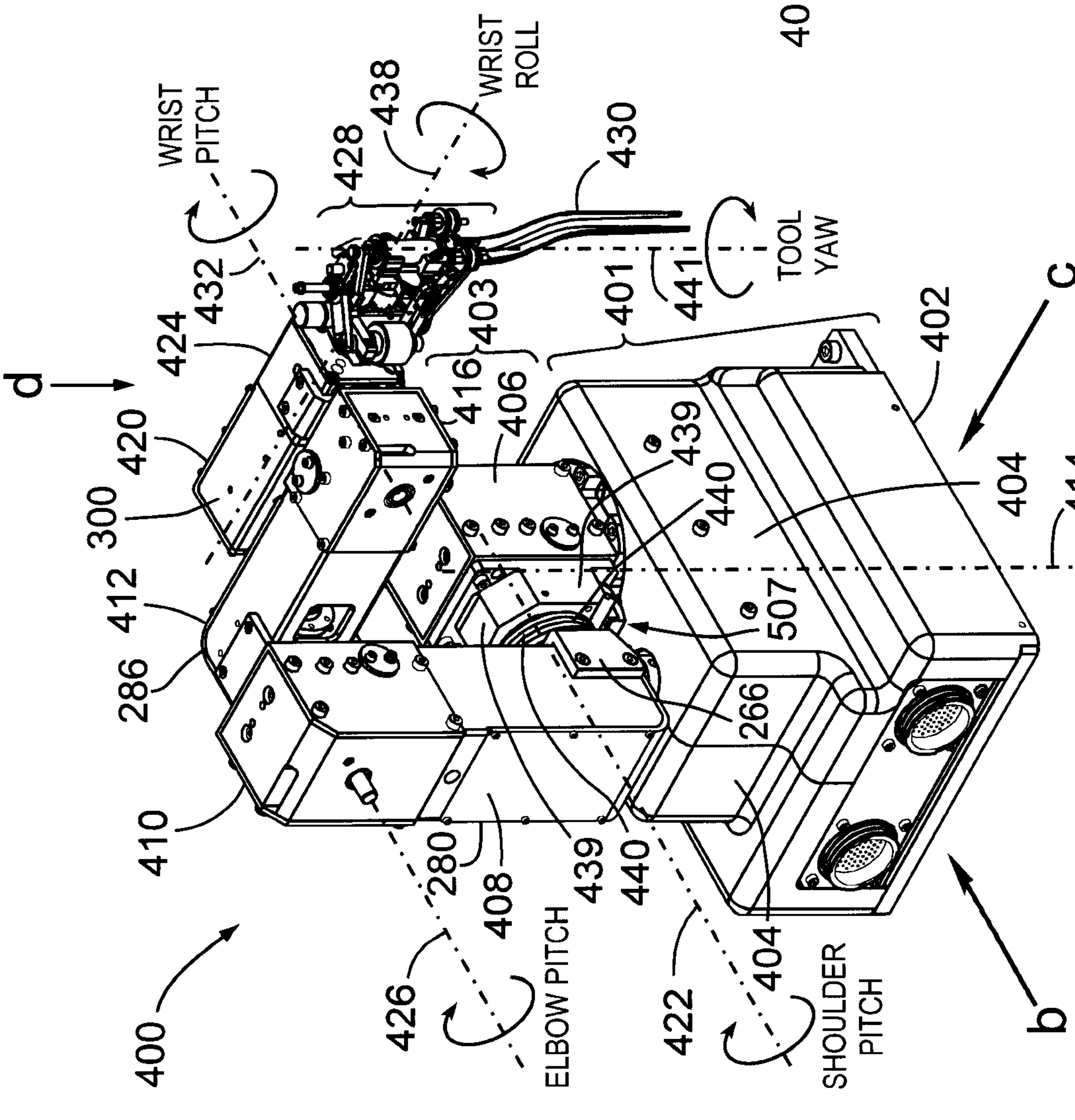


FIG. 16a

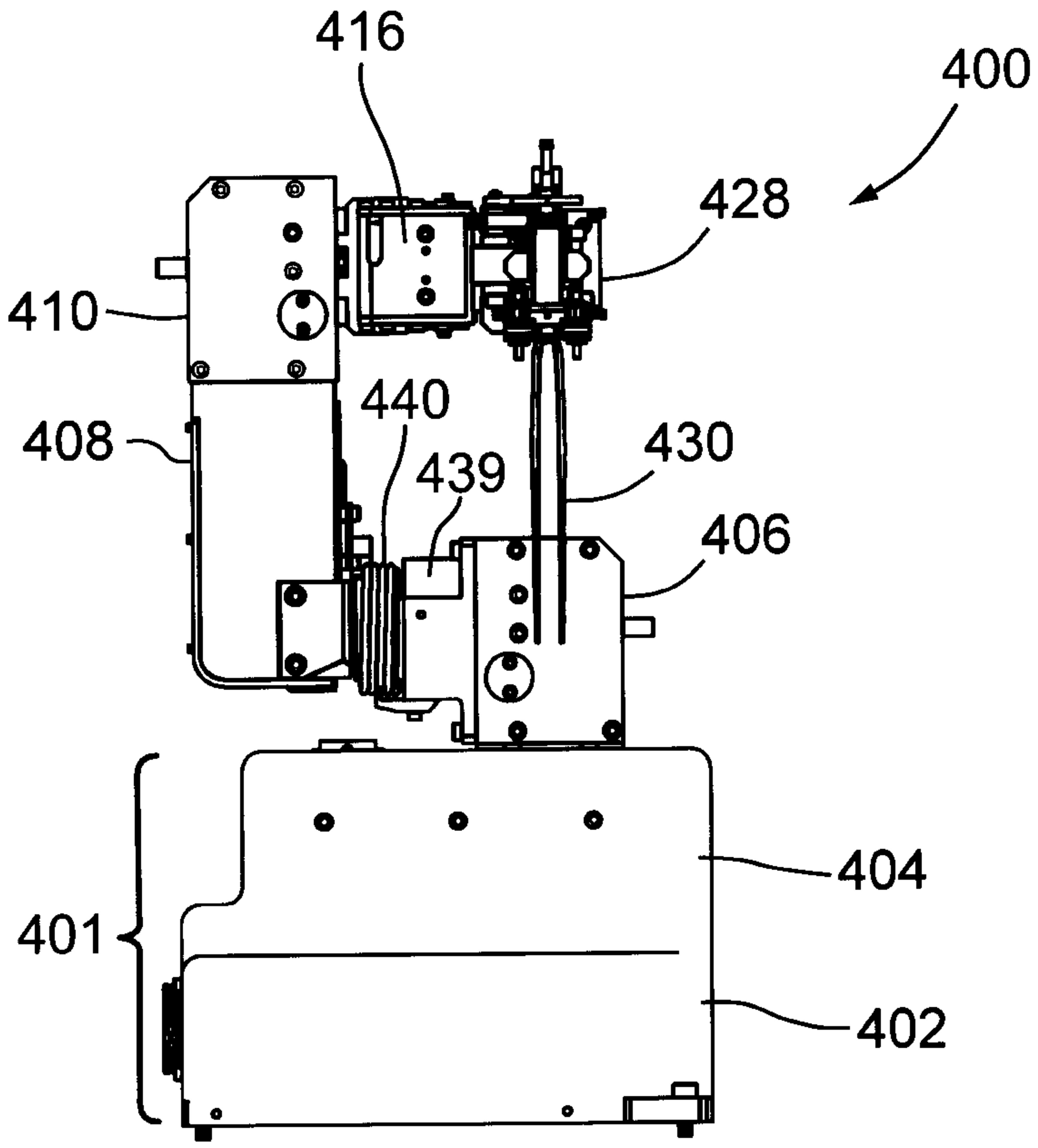


FIG. 16c

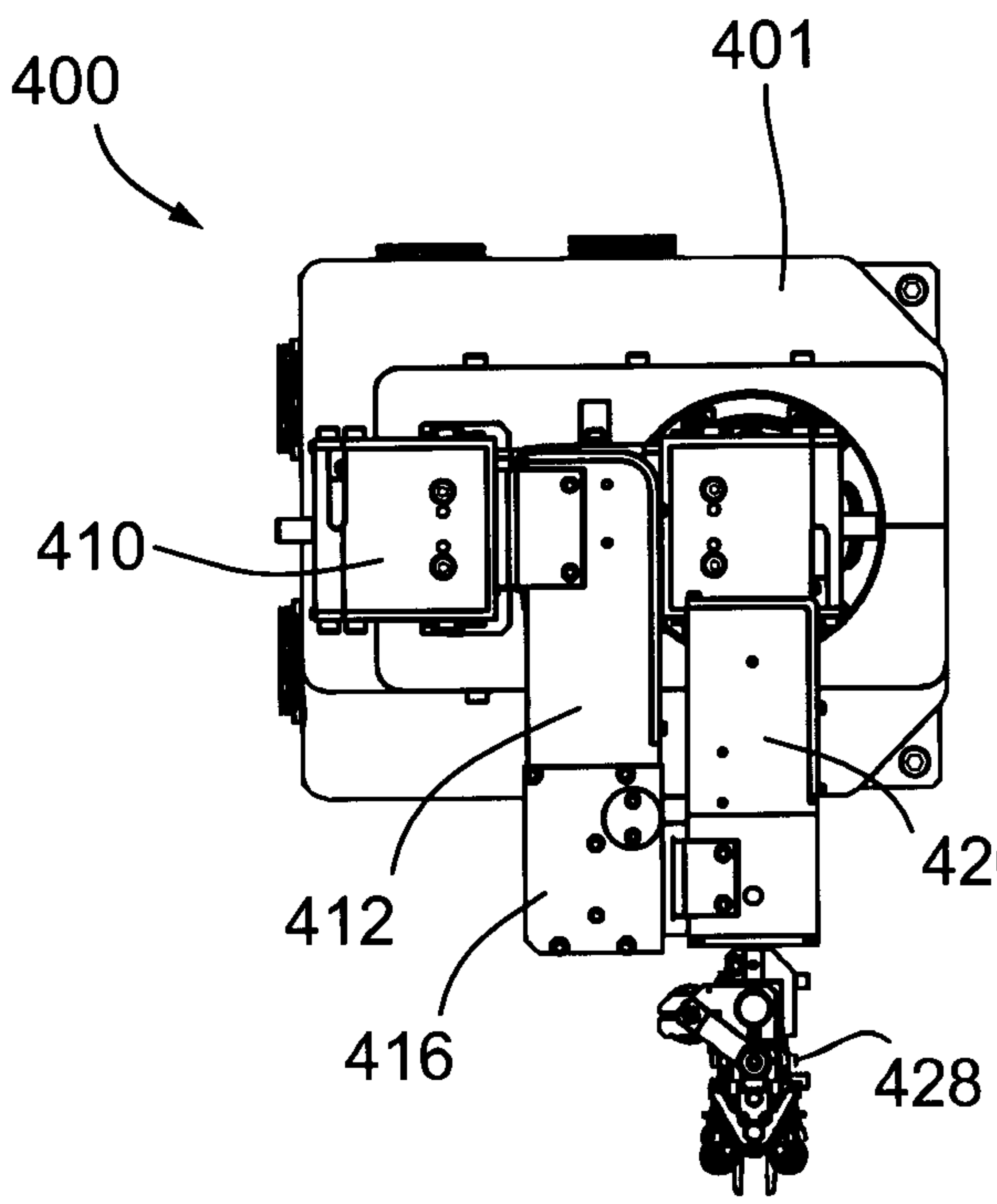


FIG. 16d

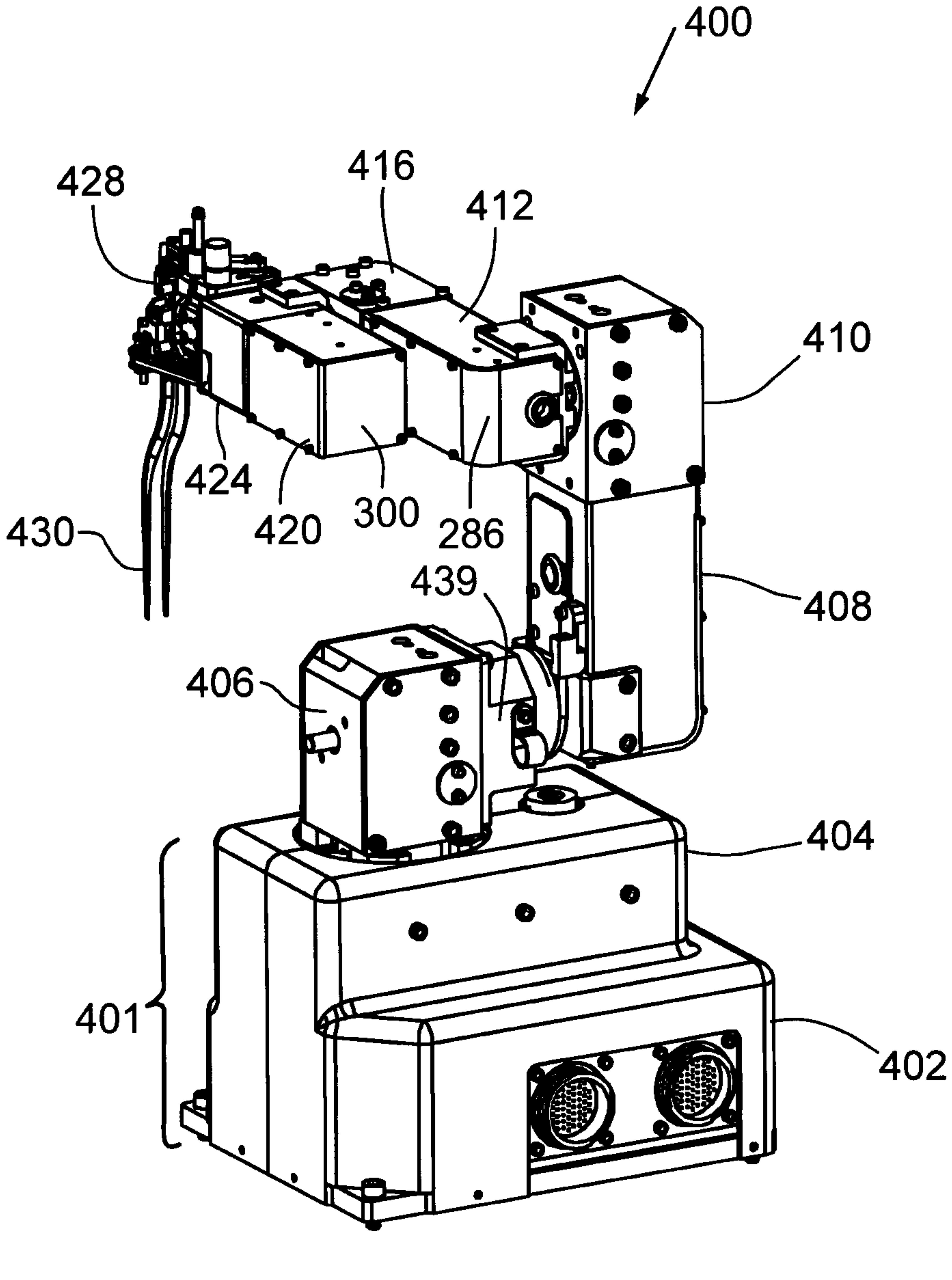


FIG. 16e

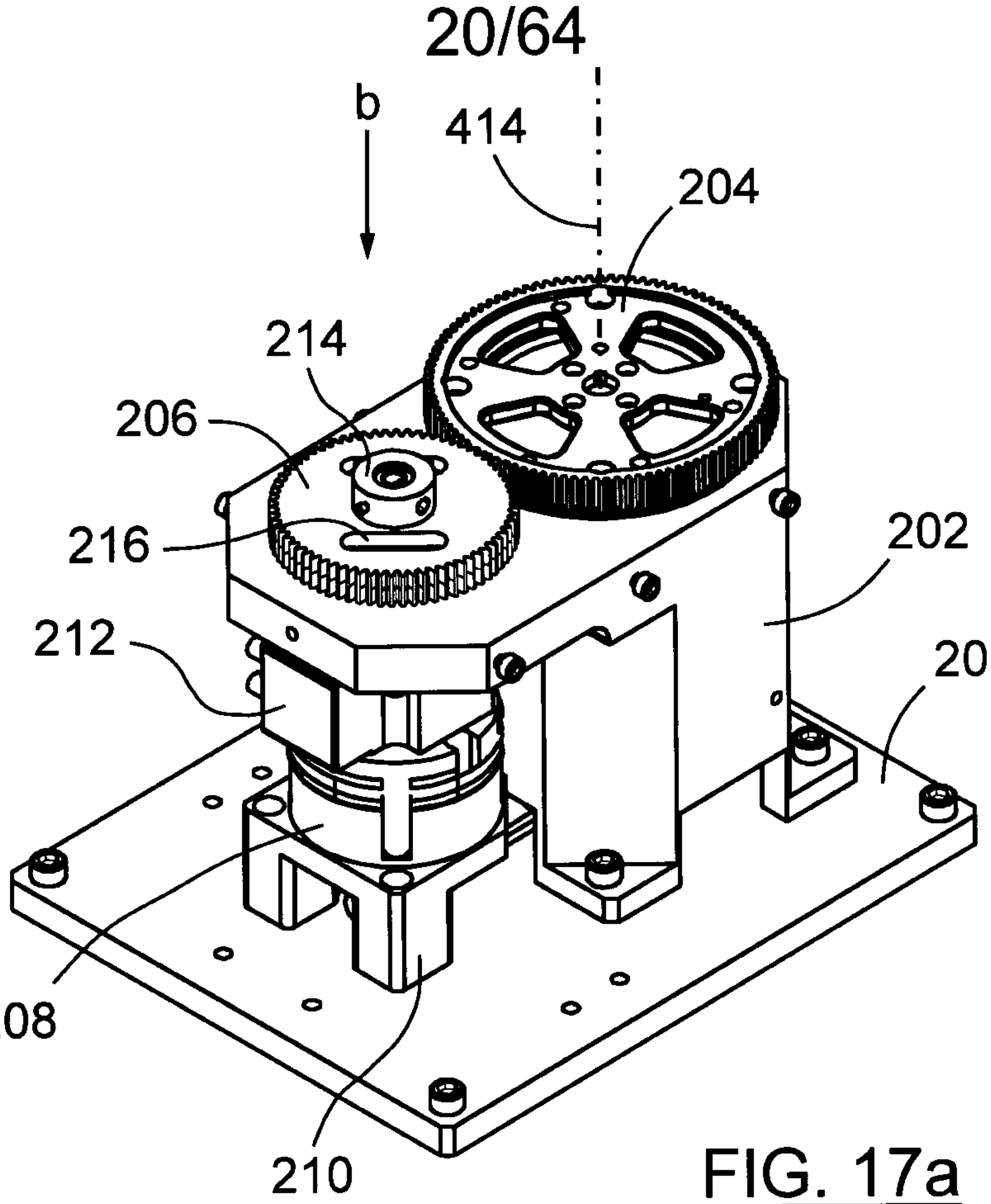


FIG. 17a

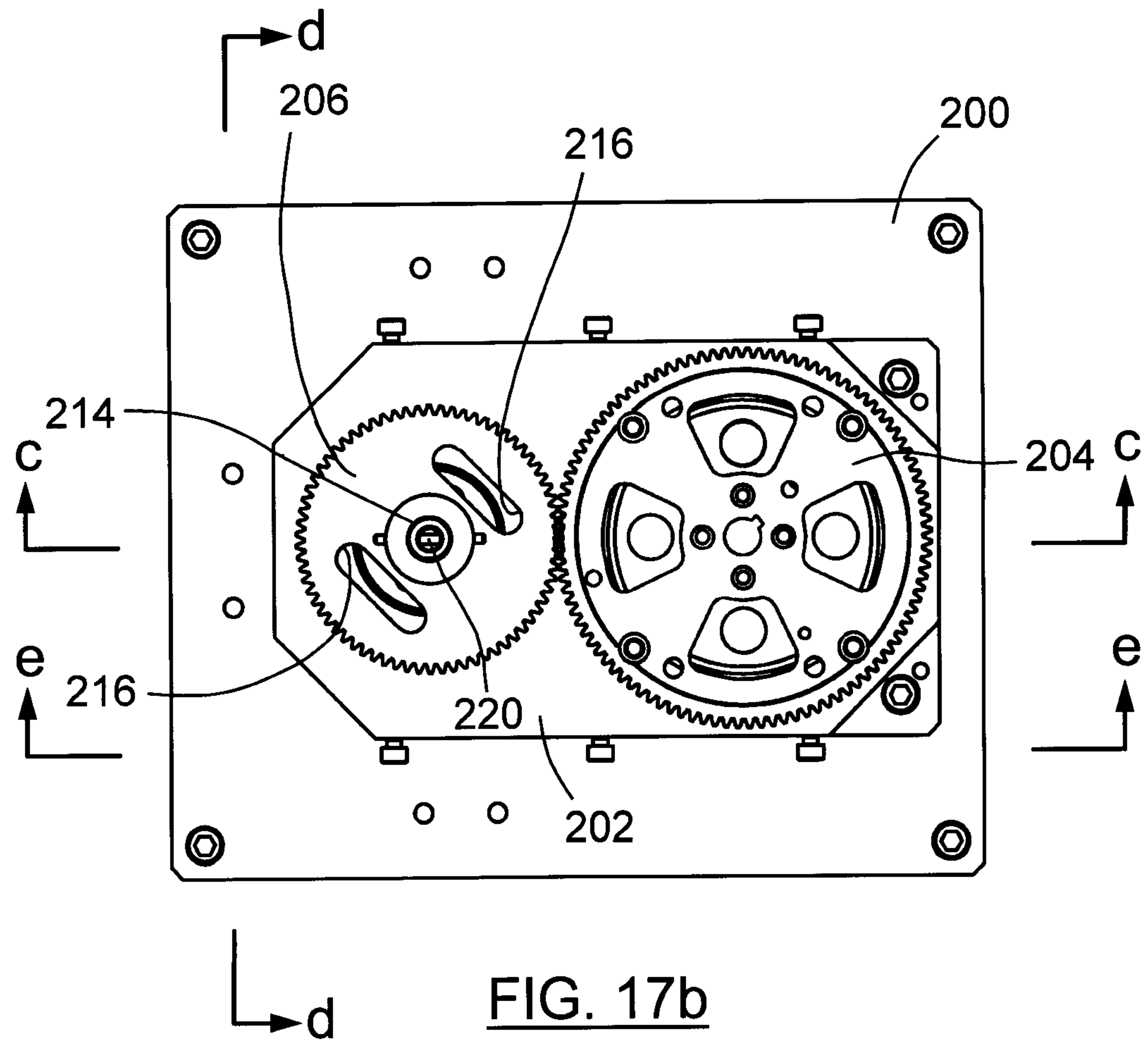


FIG. 17b

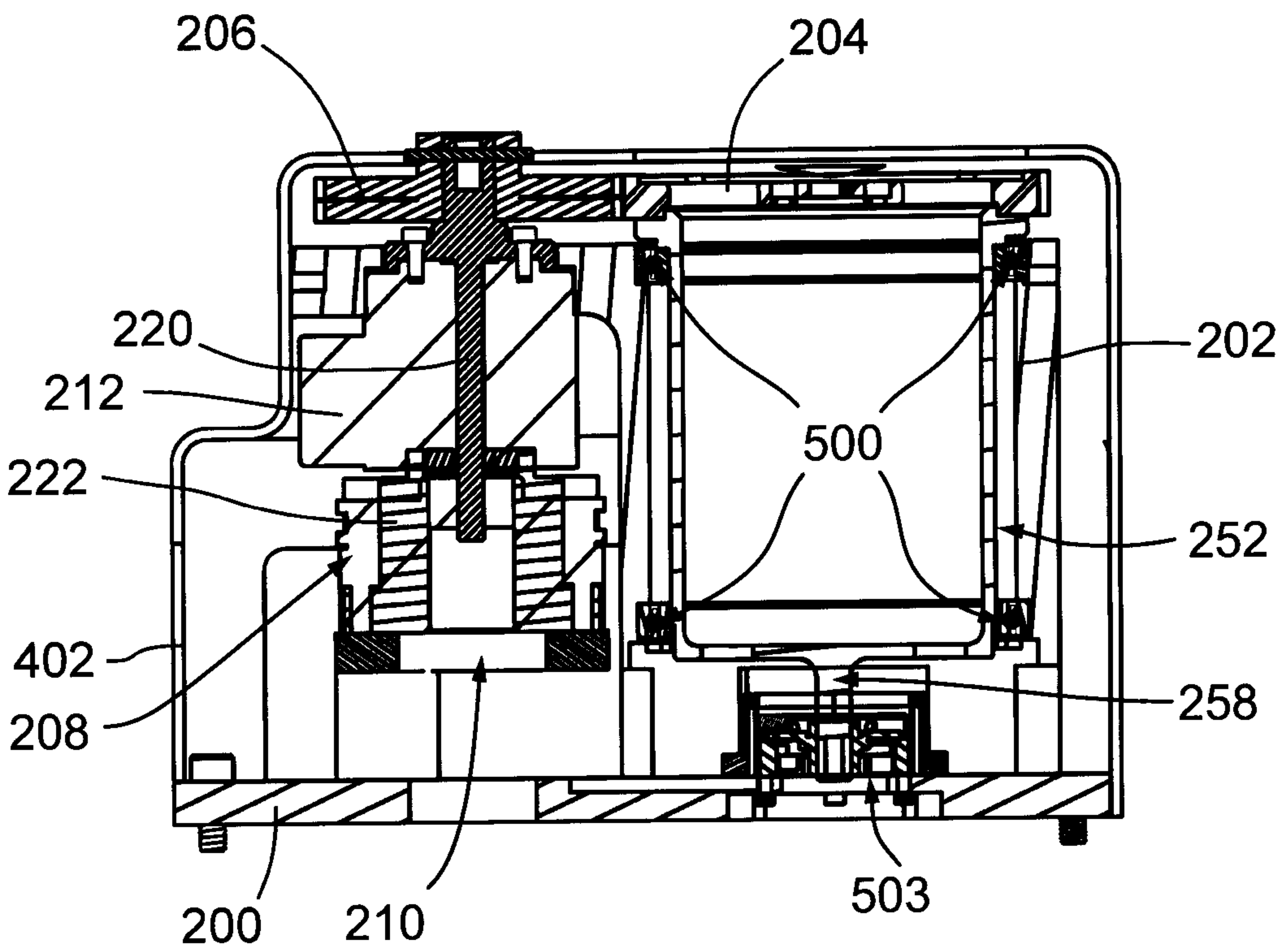


FIG. 17c

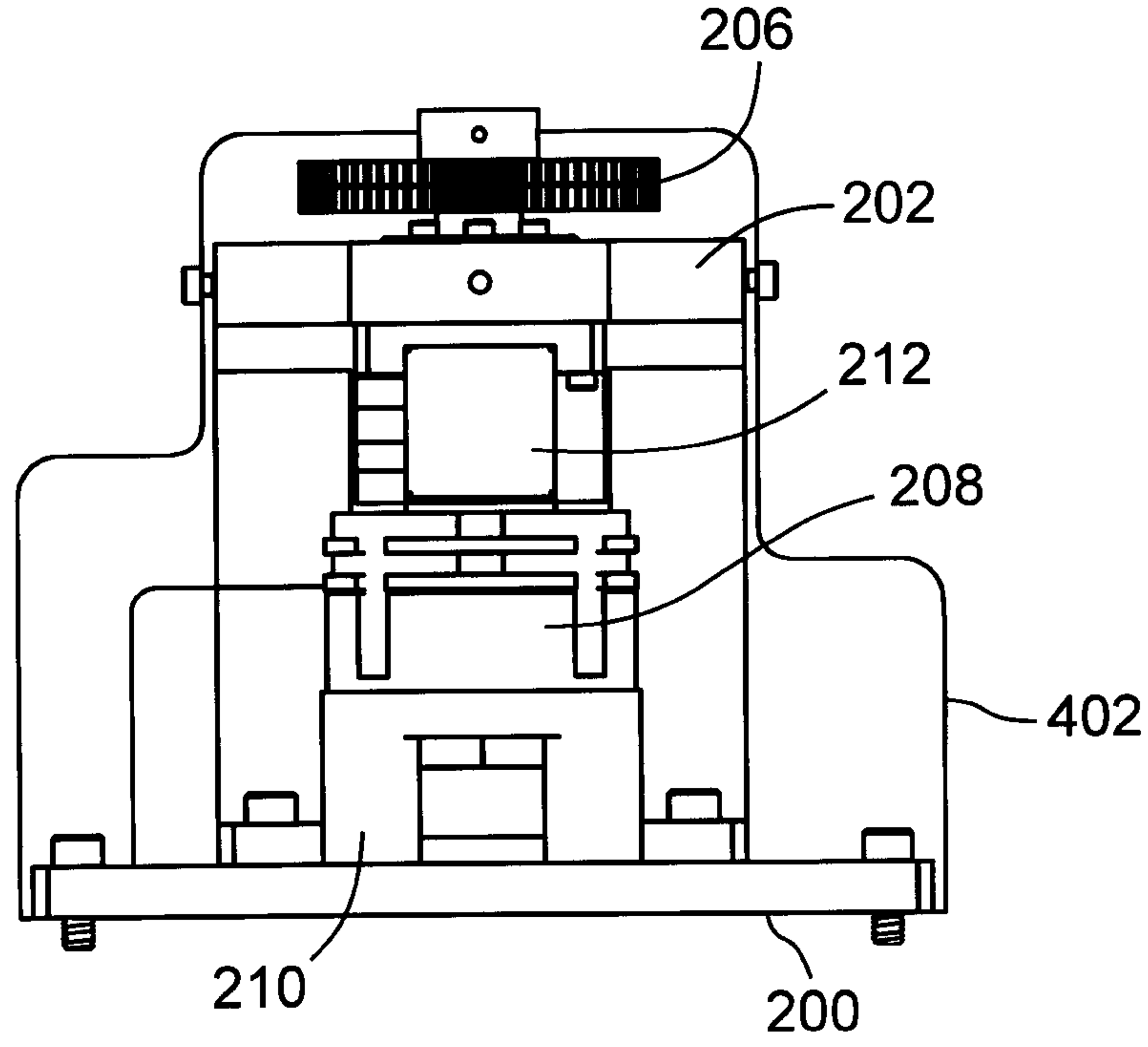


FIG. 17d

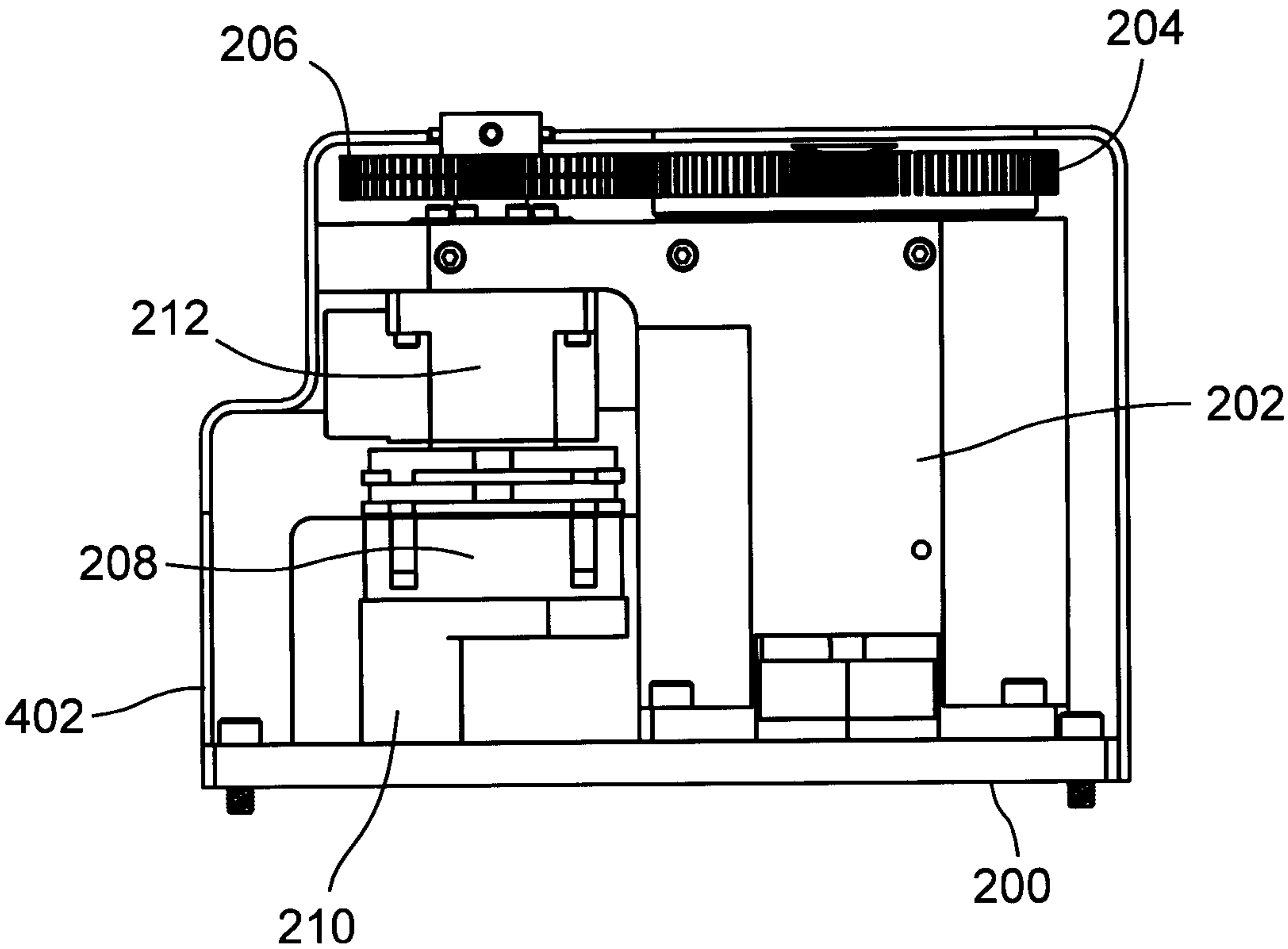


FIG. 17e

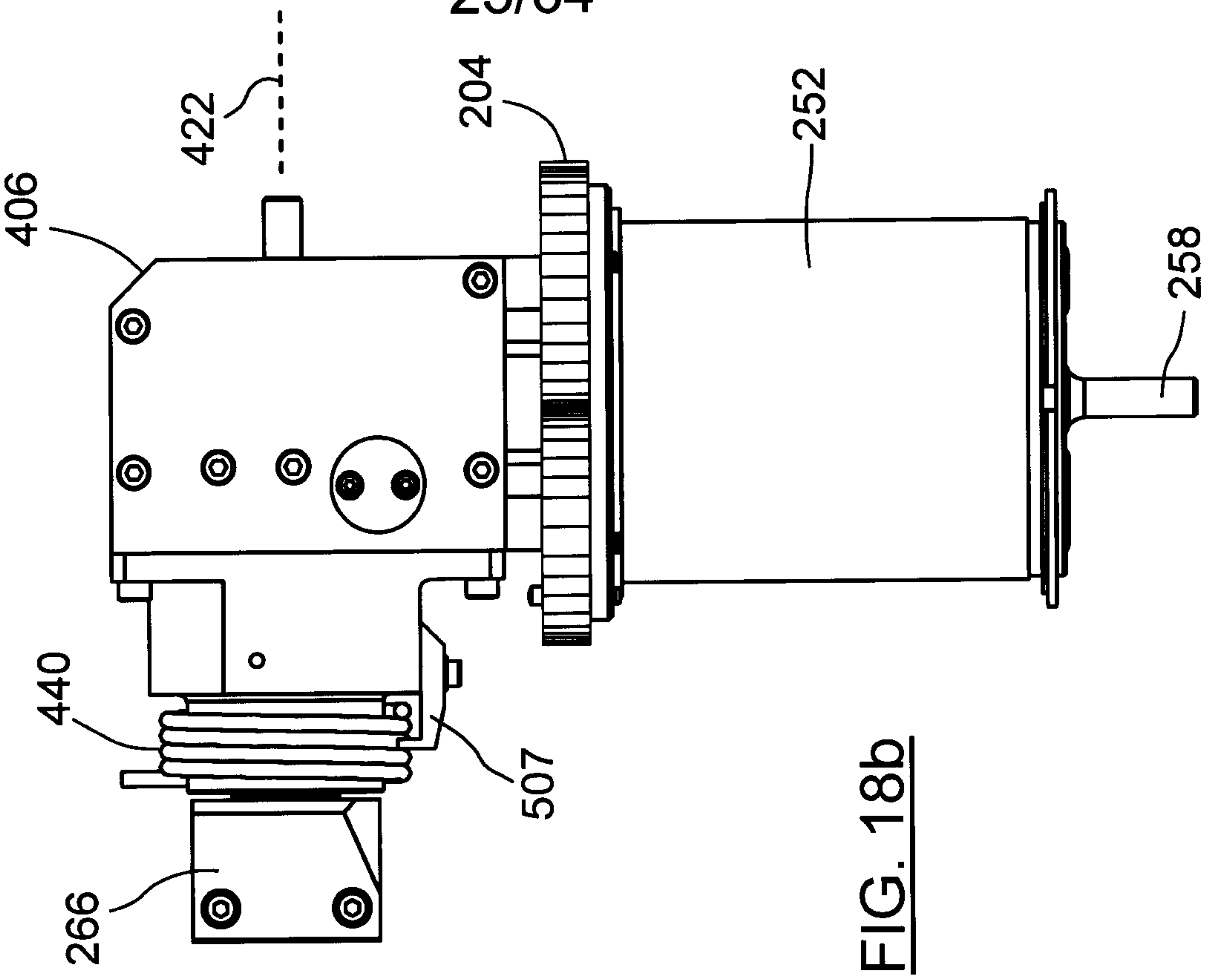


FIG. 18b

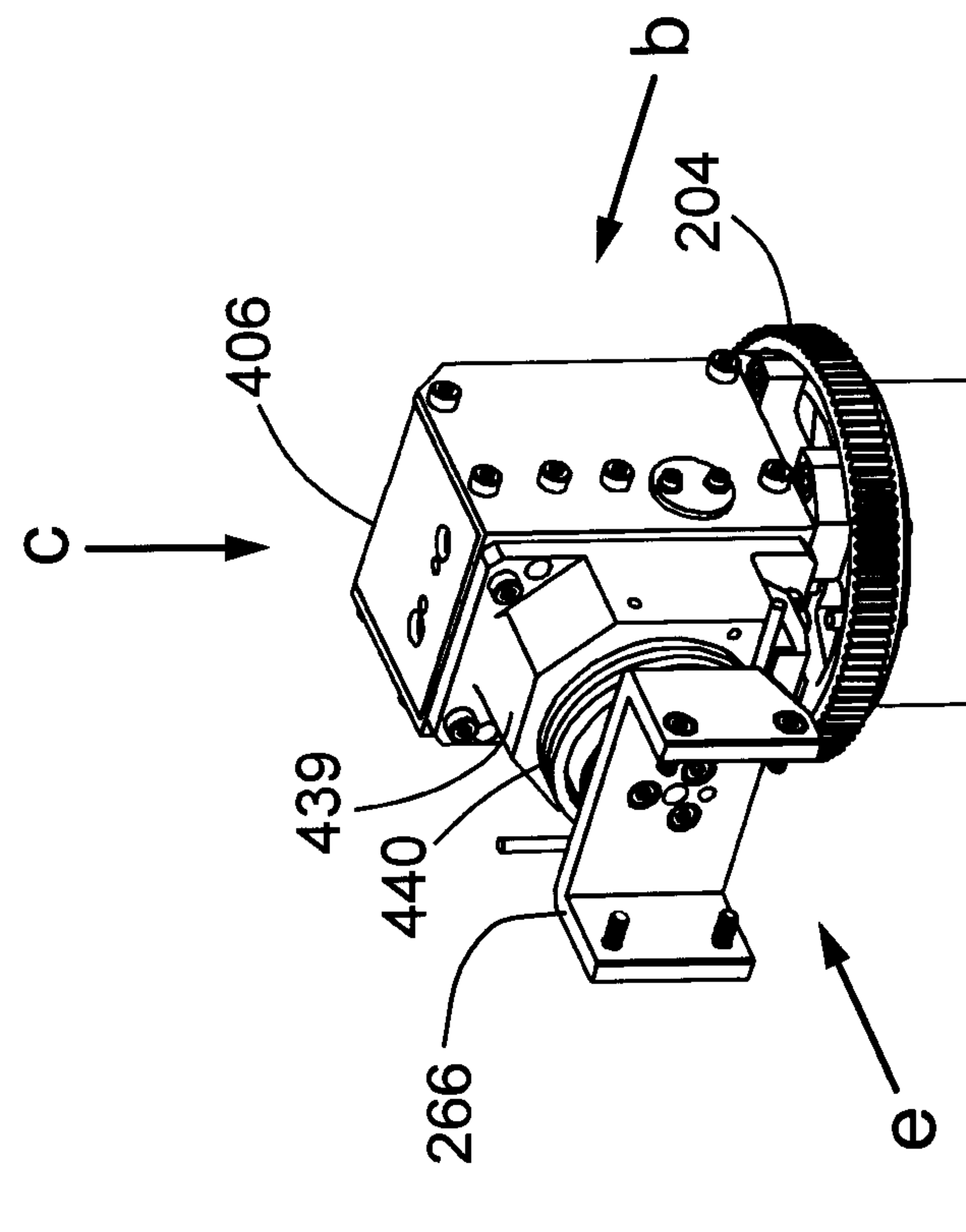


FIG. 18a

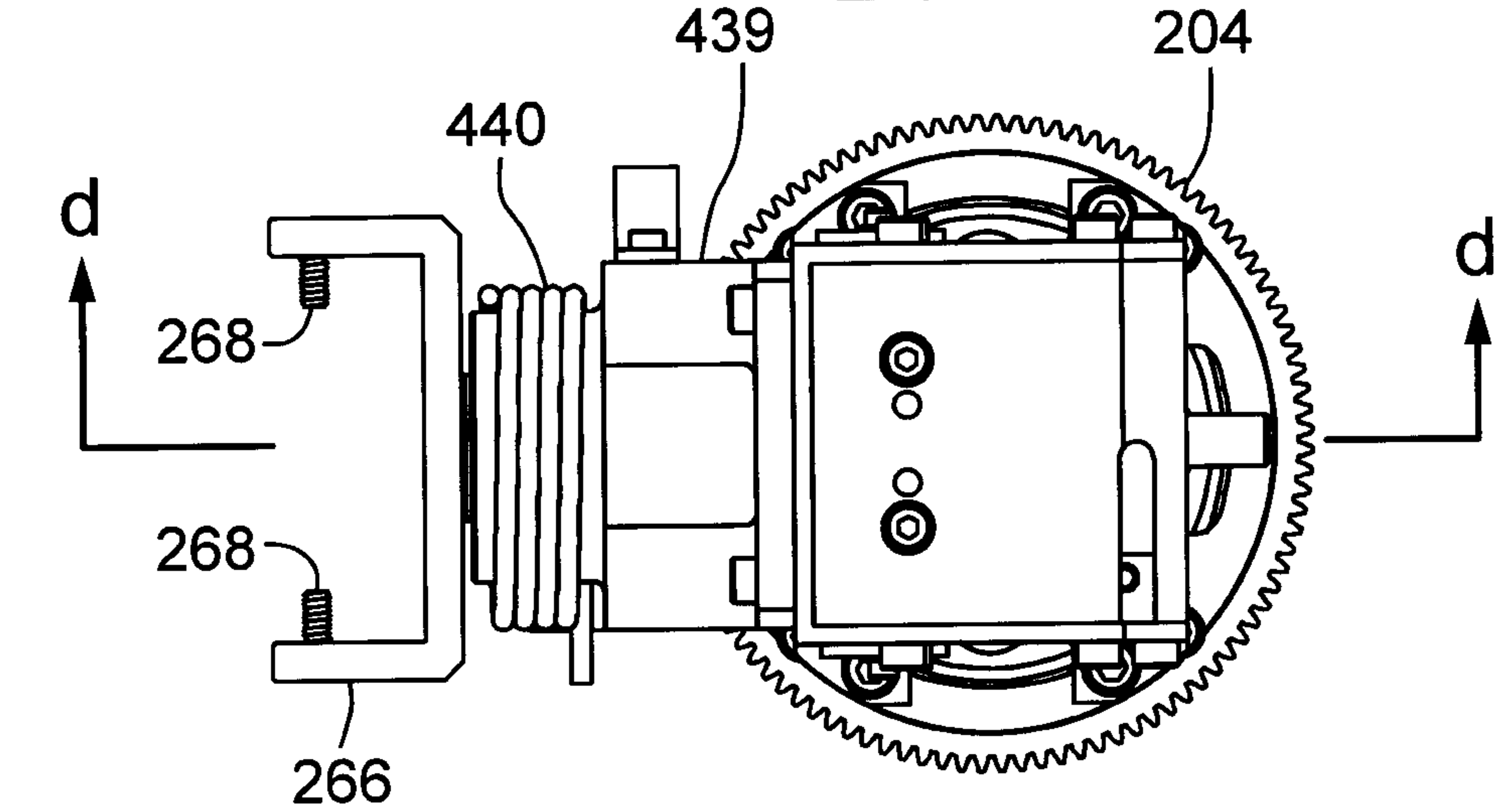


FIG. 18c

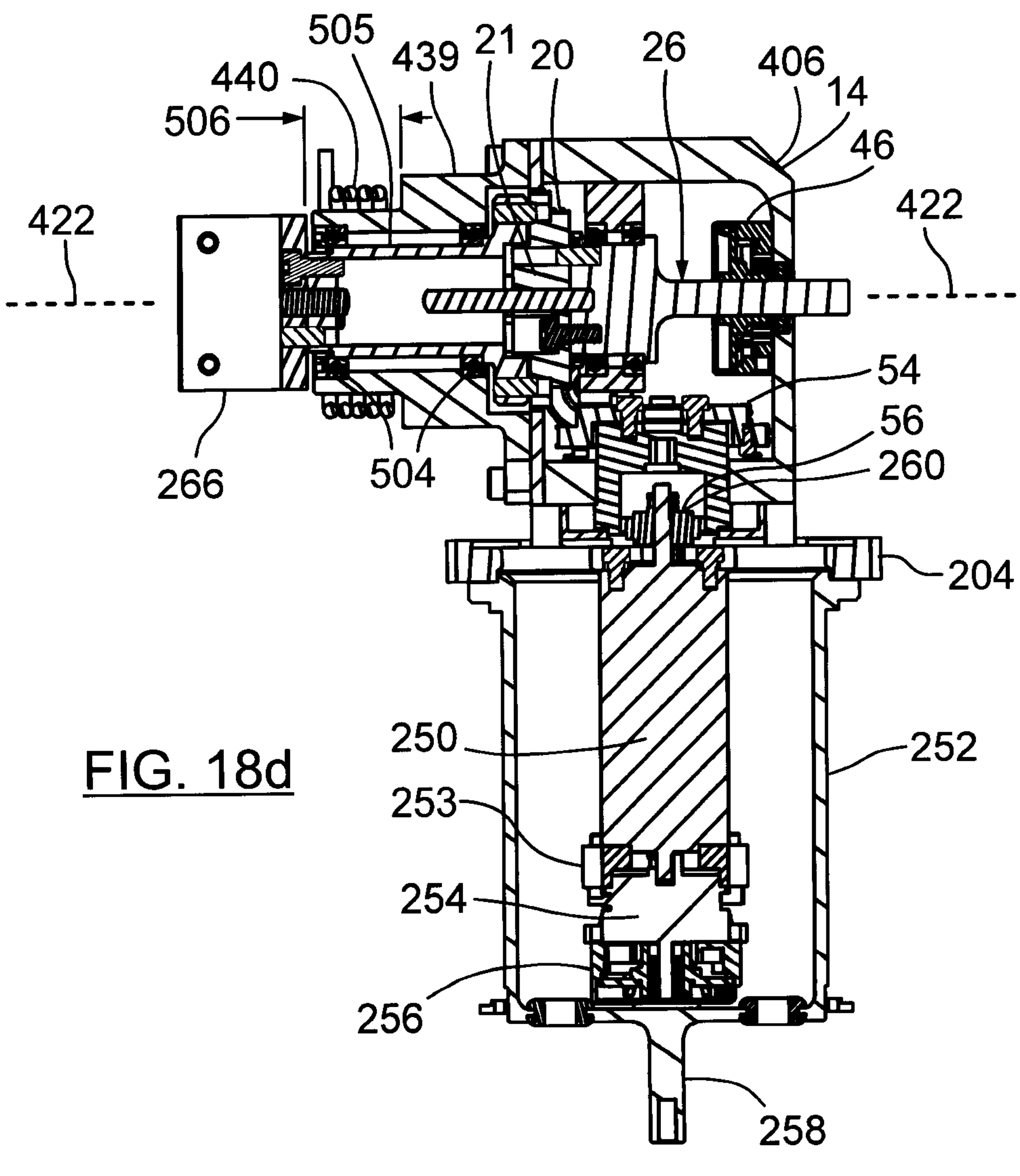


FIG. 18d

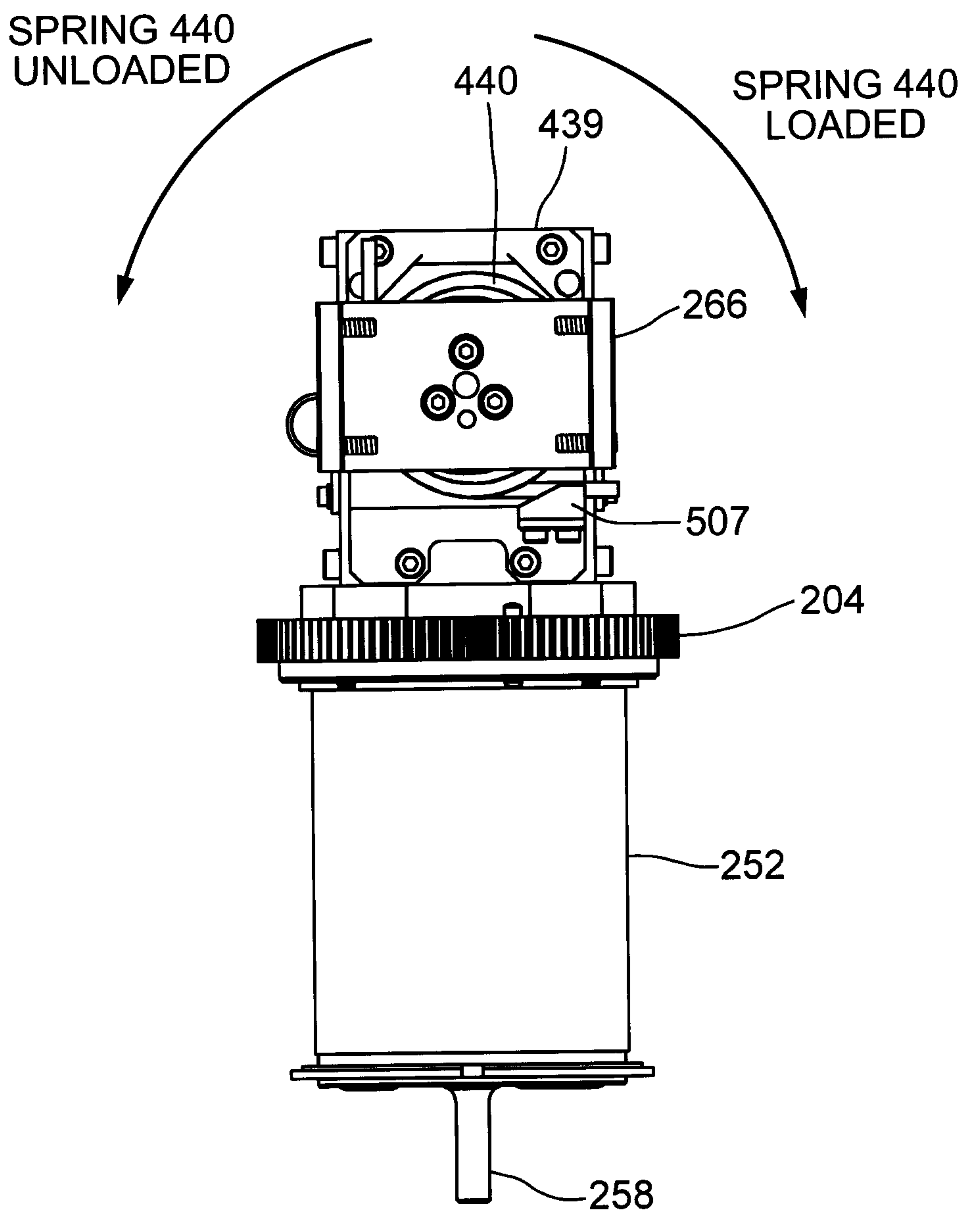

SPRING 440 UNLOADED
SPRING 440 LOADED
440
439
266
507
204
252
258

FIG. 18e

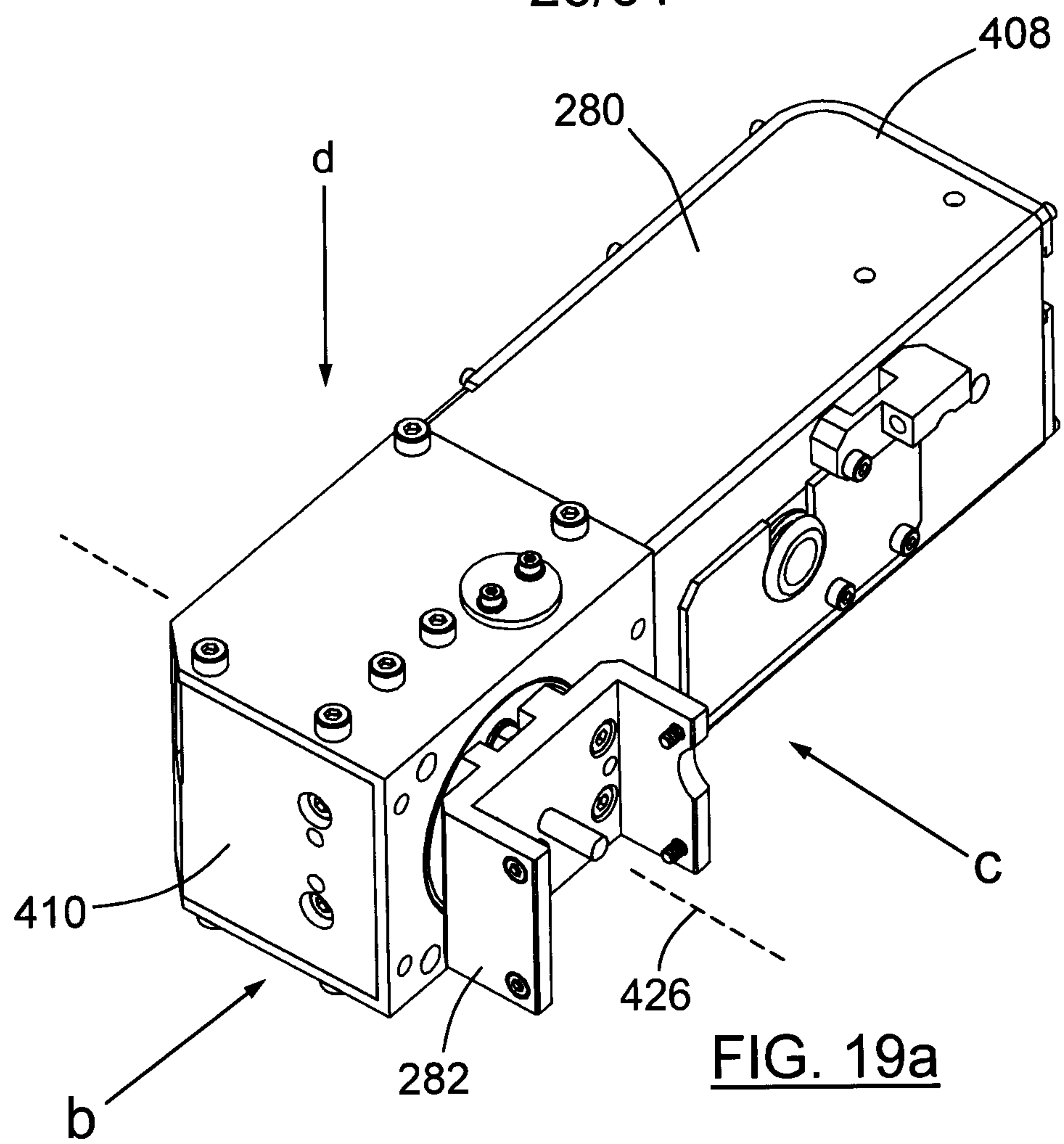


FIG. 19a

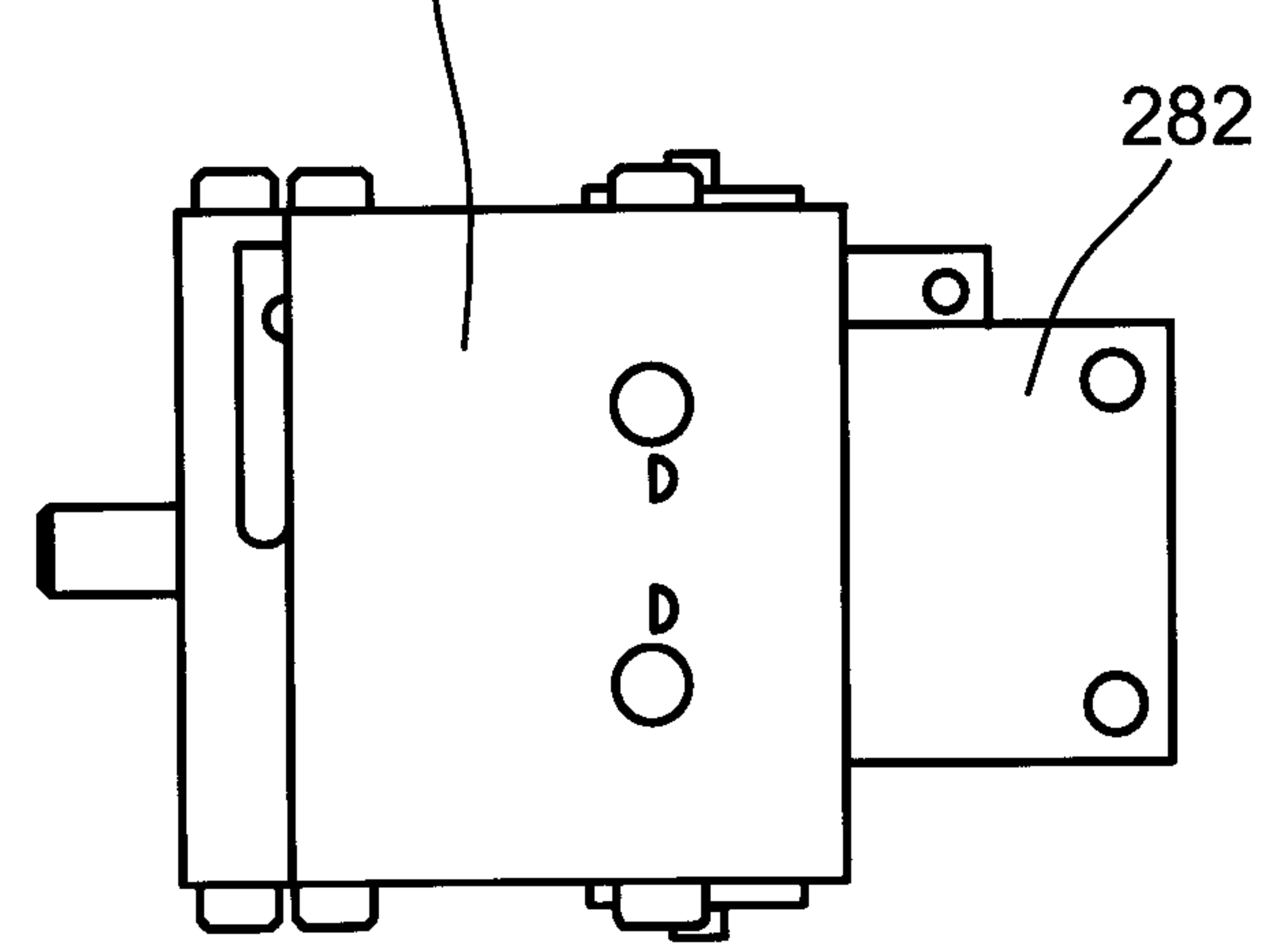
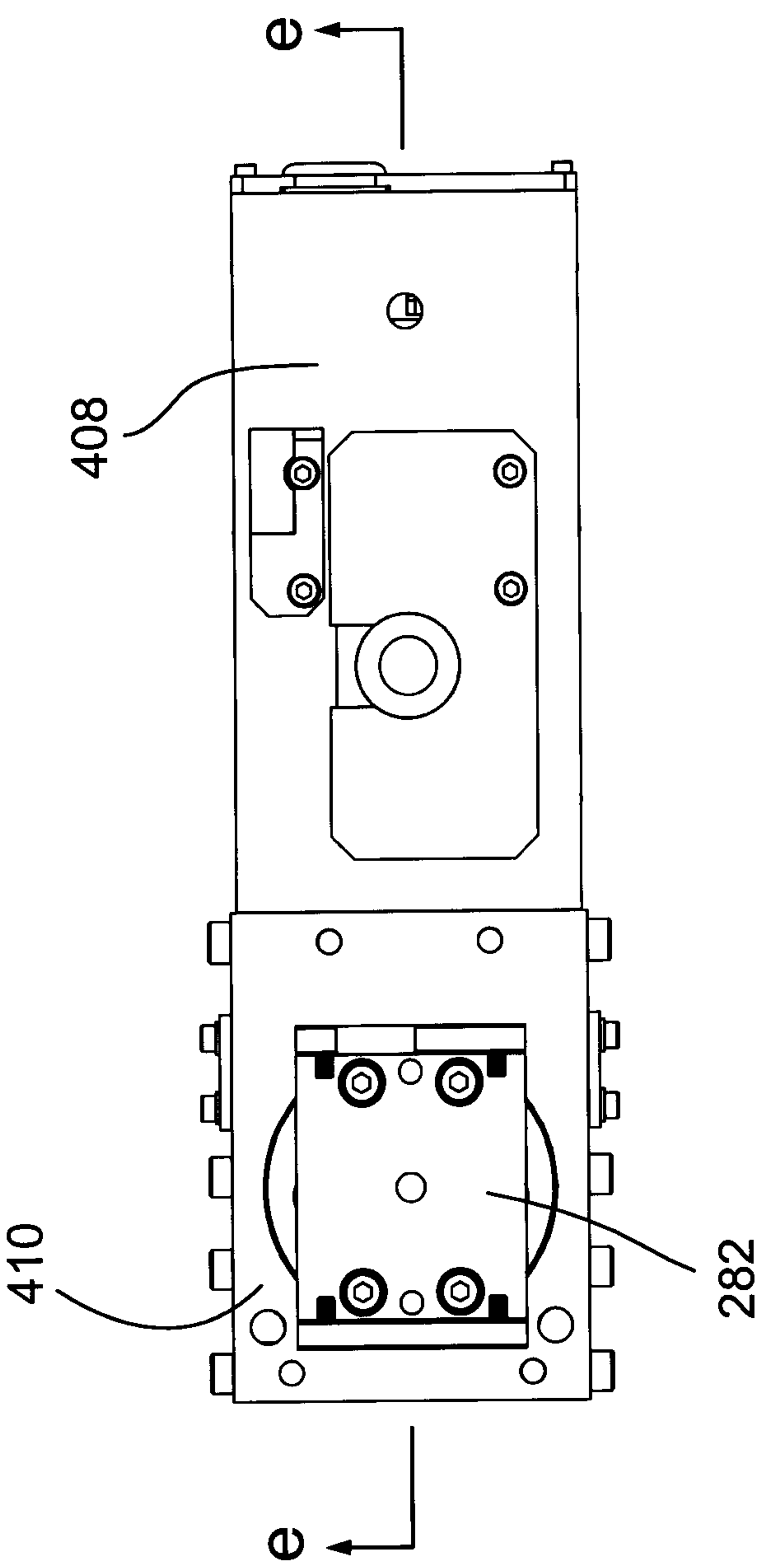


FIG. 19b

FIG. 19c



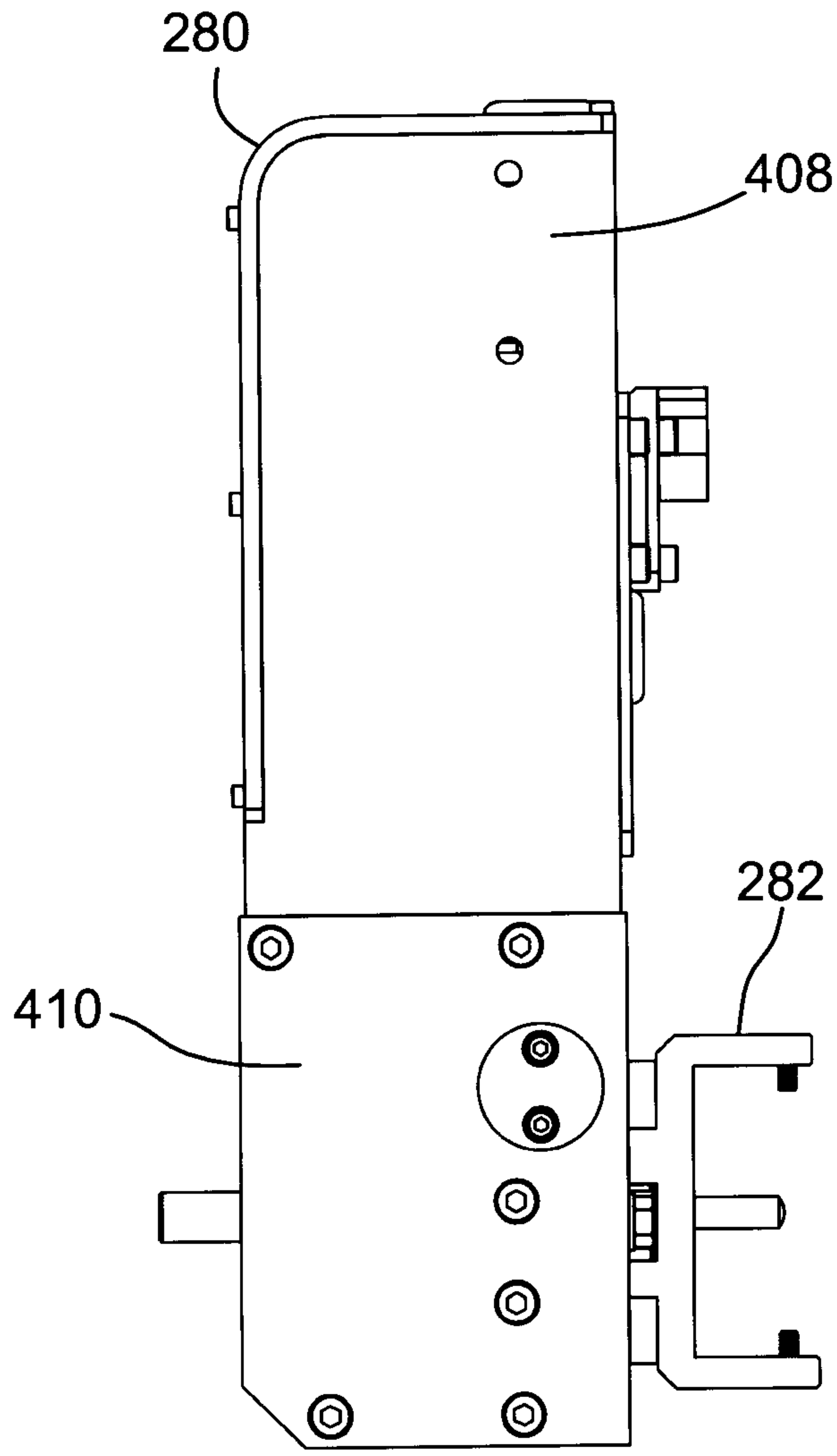


FIG. 19d

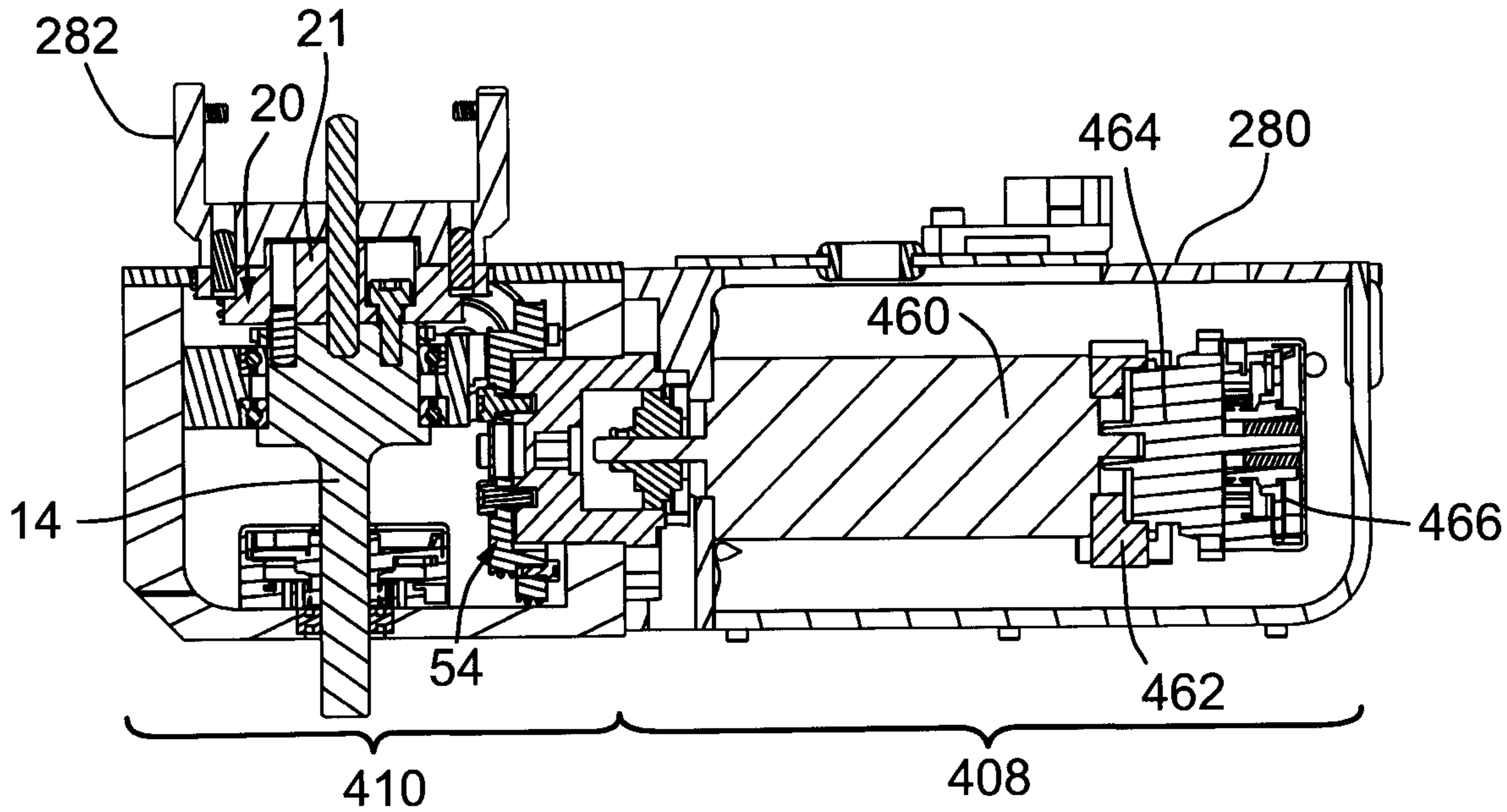


FIG. 19e

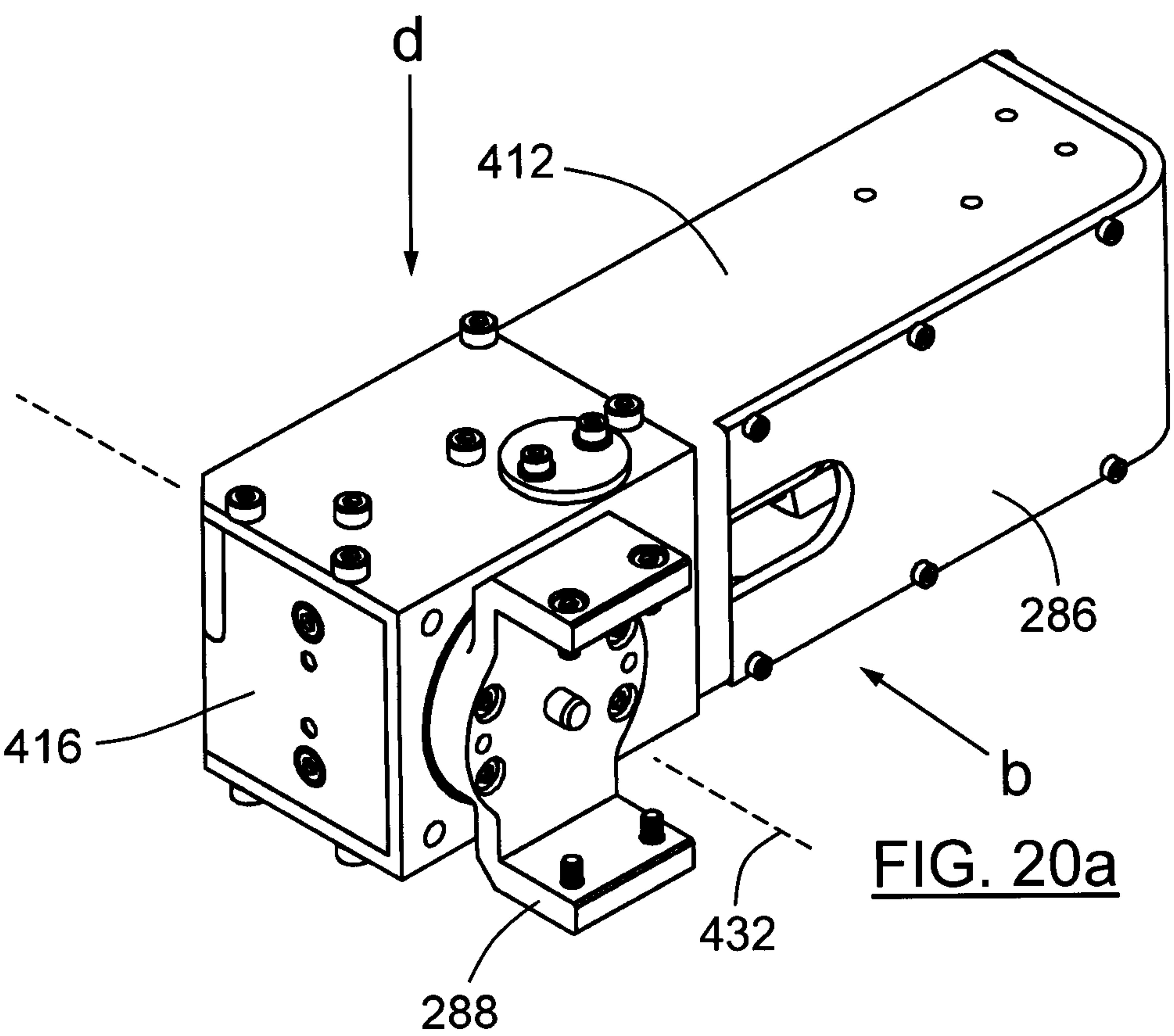


FIG. 20a

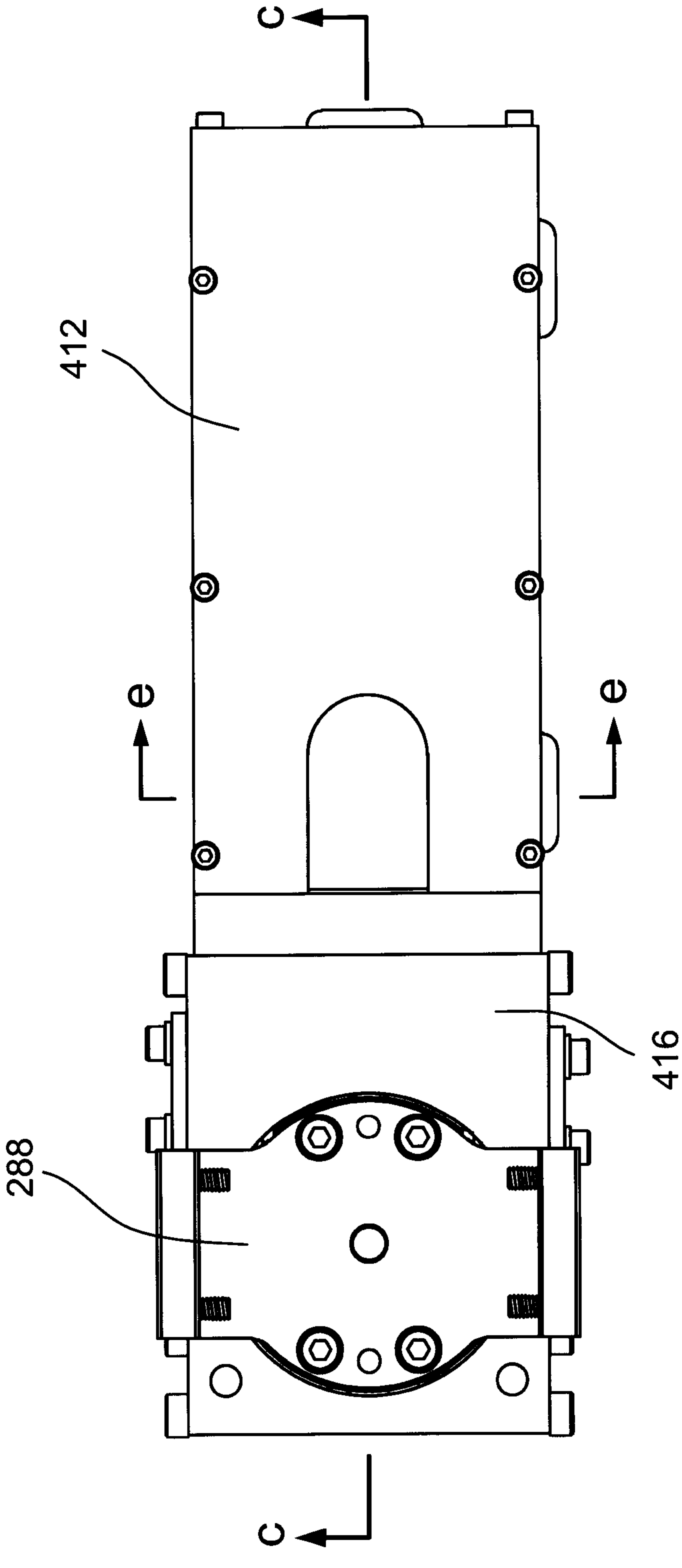


FIG. 20b

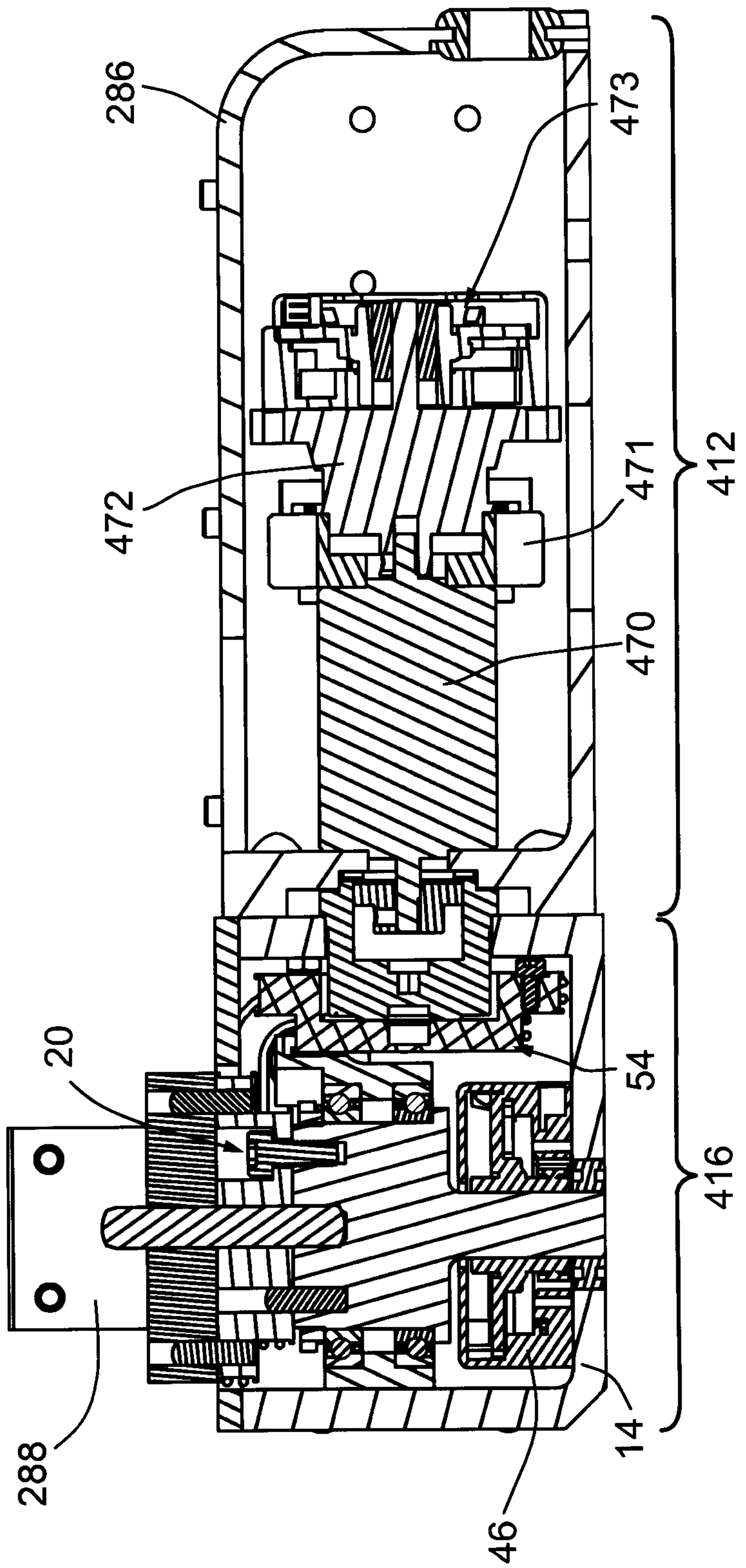


FIG. 20c

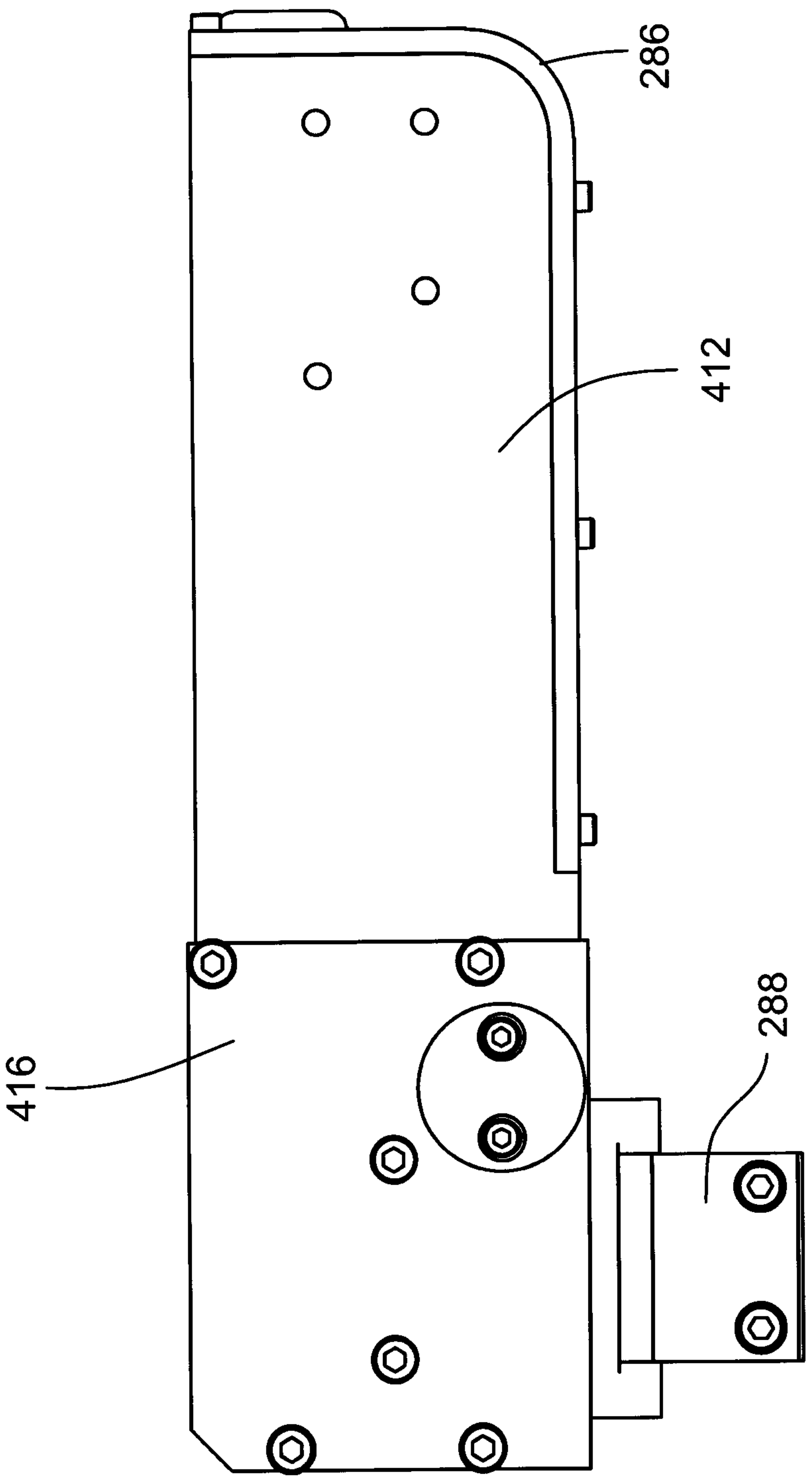


FIG. 20d

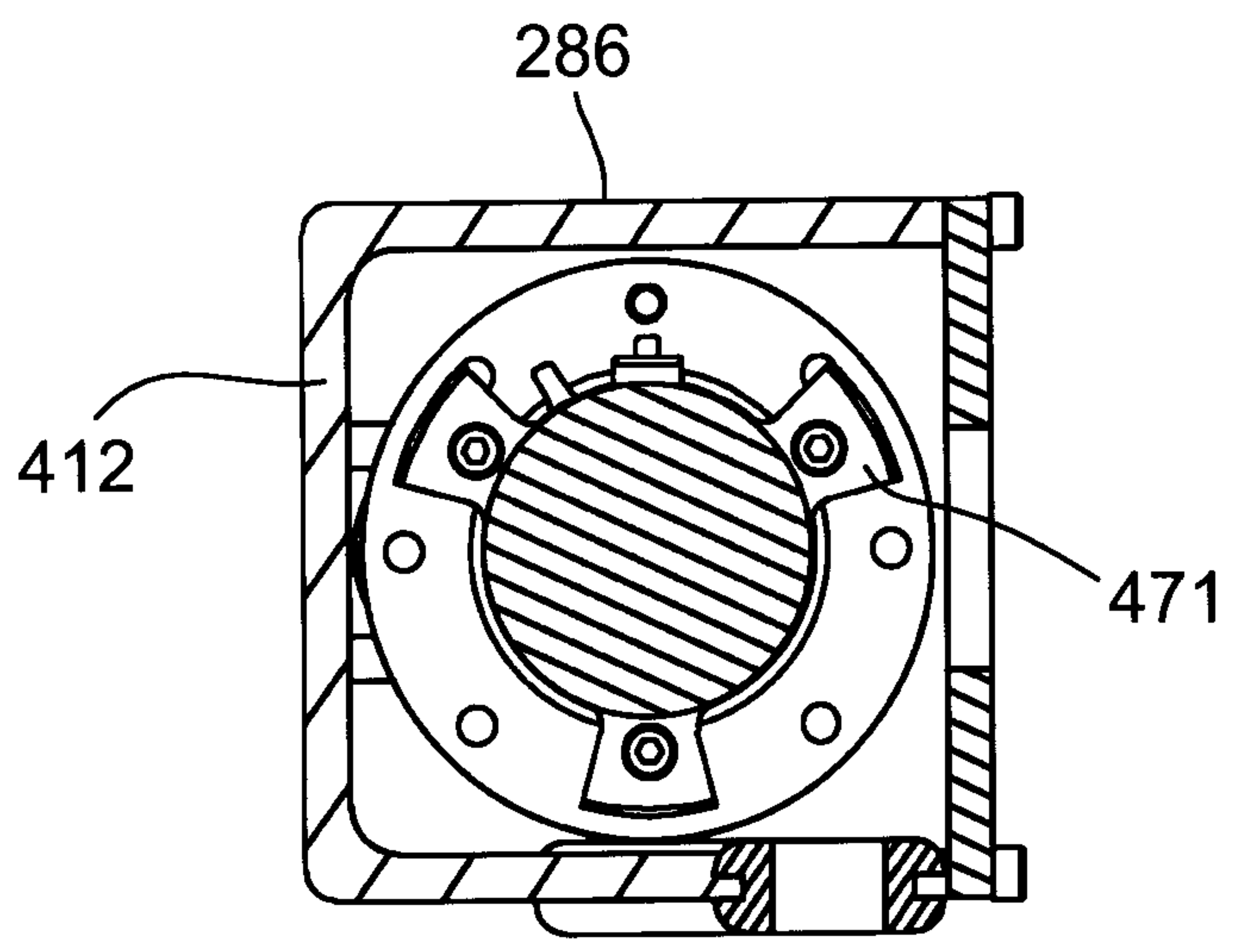


FIG. 20e

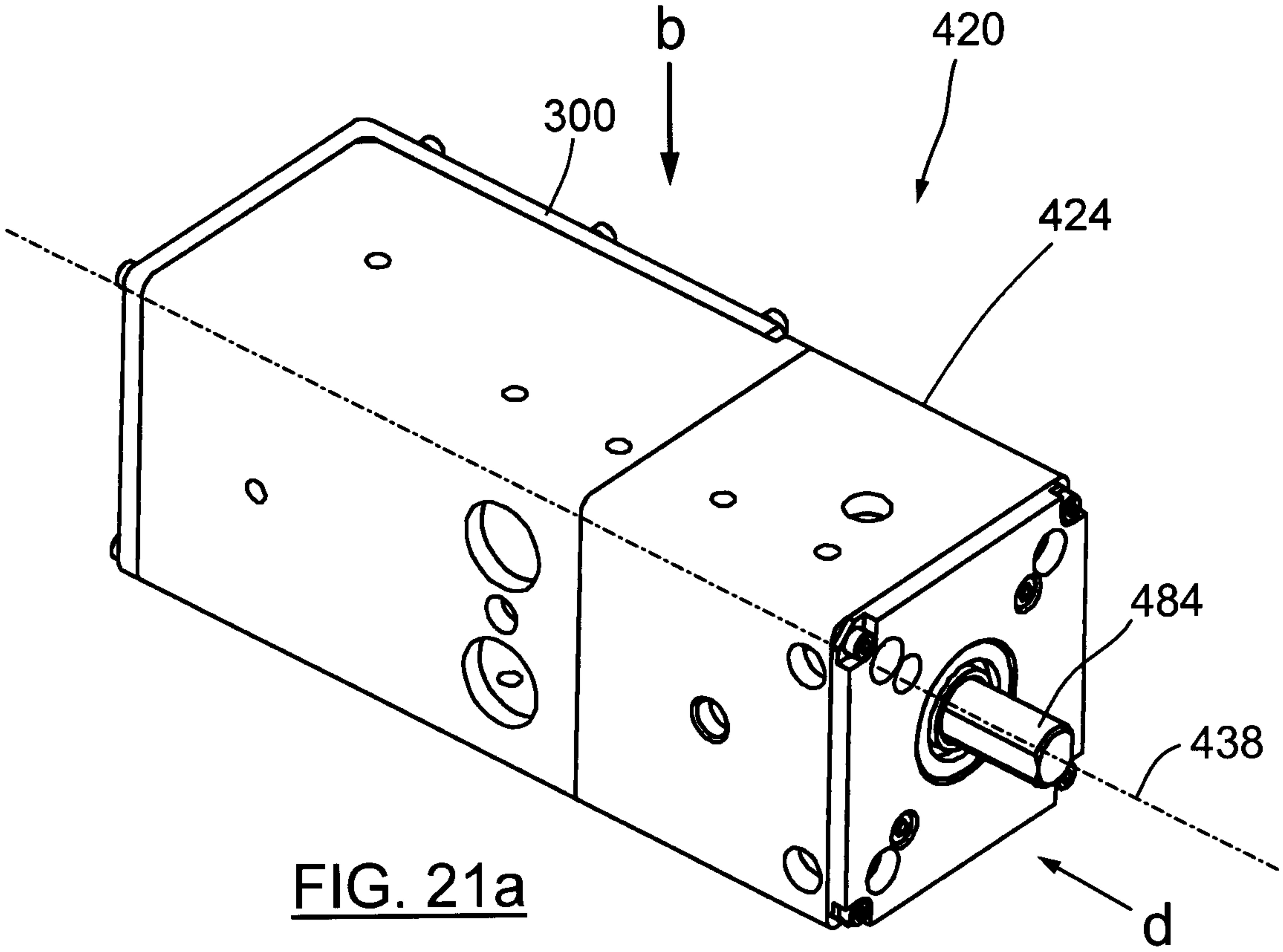


FIG. 21a

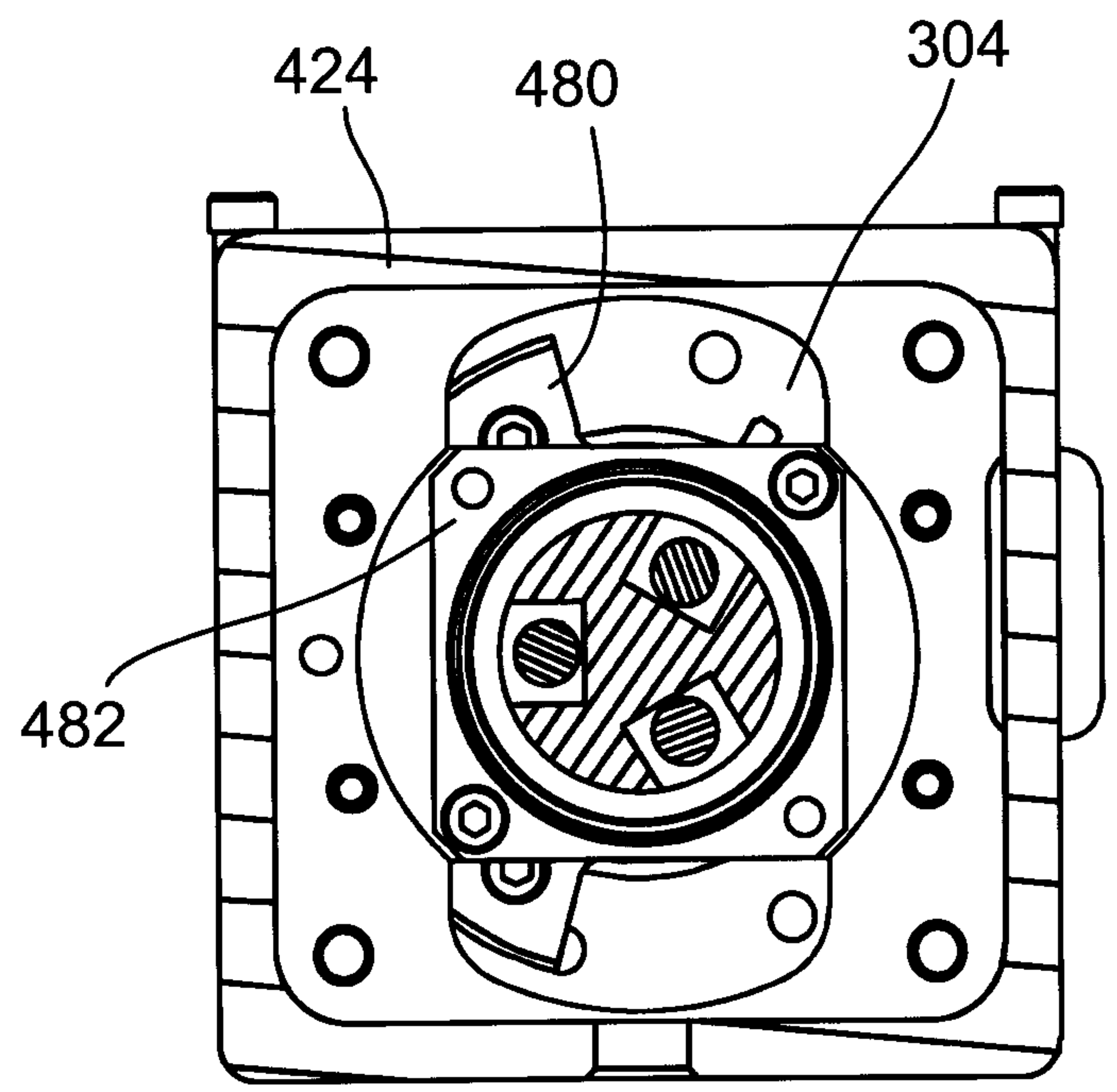


FIG. 21c

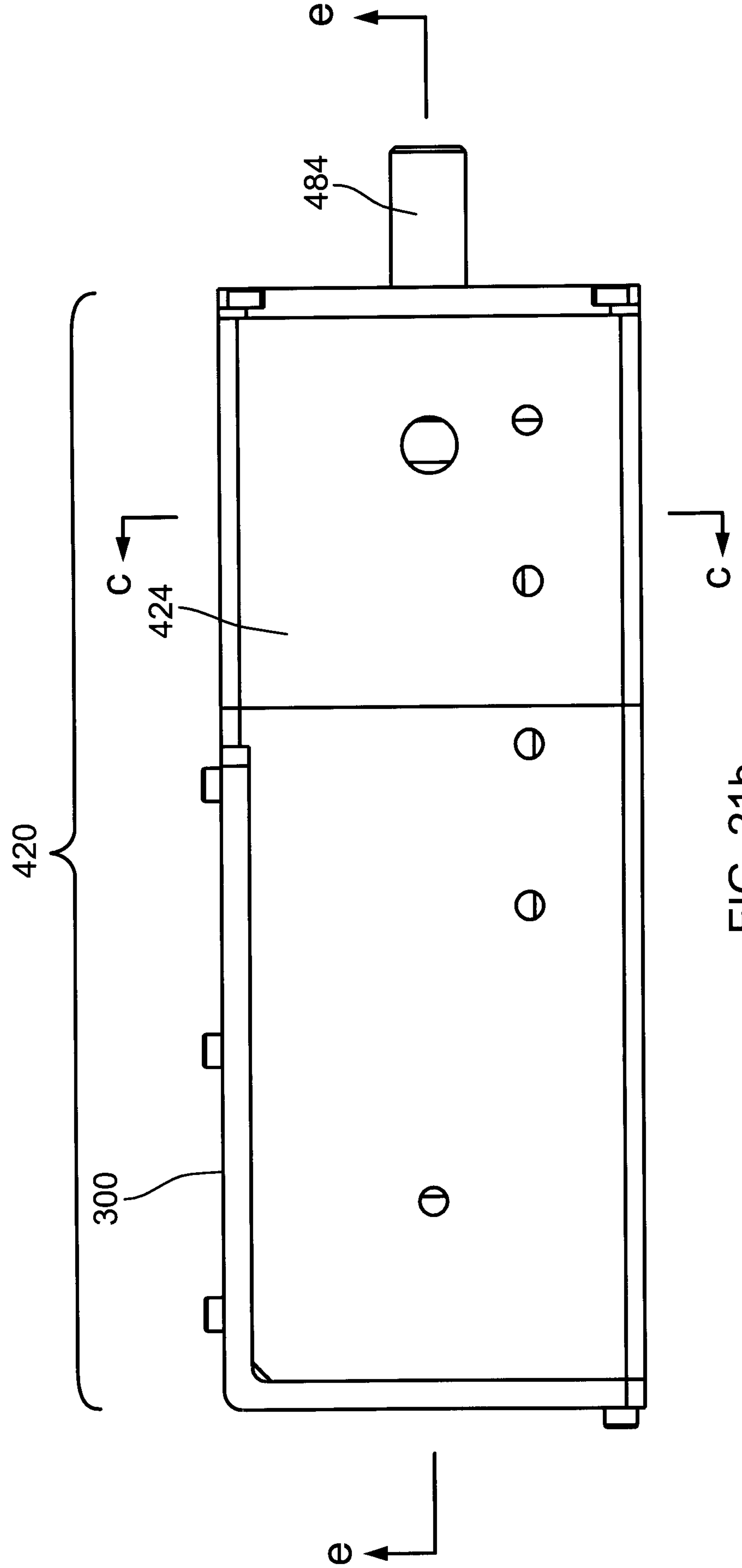


FIG. 21b

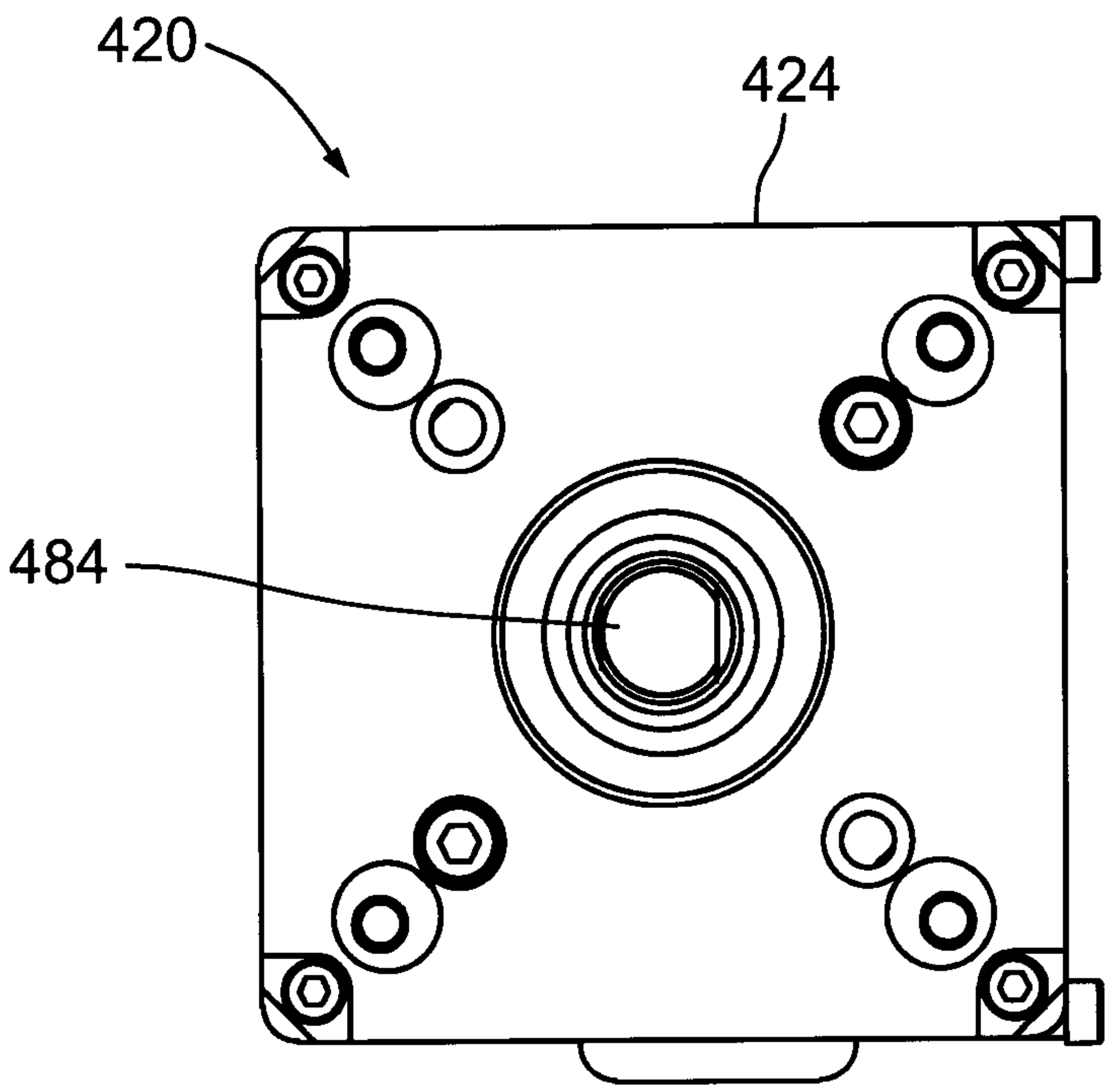


FIG. 21d

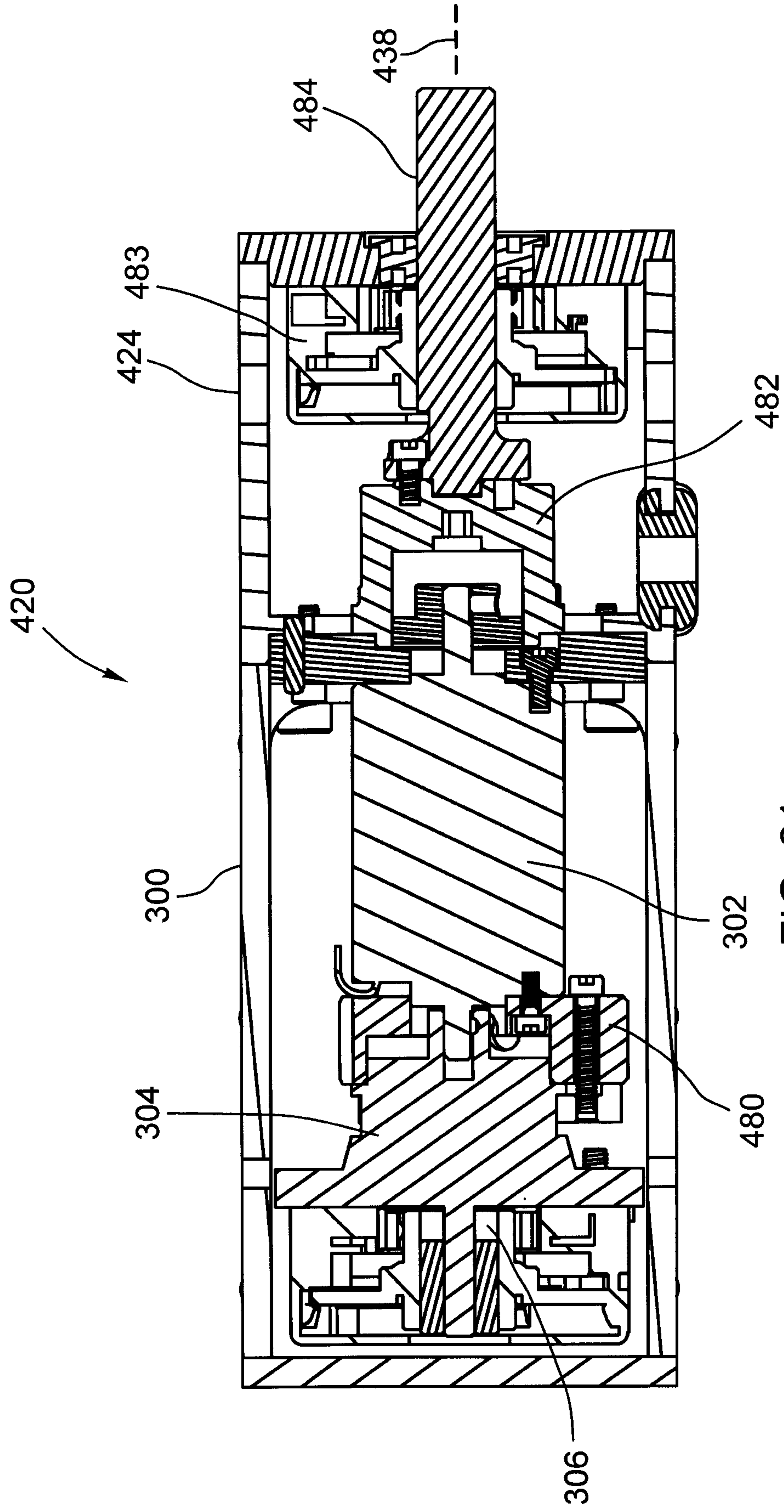


FIG. 21e

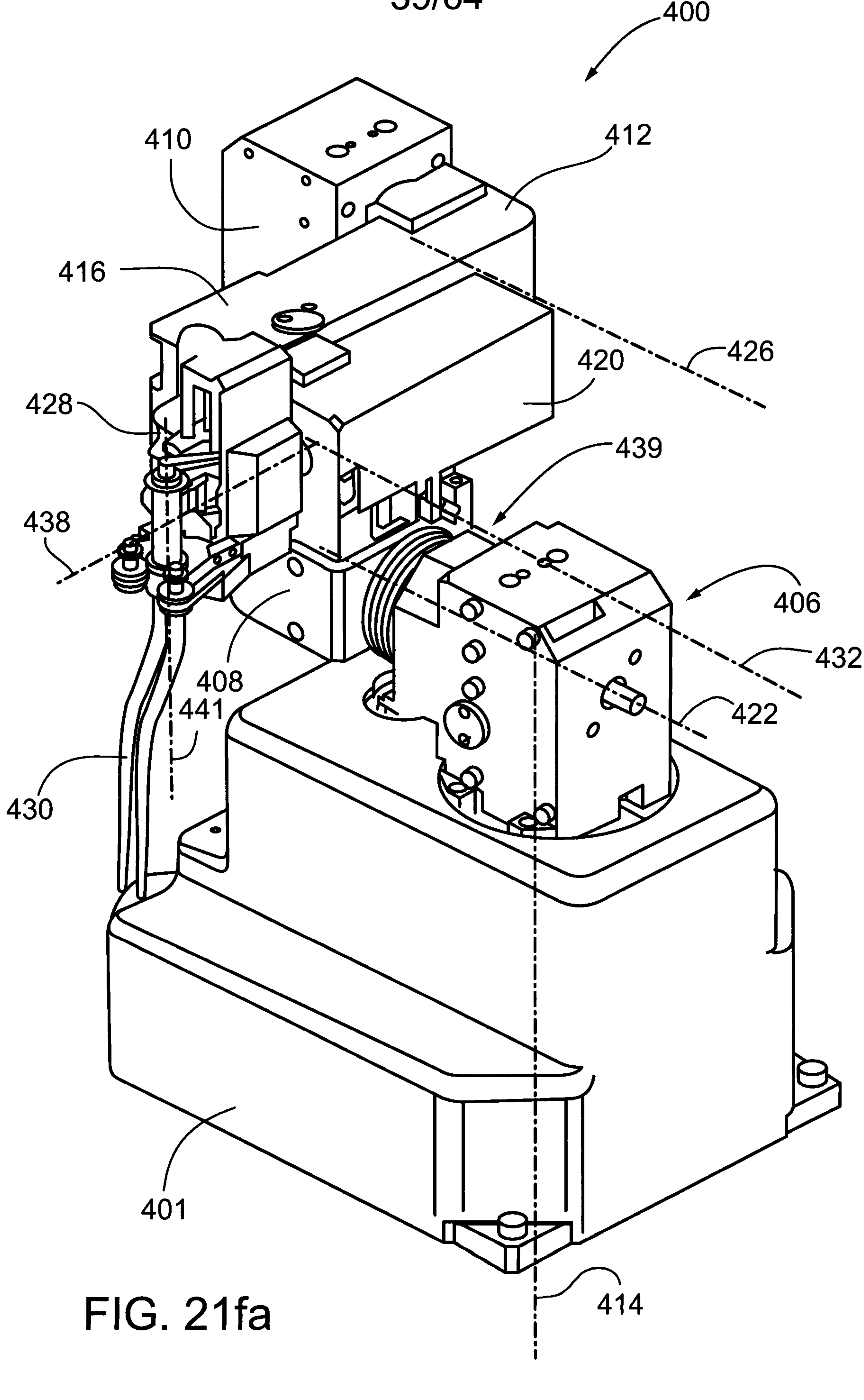

400
410
412
416
420
426
428
439
438
406
432
408
422
441
430
401
414

FIG. 21fa

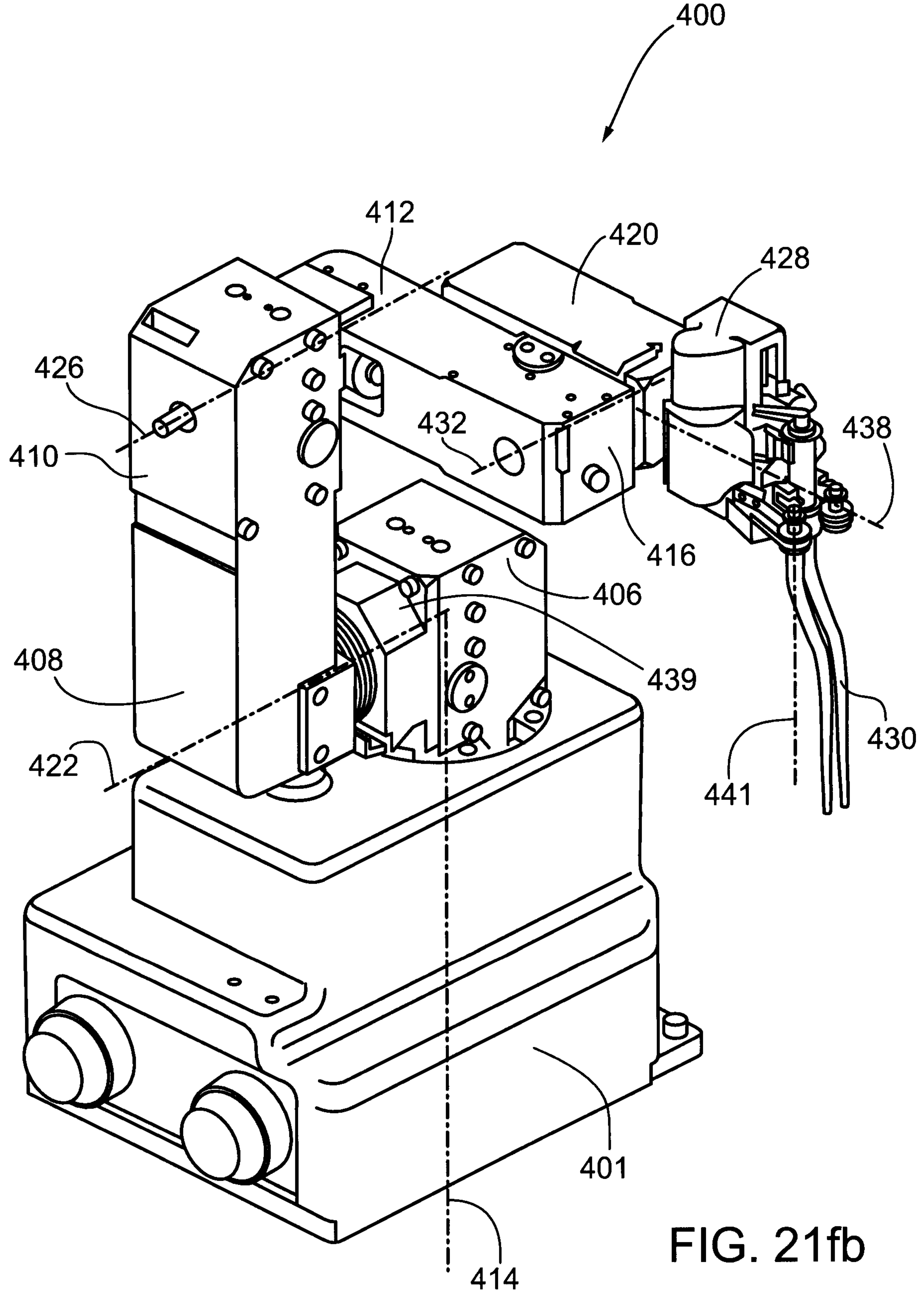

400
412
420
428
426
432
438
410
416
406
439
408
430
422
441
401
414

FIG. 21fb

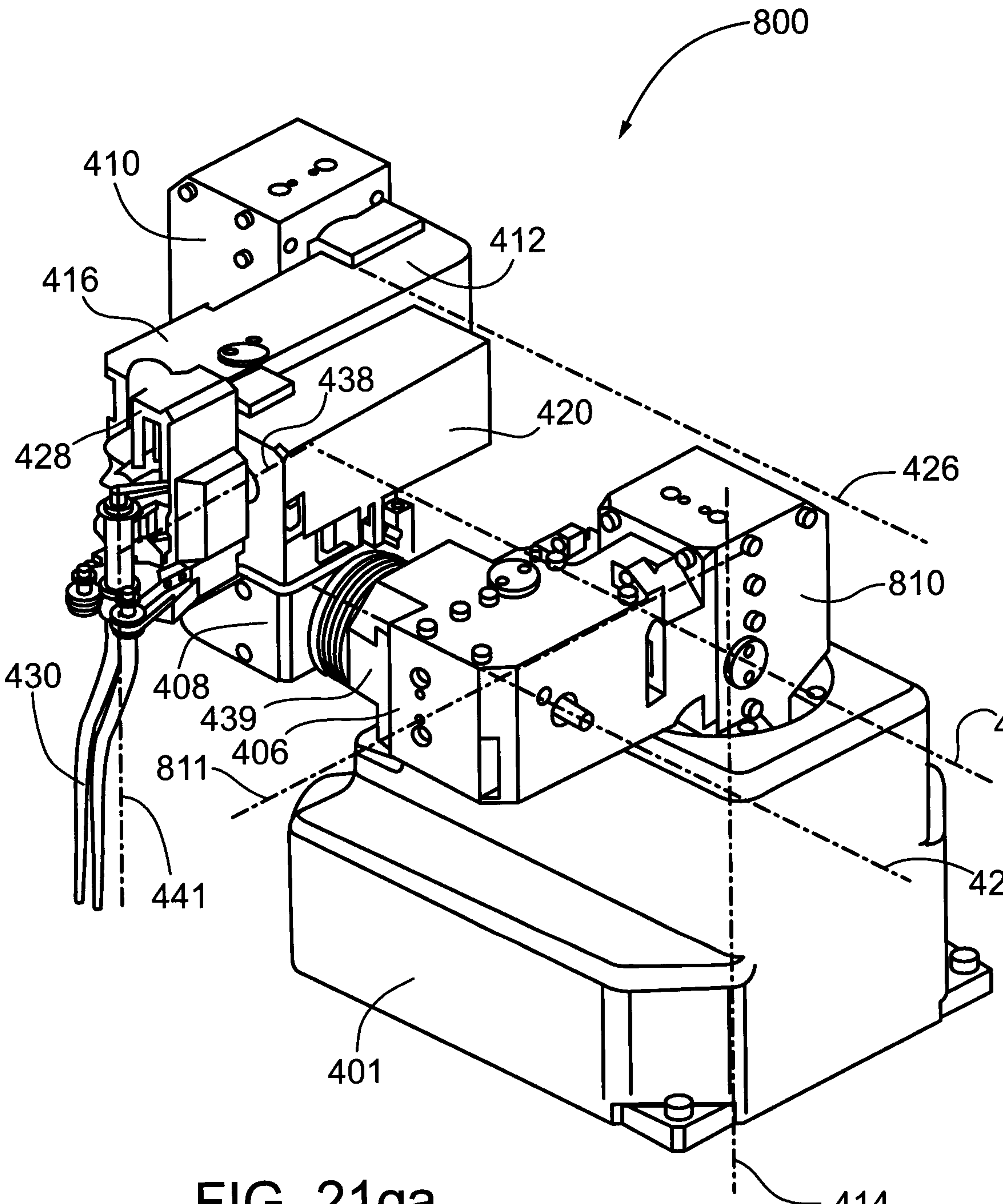

800
410
412
416
438
420
428
426
810
430
408
439
406
432
811
441
422
401
414

FIG. 21ga

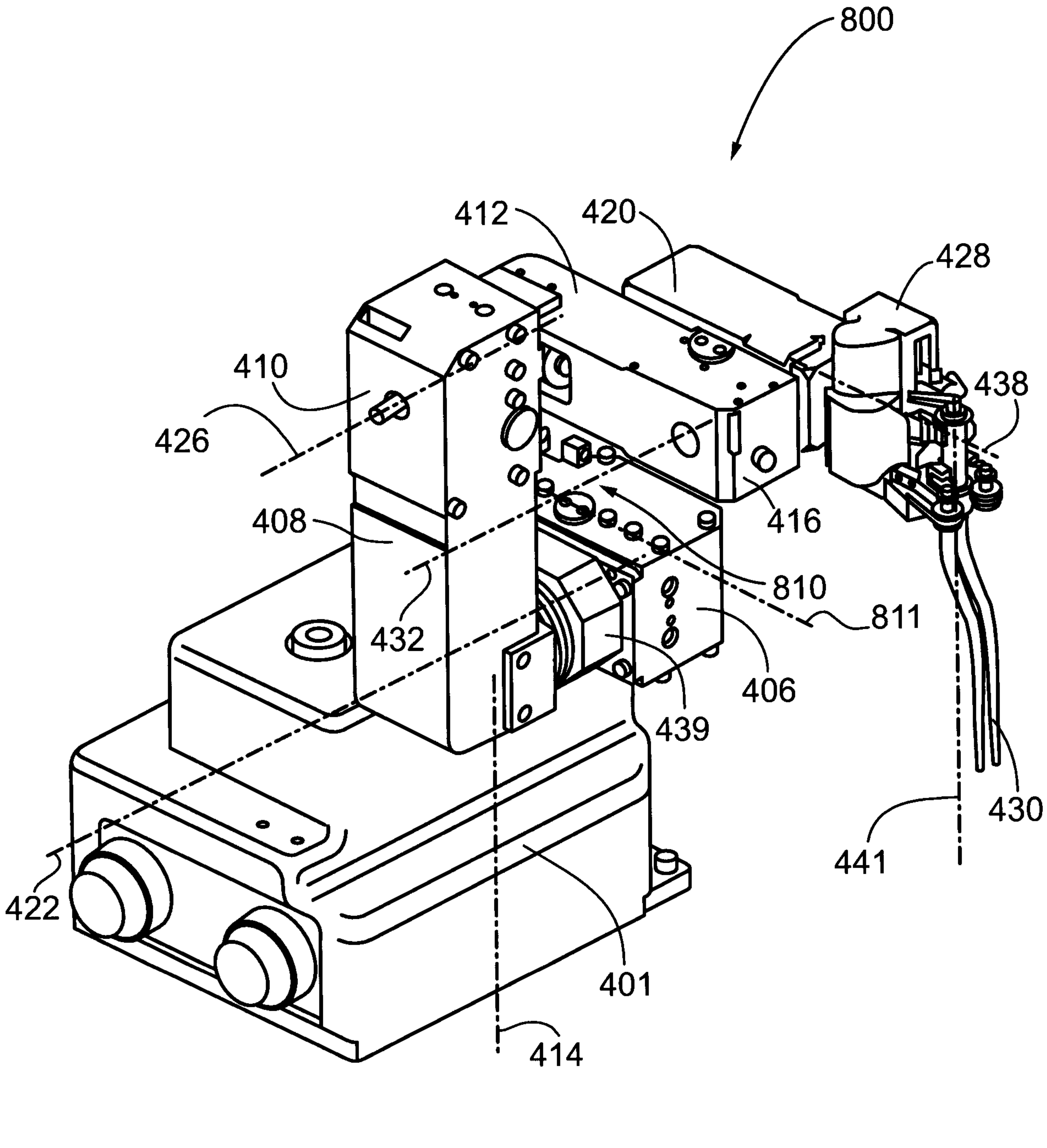

800
412
420
428
410
438
426
416
408
810
811
432
406
439
430
441
422
401
414

FIG. 21gb

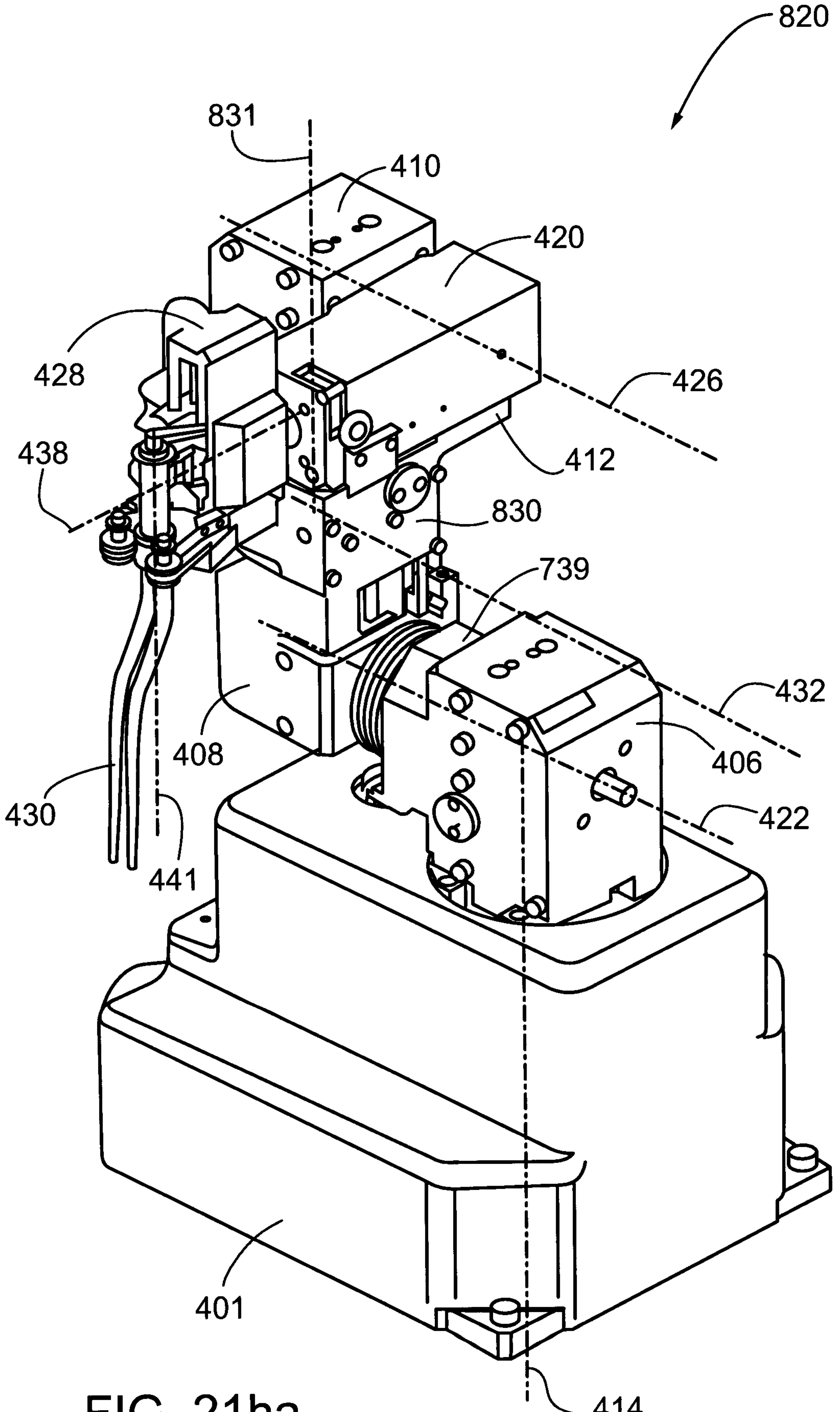

820
831
410
420
428
426
438
412
830
739
432
408
406
430
422
441
401
414

FIG. 21ha

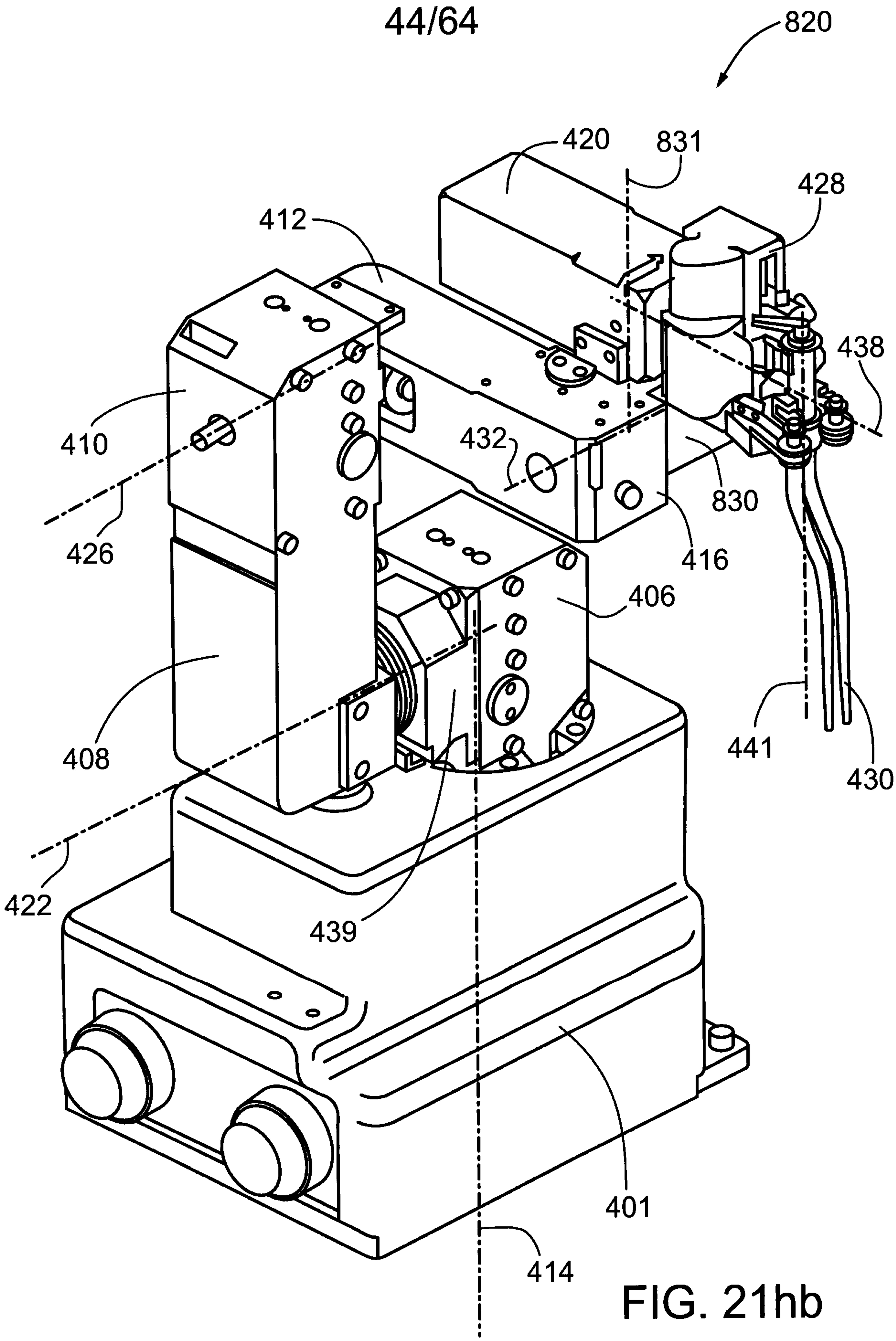

820
420
831
428
412
438
410
432
830
426
416
406
408
441
430
422
439
401
414

FIG. 21hb

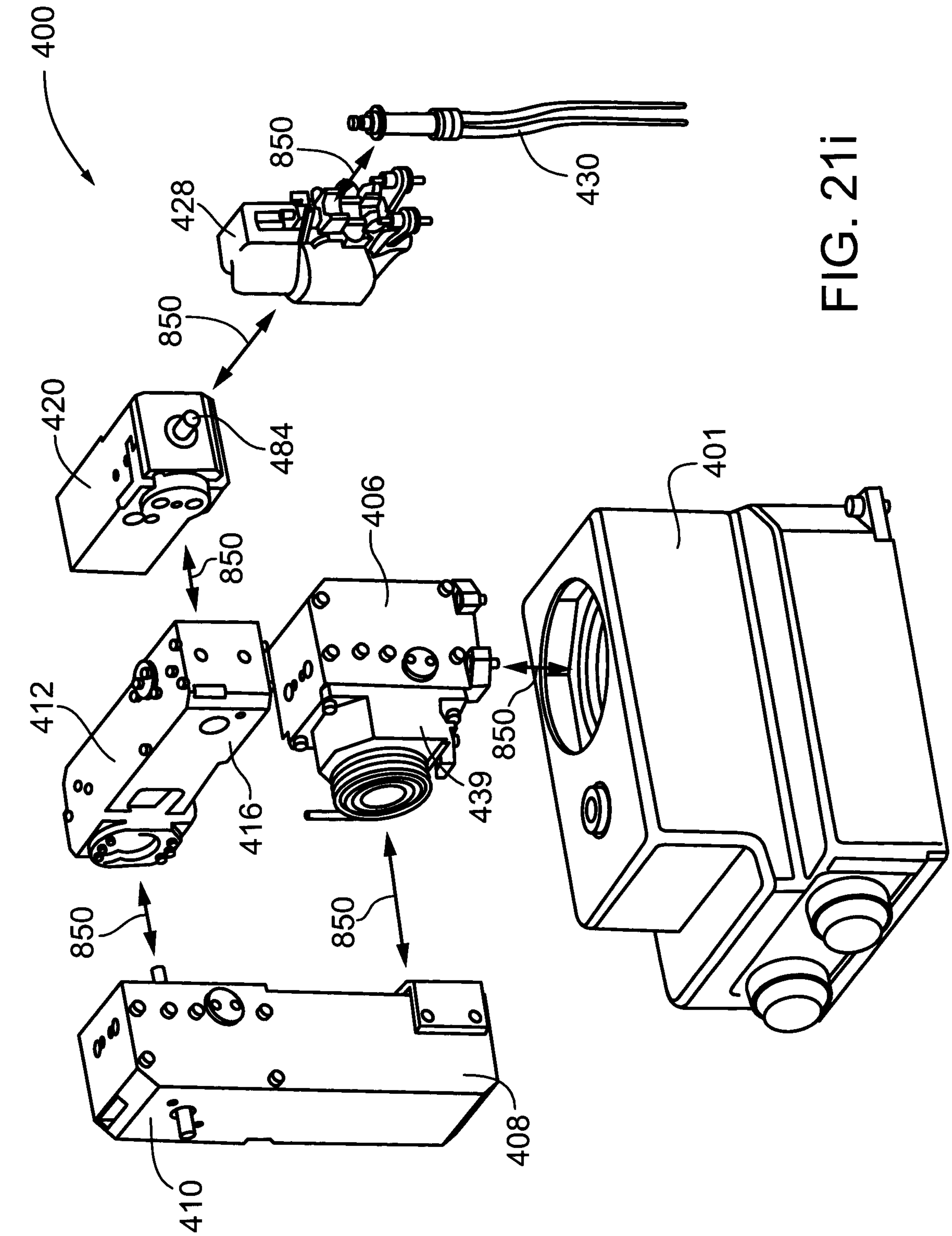

400
428
850
430
420
850
484
406
401
412
850
416
439
850
850
850
408
410

FIG. 21i

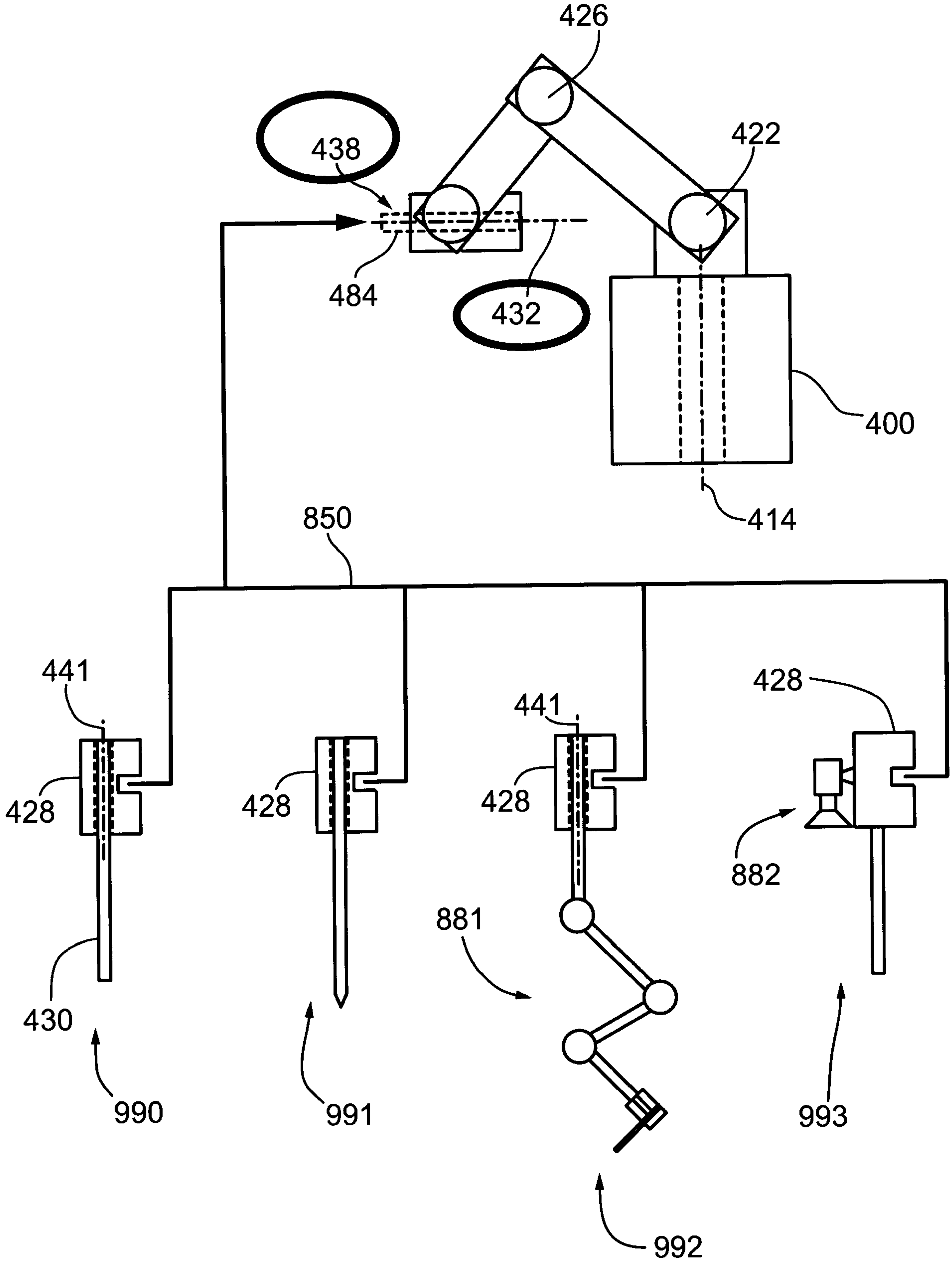

426
438
422
484
432
400
414
850
441
428
428
441
428
428
882
430
881
990
991
993
992

FIG. 21j

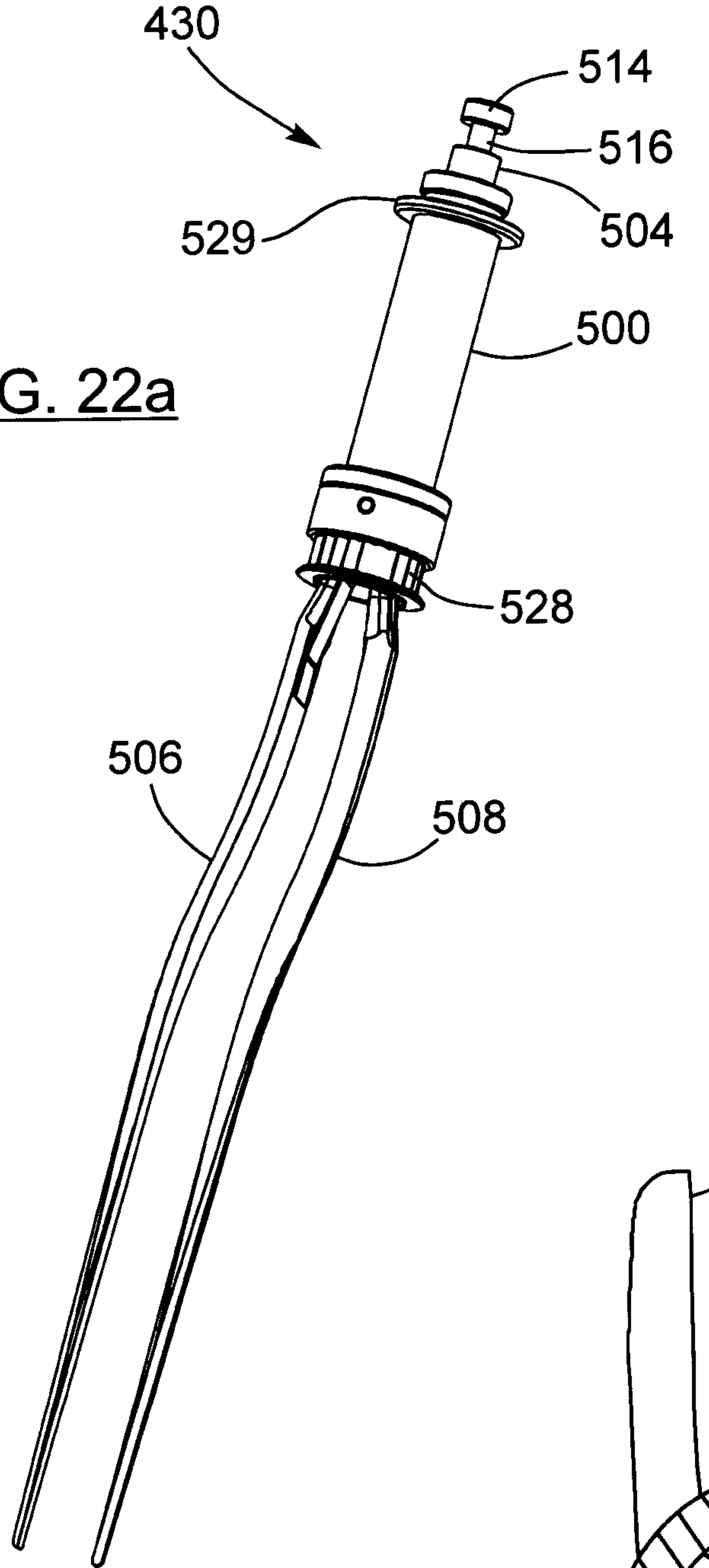


FIG. 22a

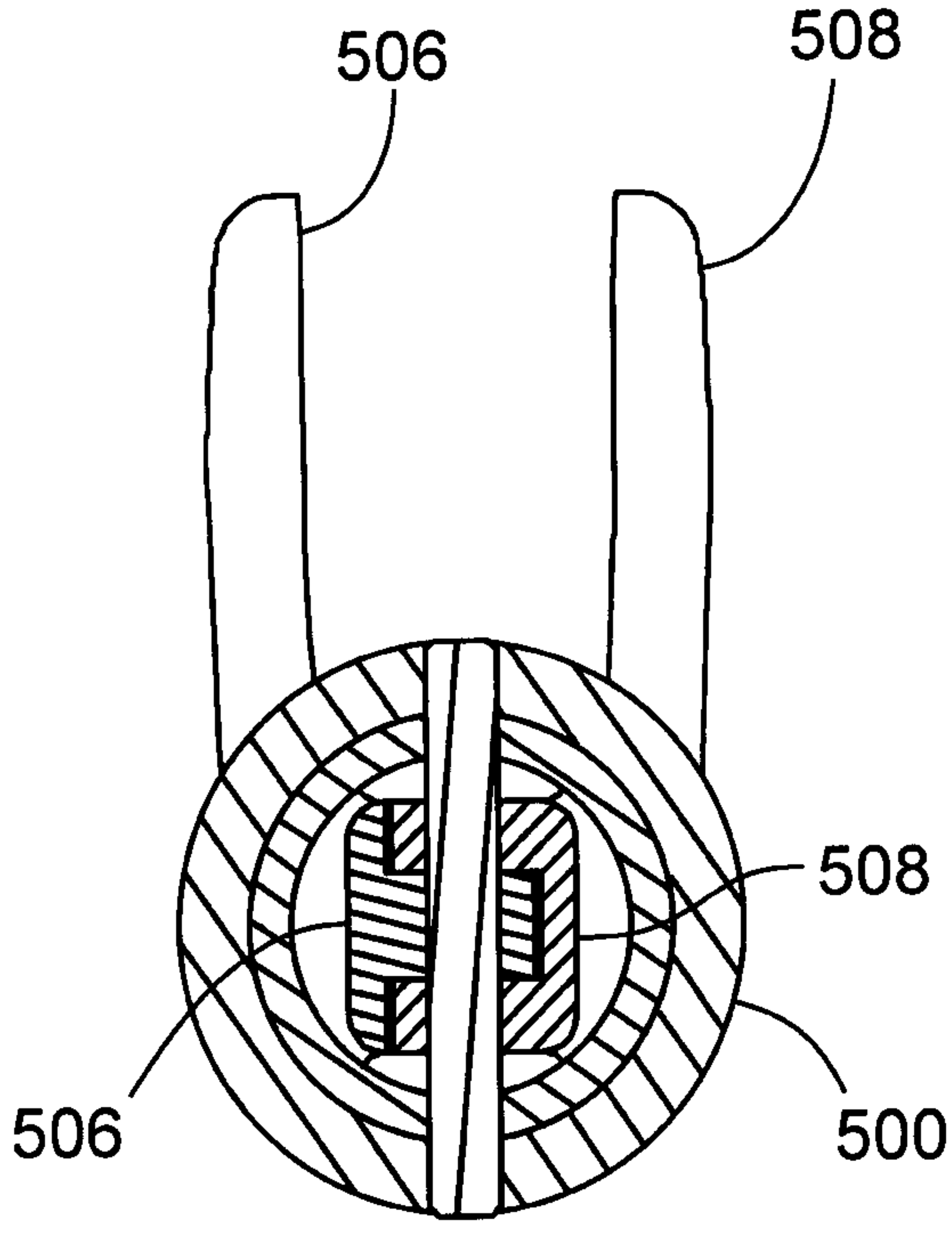


FIG. 22e

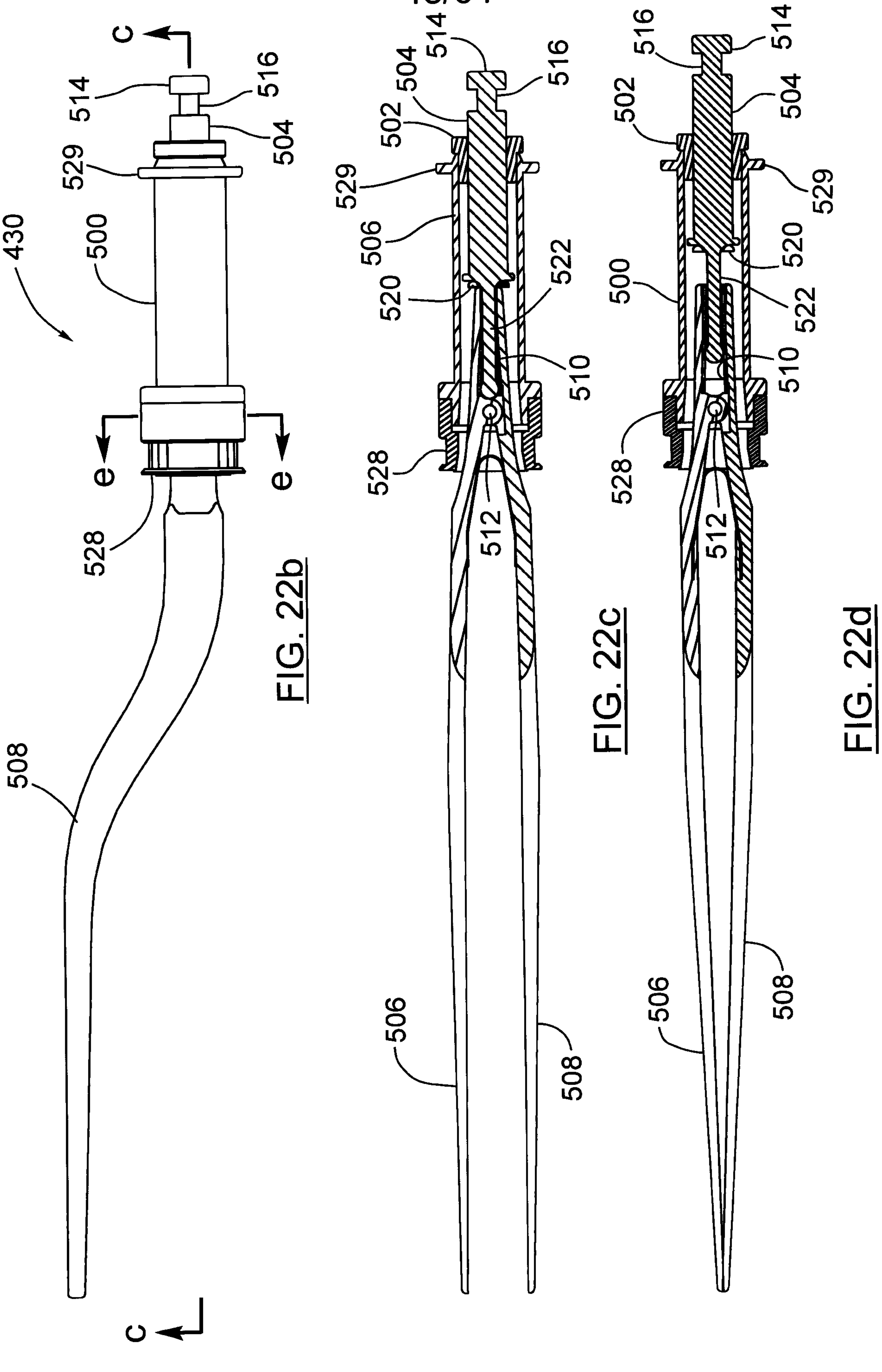


FIG. 22b

FIG. 22c

FIG. 22d

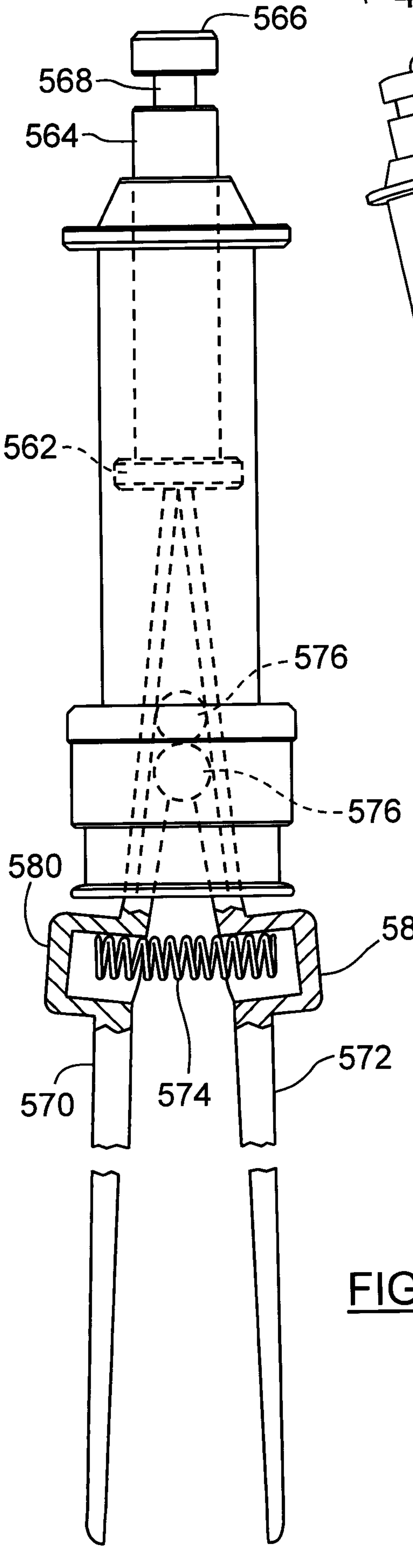


FIG. 23b

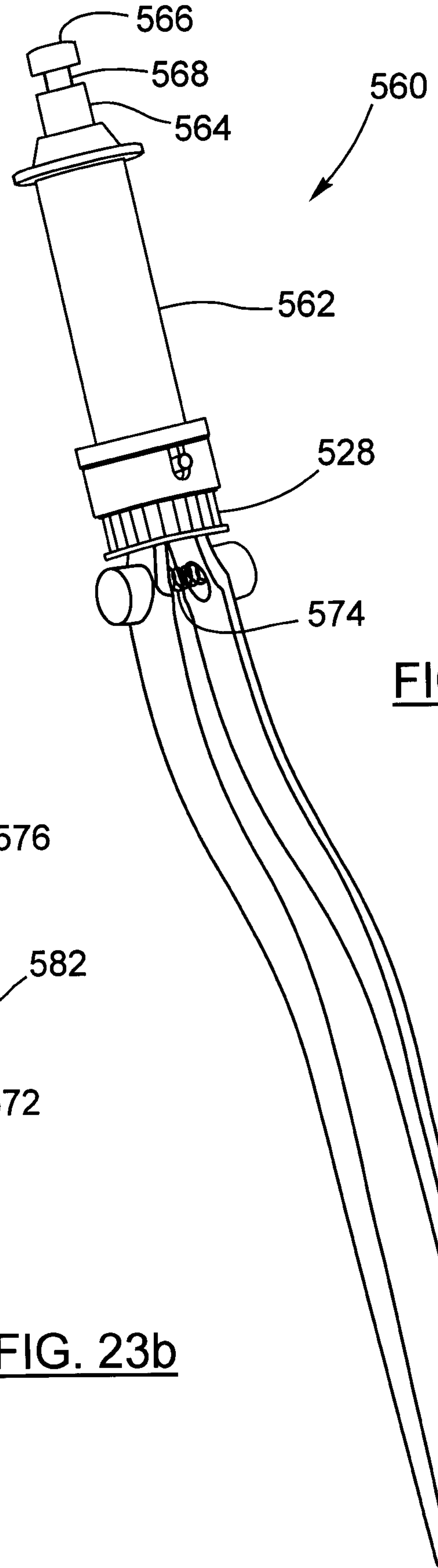


FIG. 23a

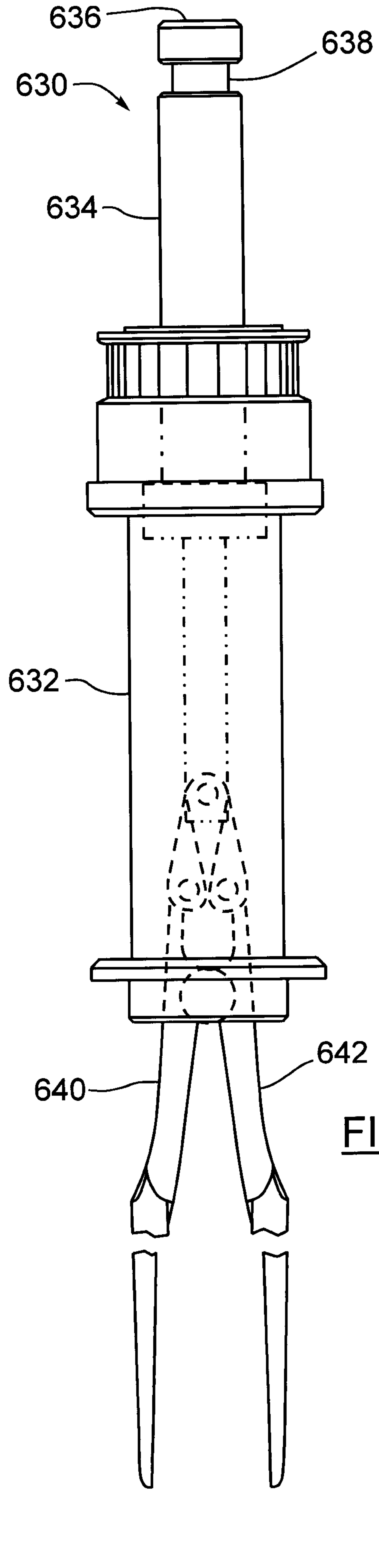


FIG. 24b

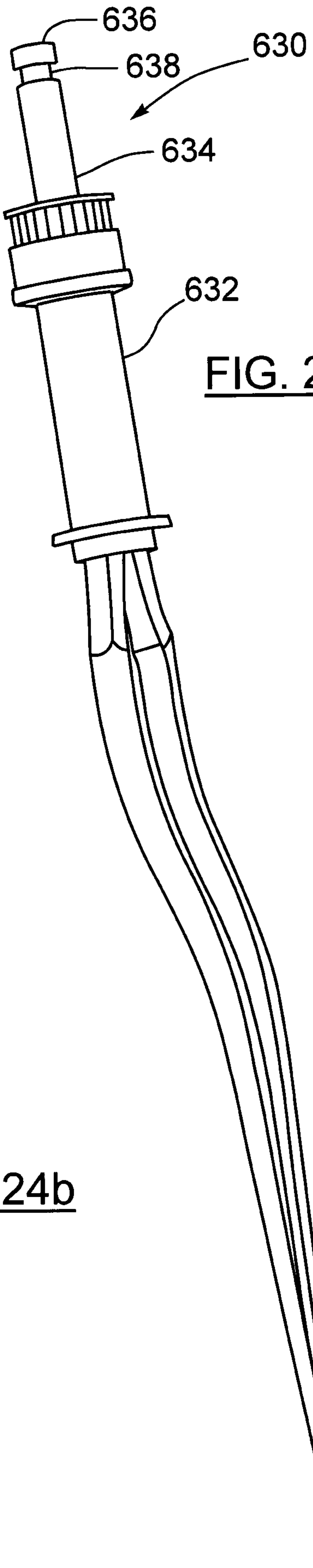


FIG. 24a

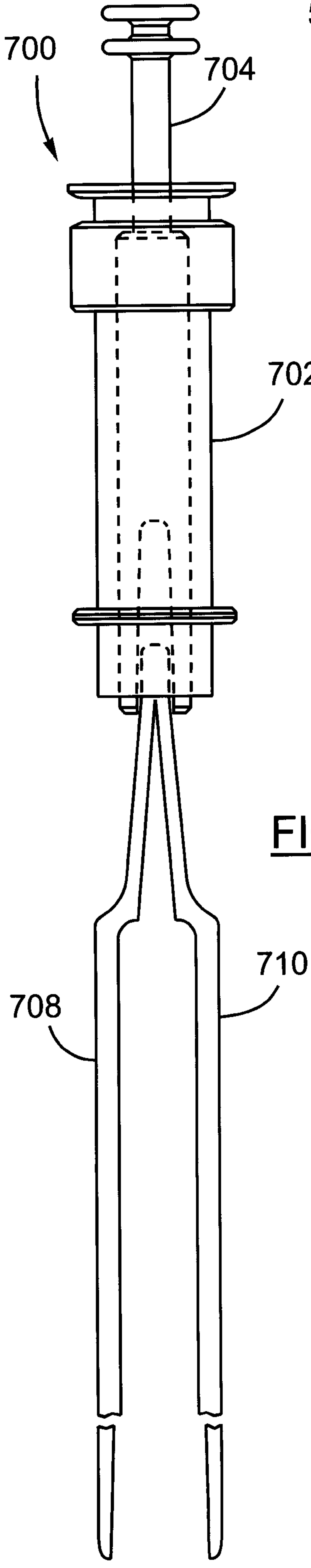


FIG. 25b

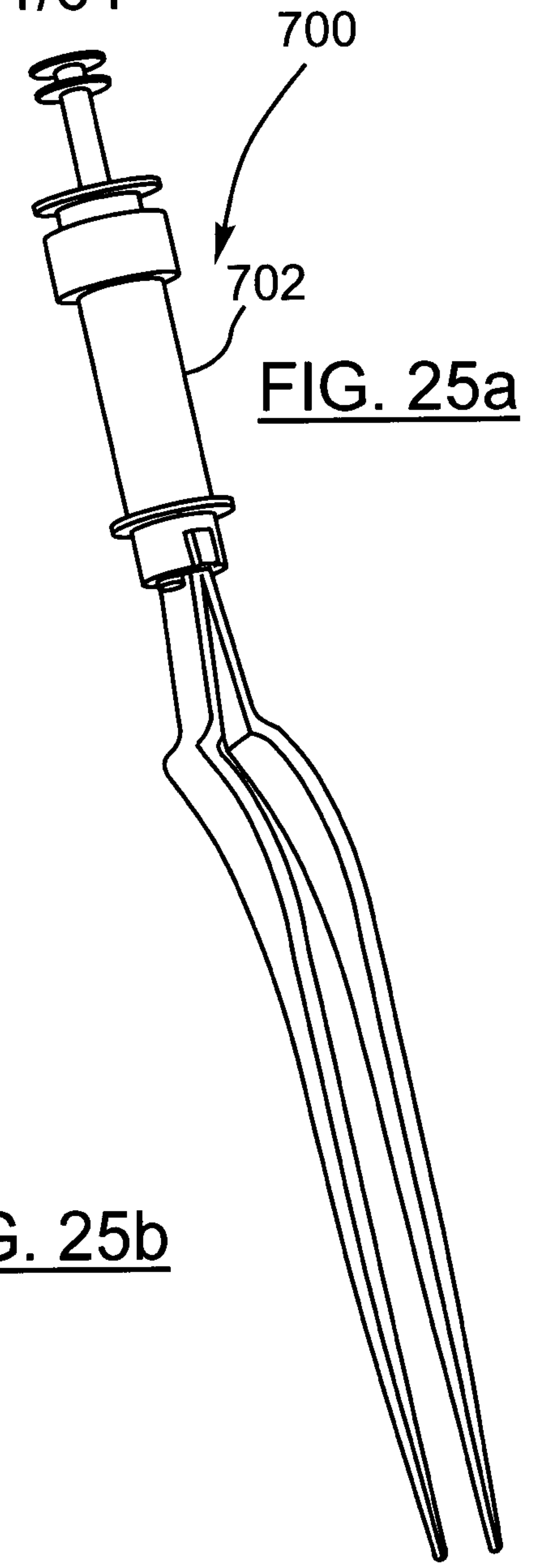


FIG. 25a

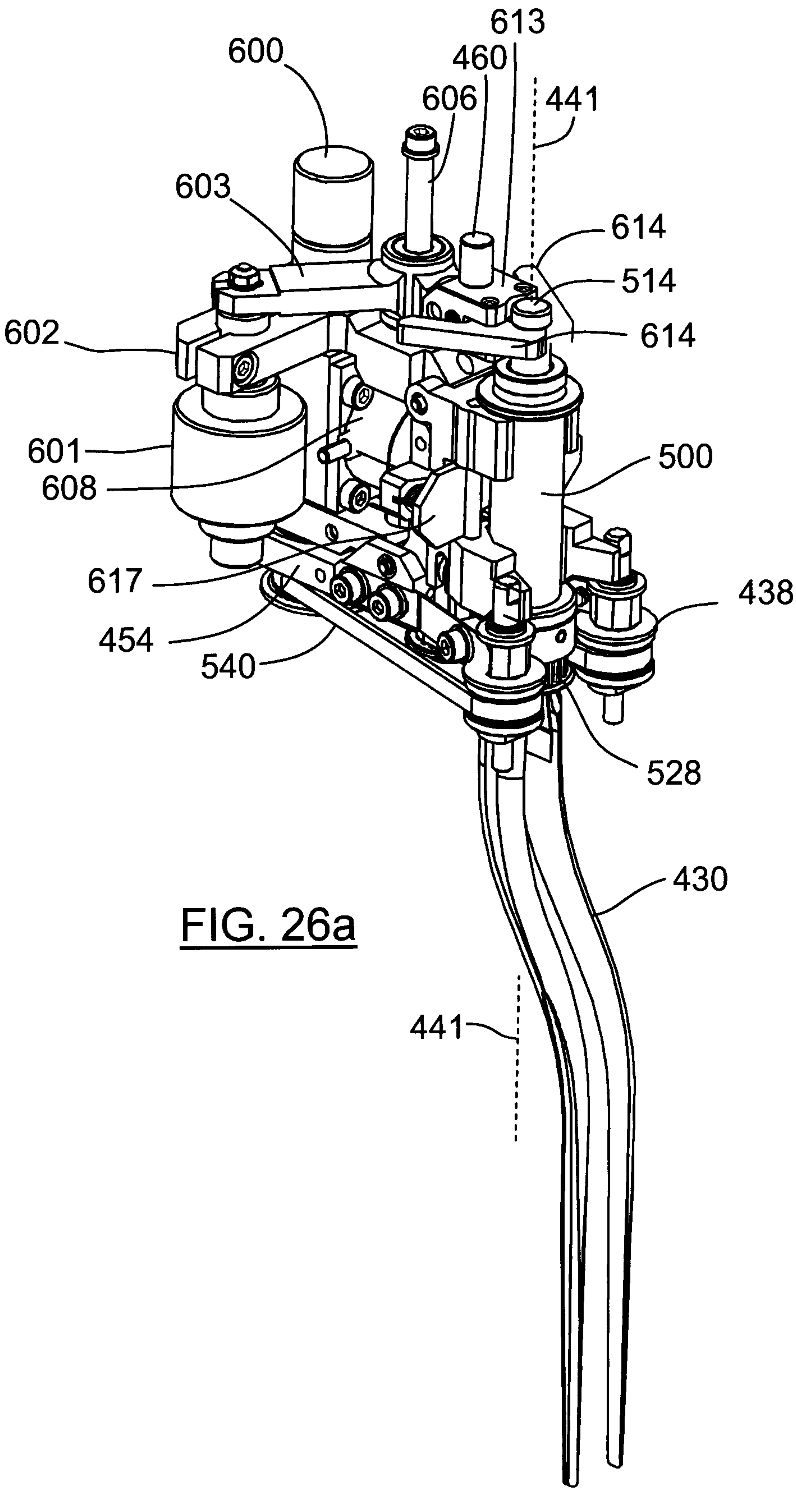

613
600
460
606
441
603
614
514
602
614
601
500
608
617
438
454
540
528
430
441

FIG. 26a

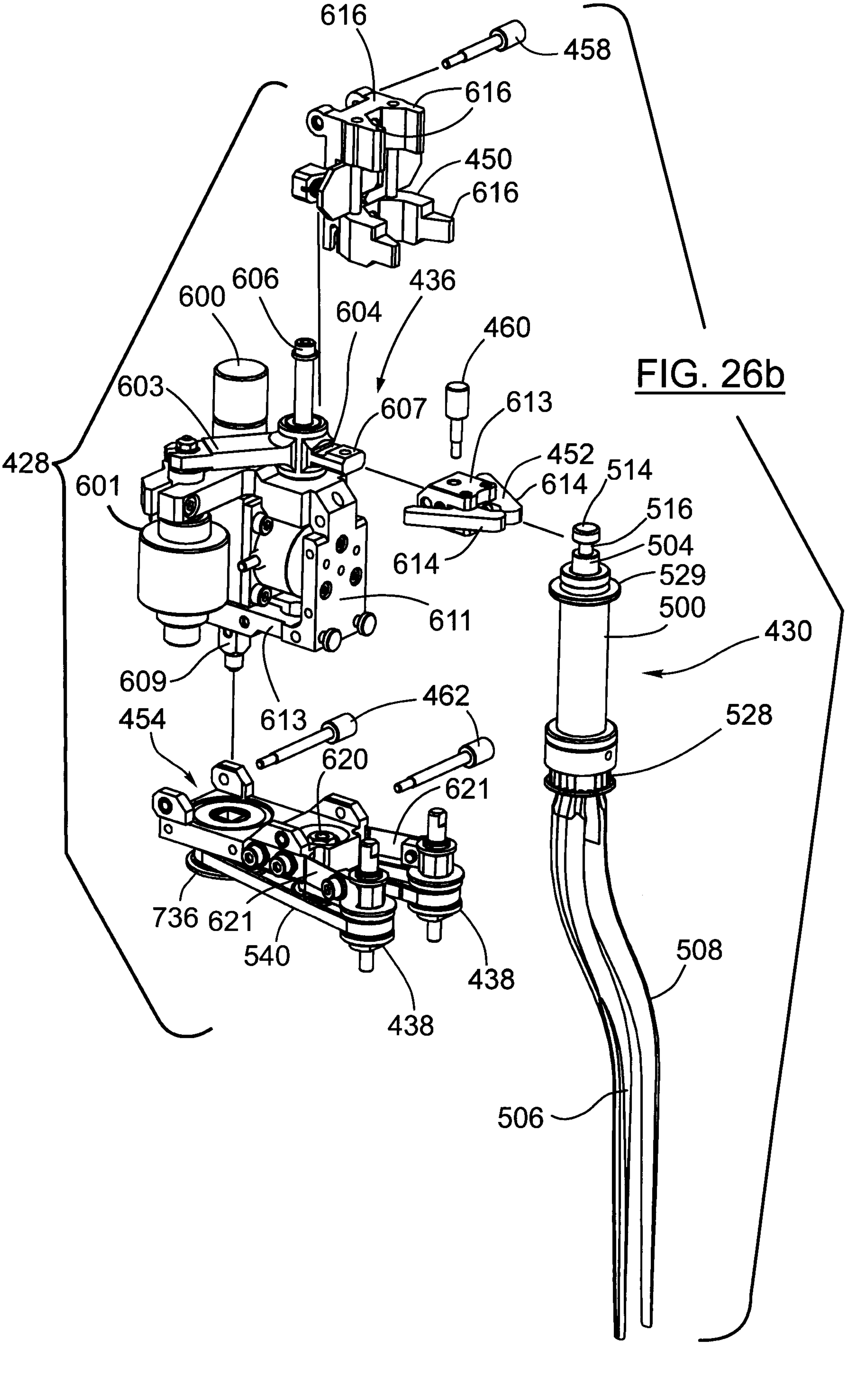

616
458
616
450
616
606
436
600
604
460
603
607
613
428
452
514
601
614
516
504
614
529
500
611
430
609
613
528
454
462
620
621
736
621
540
438
438
508
506

FIG. 26b

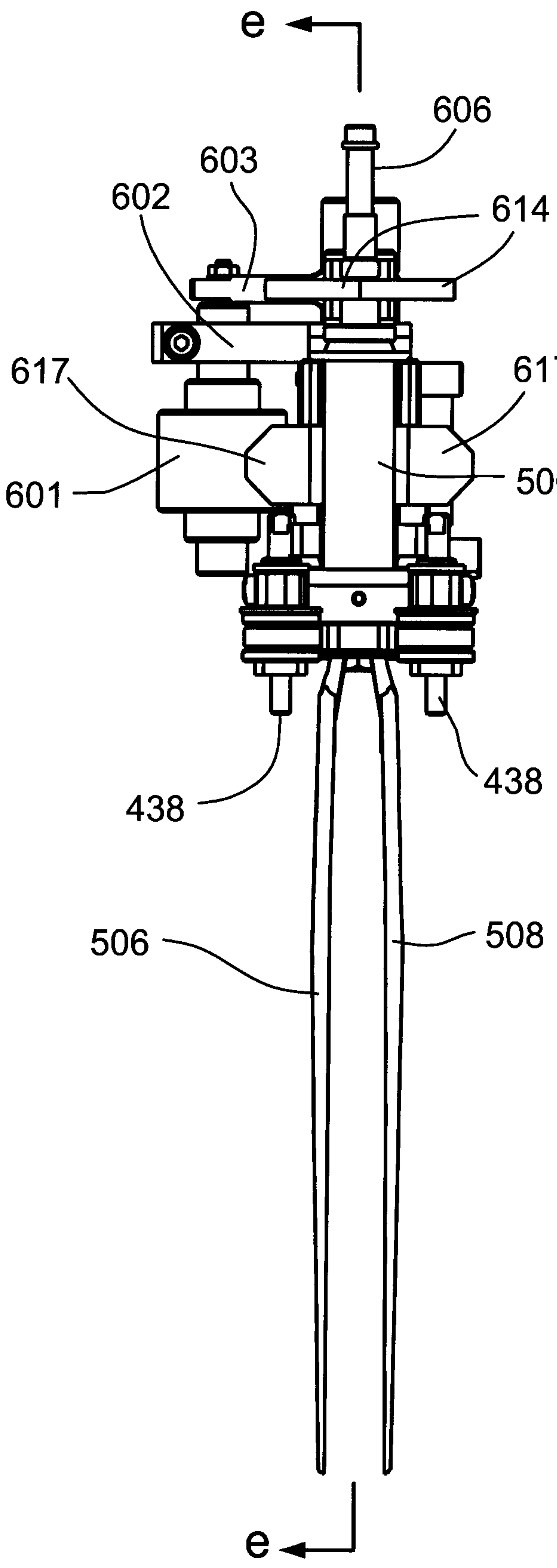


FIG. 26c

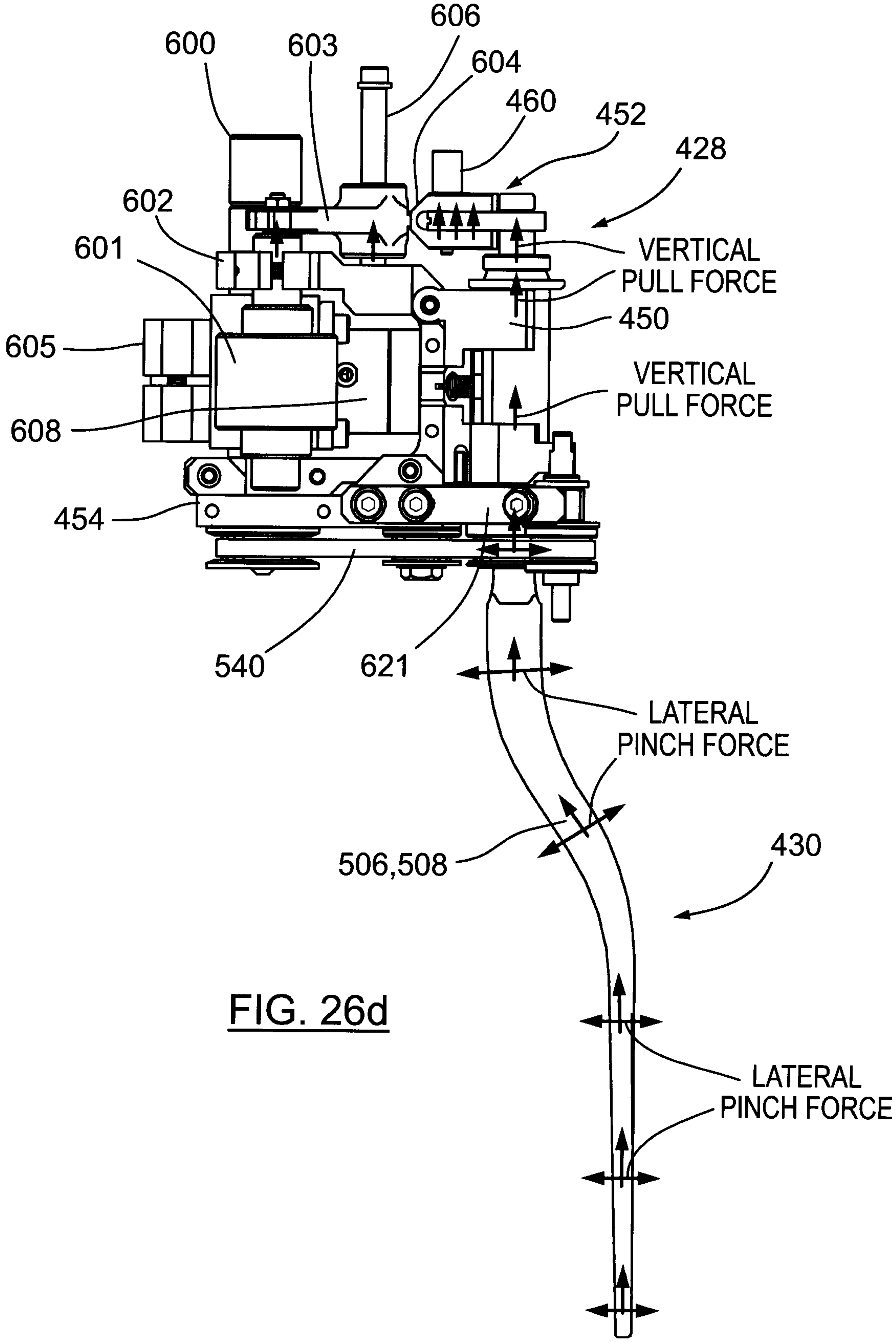

600
603
606
604
460
452
428
602
601
VERTICAL
PULL FORCE
450
605
VERTICAL
PULL FORCE
608
454
540
621
LATERAL
PINCH FORCE
506,508
430
LATERAL
PINCH FORCE

FIG. 26d

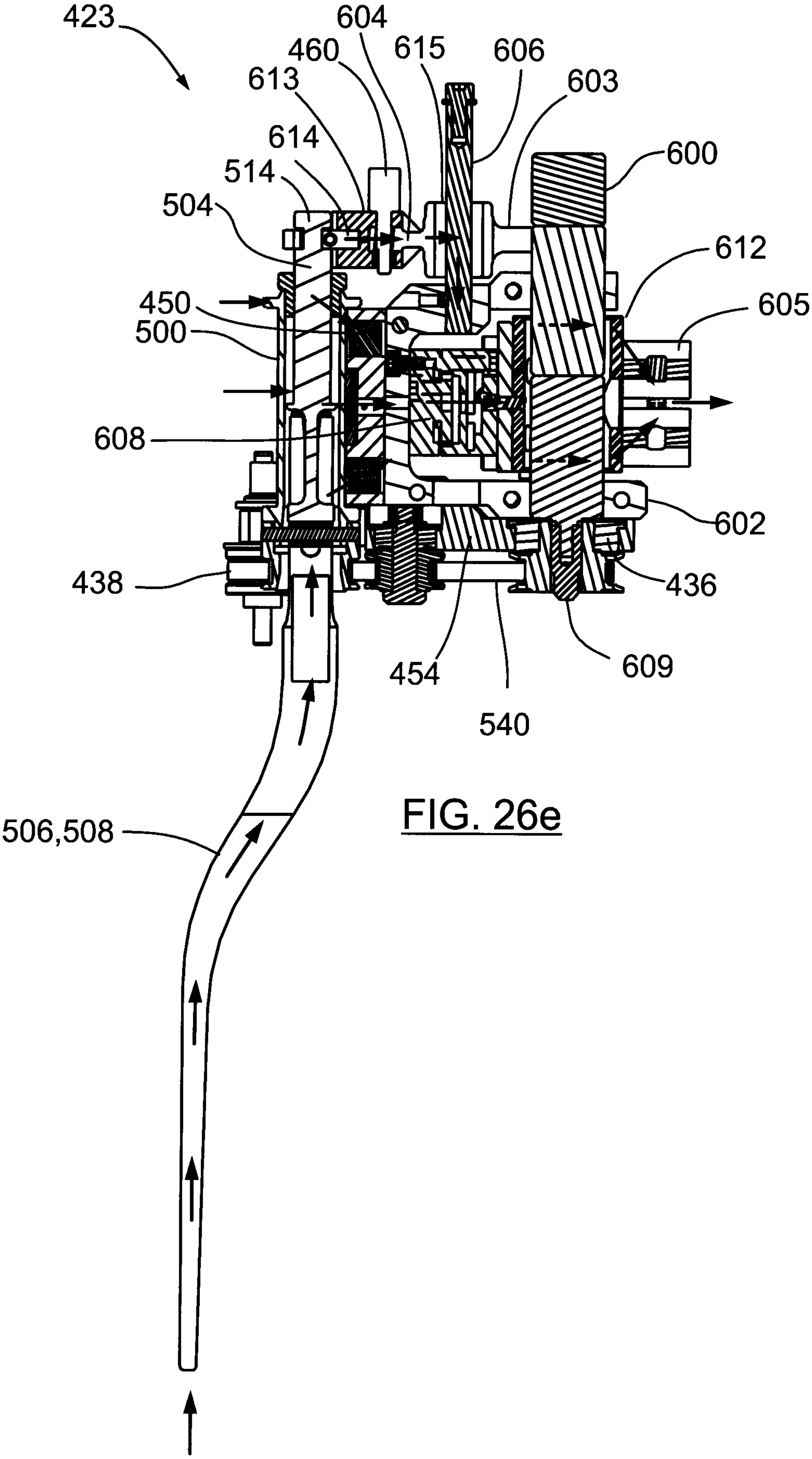

423
604
460
615
606
603
613
614
600
514
504
612
450
605
500
608
602
438
436
454
609
540
506,508

FIG. 26e

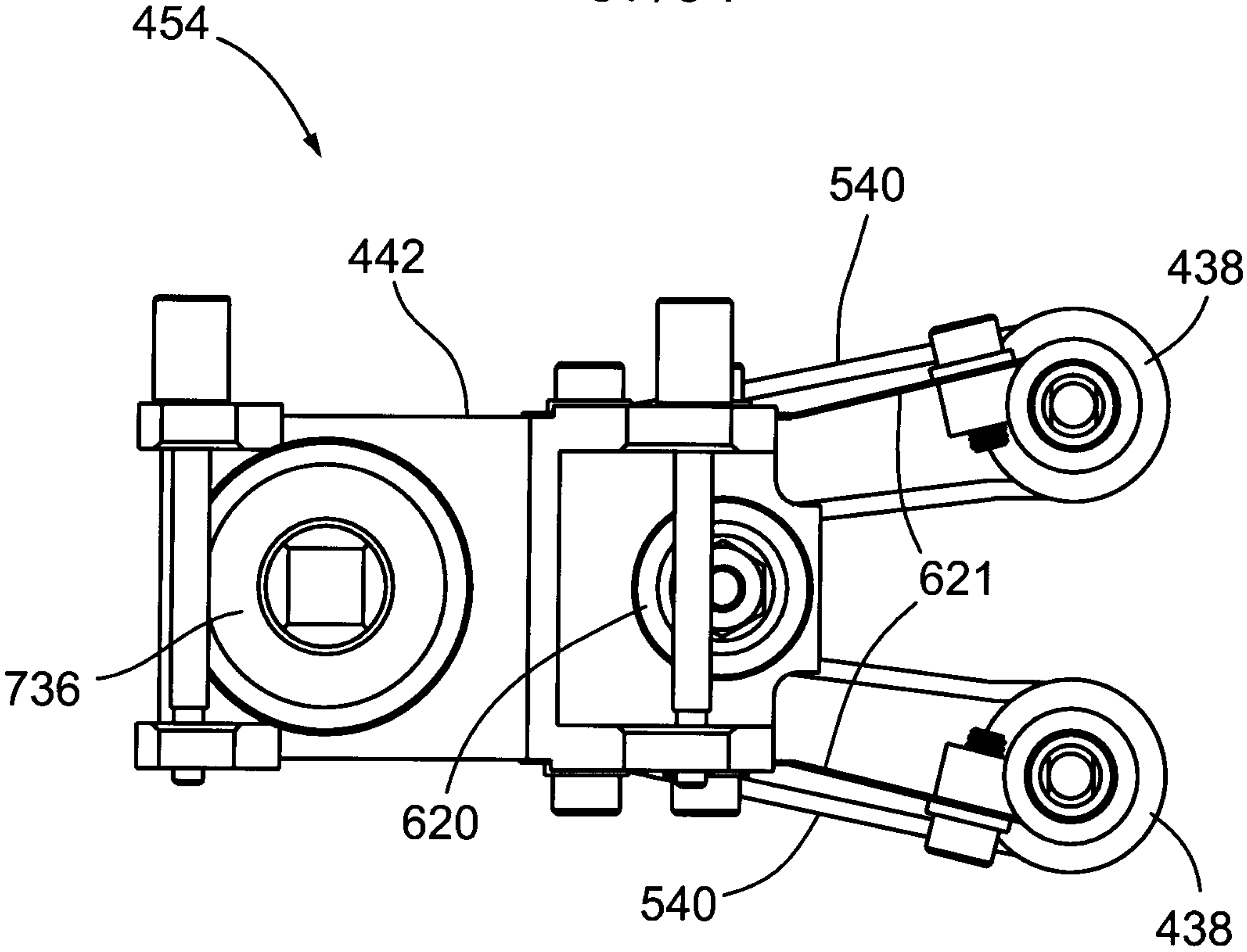


FIG. 27a

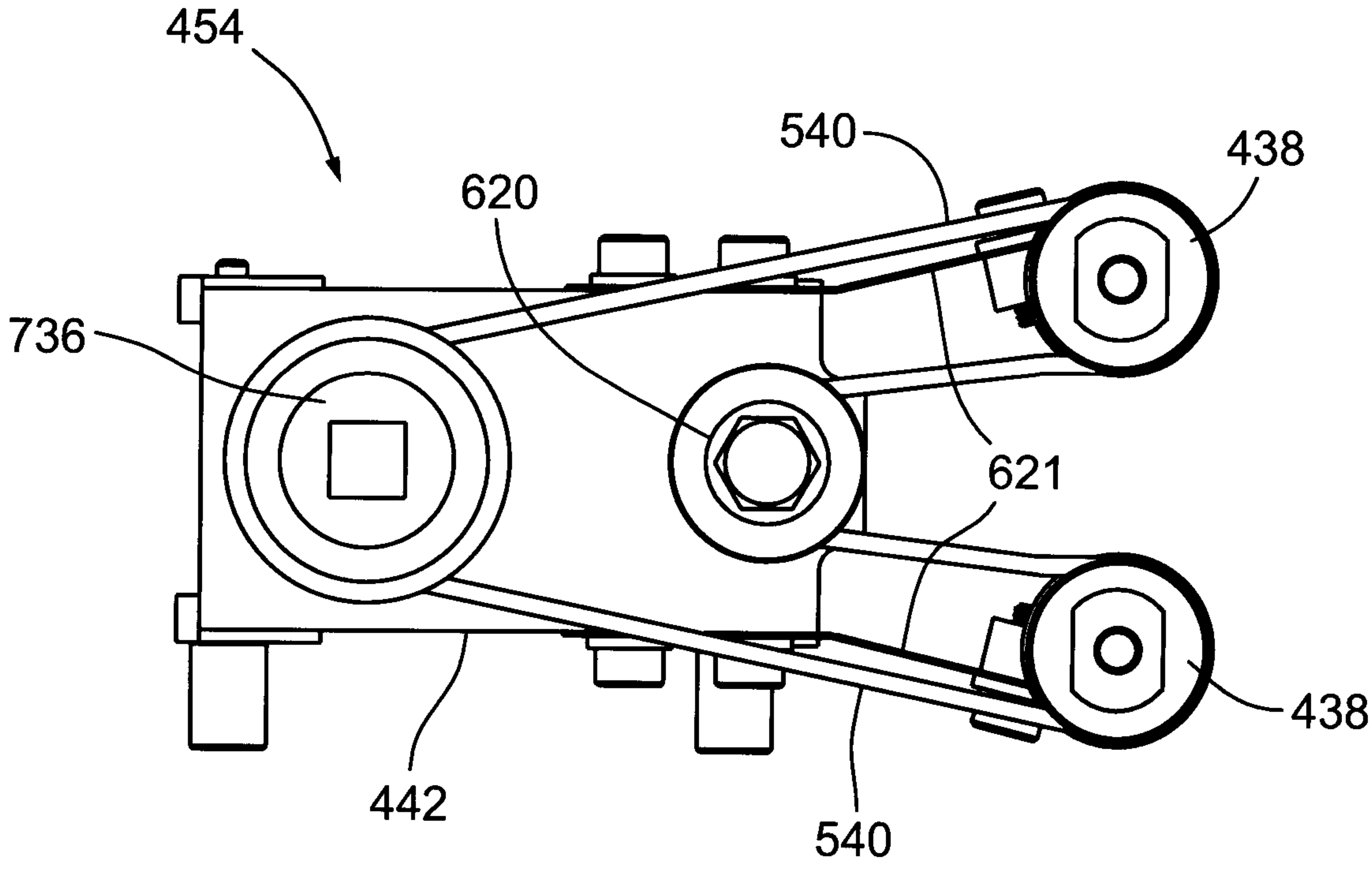


FIG. 27b

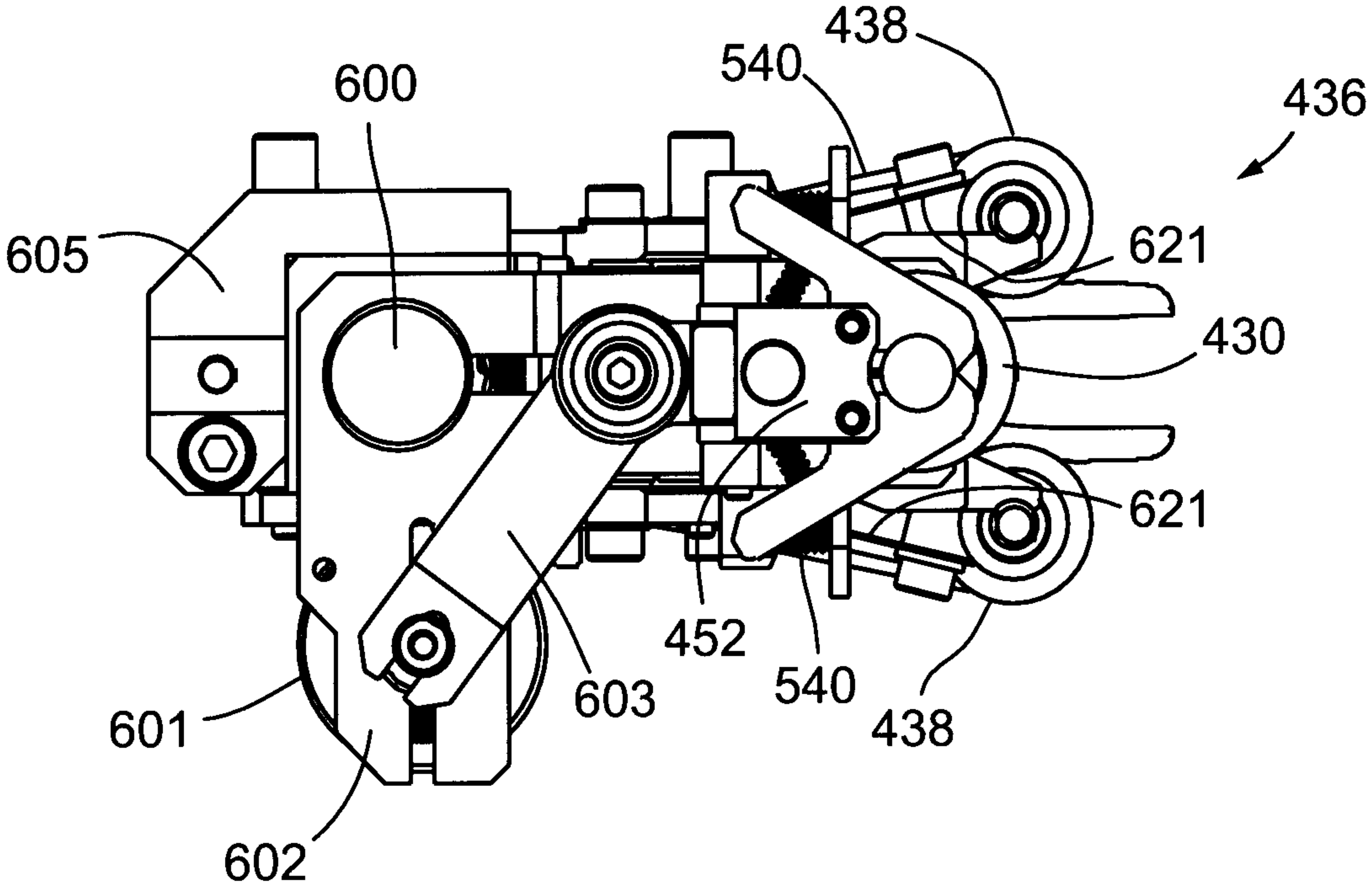


FIG. 27c

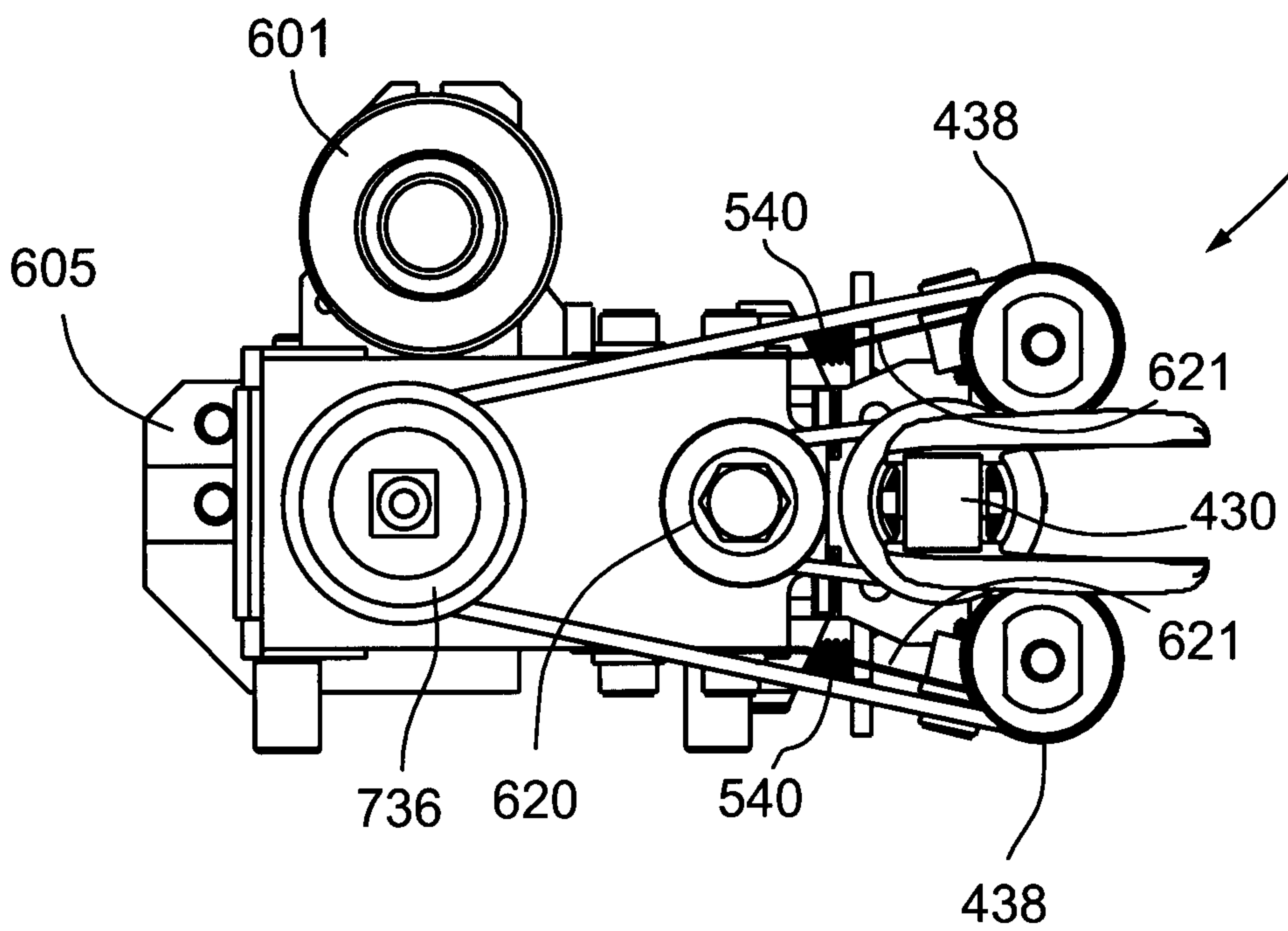


FIG. 27d

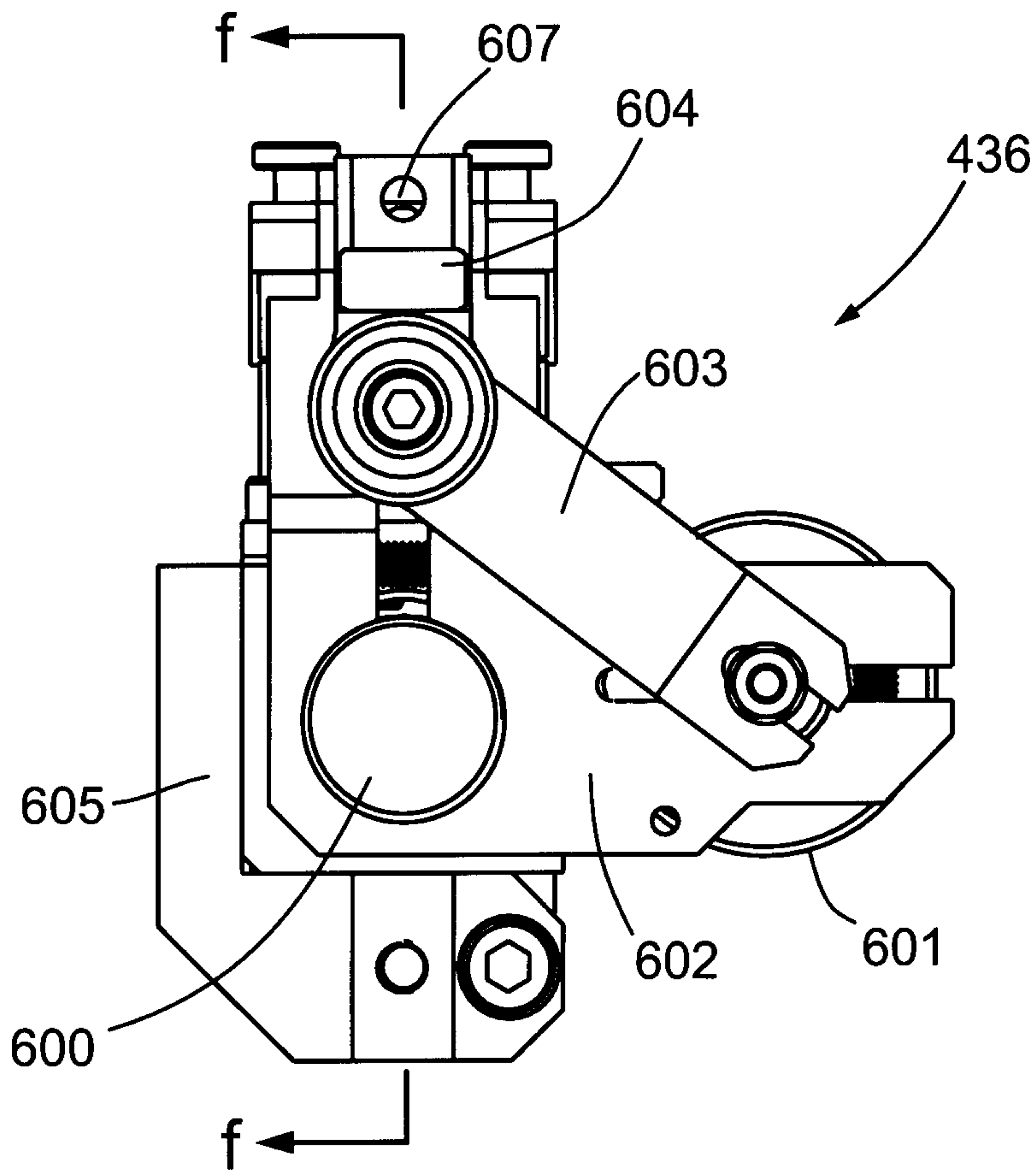


FIG. 27e

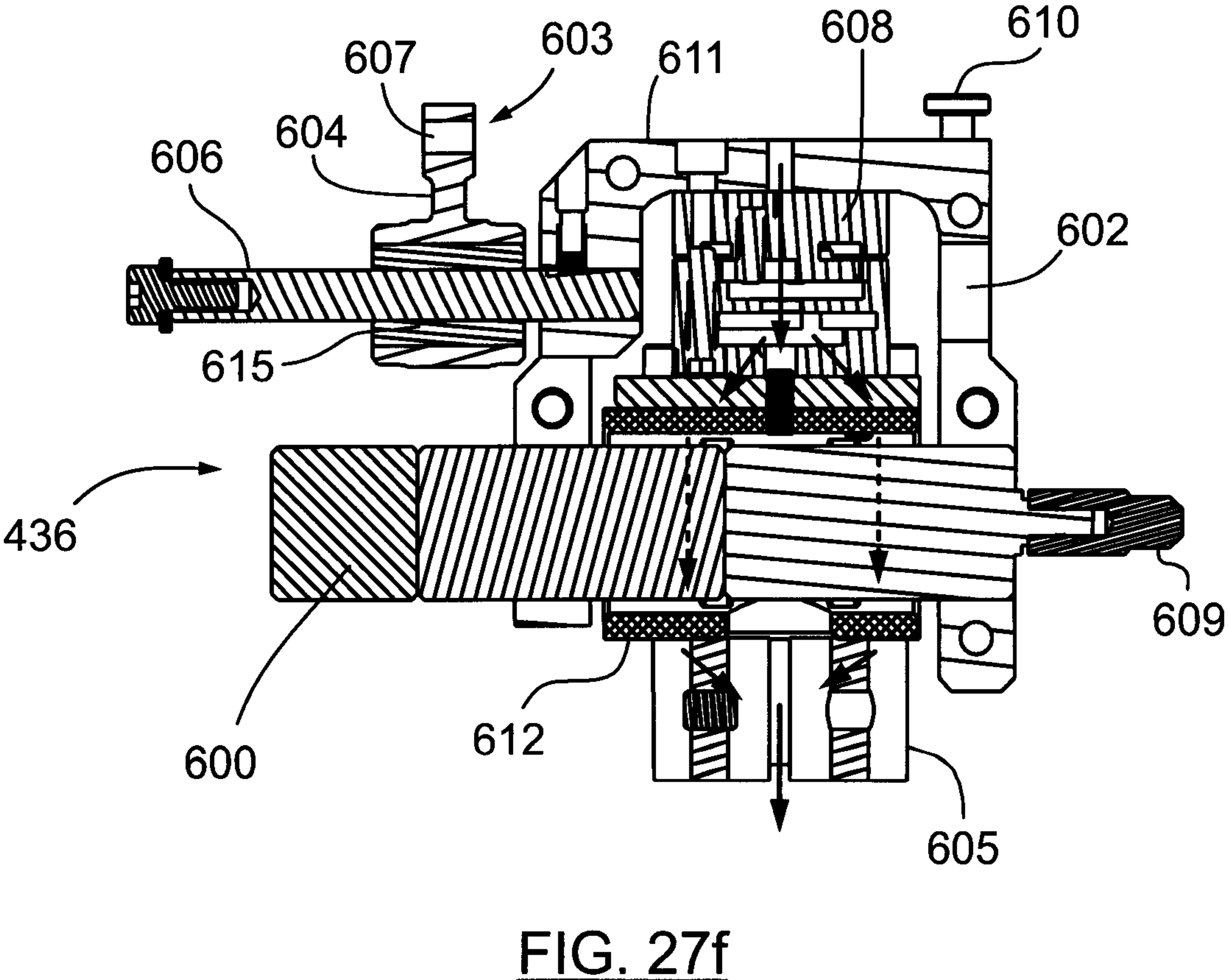


FIG. 27f

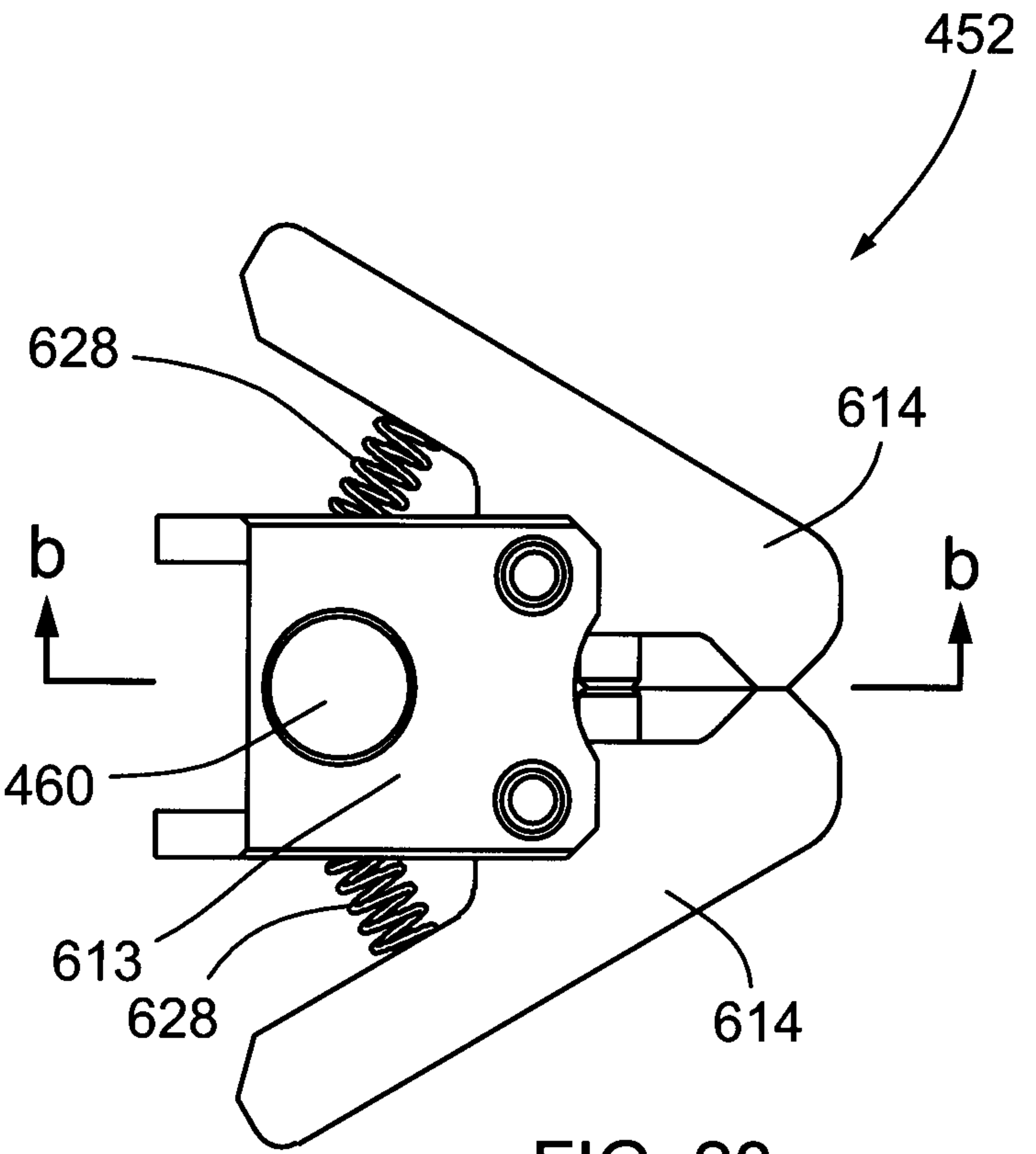


FIG. 28a

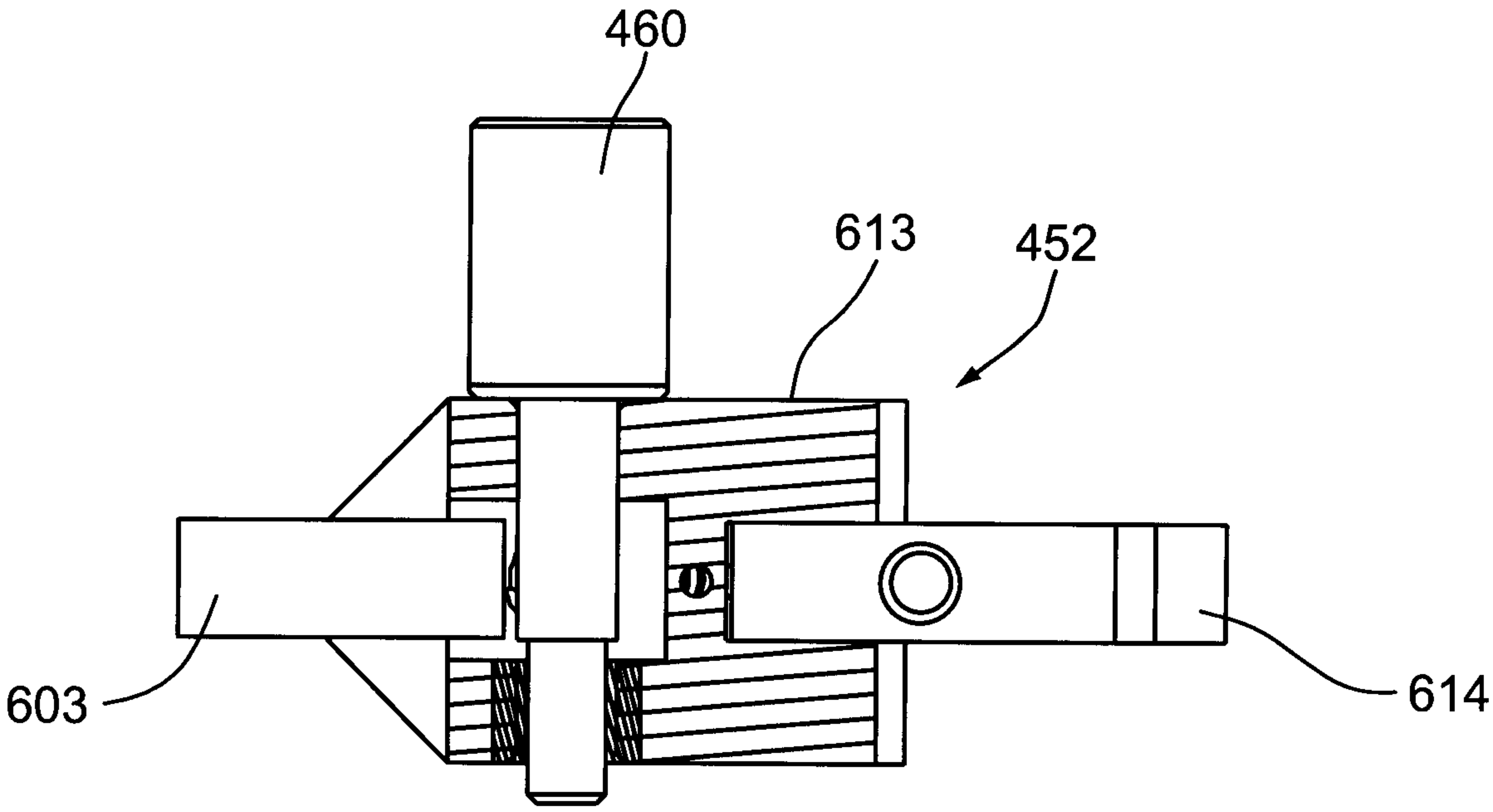


FIG. 28b

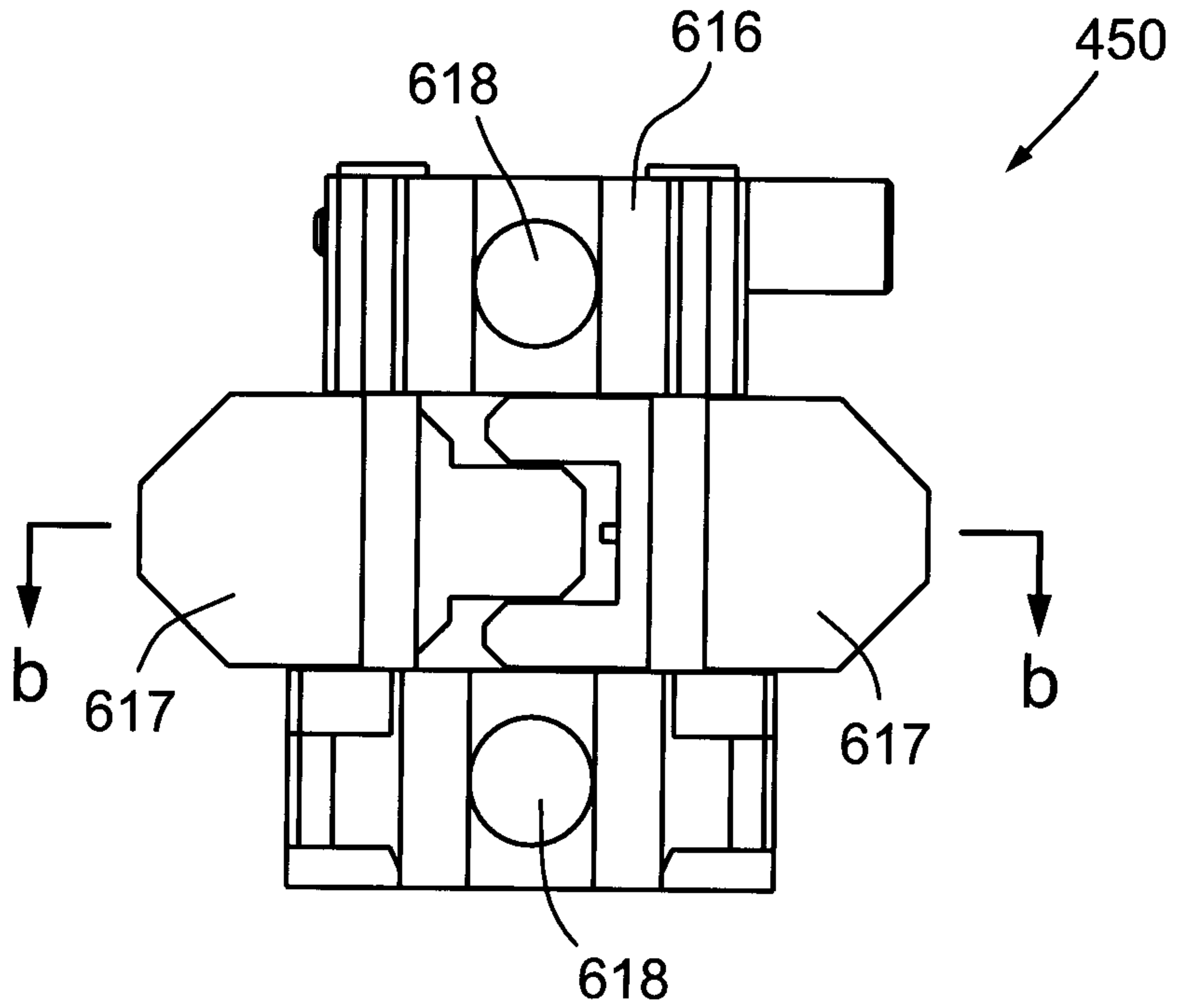


FIG. 29a

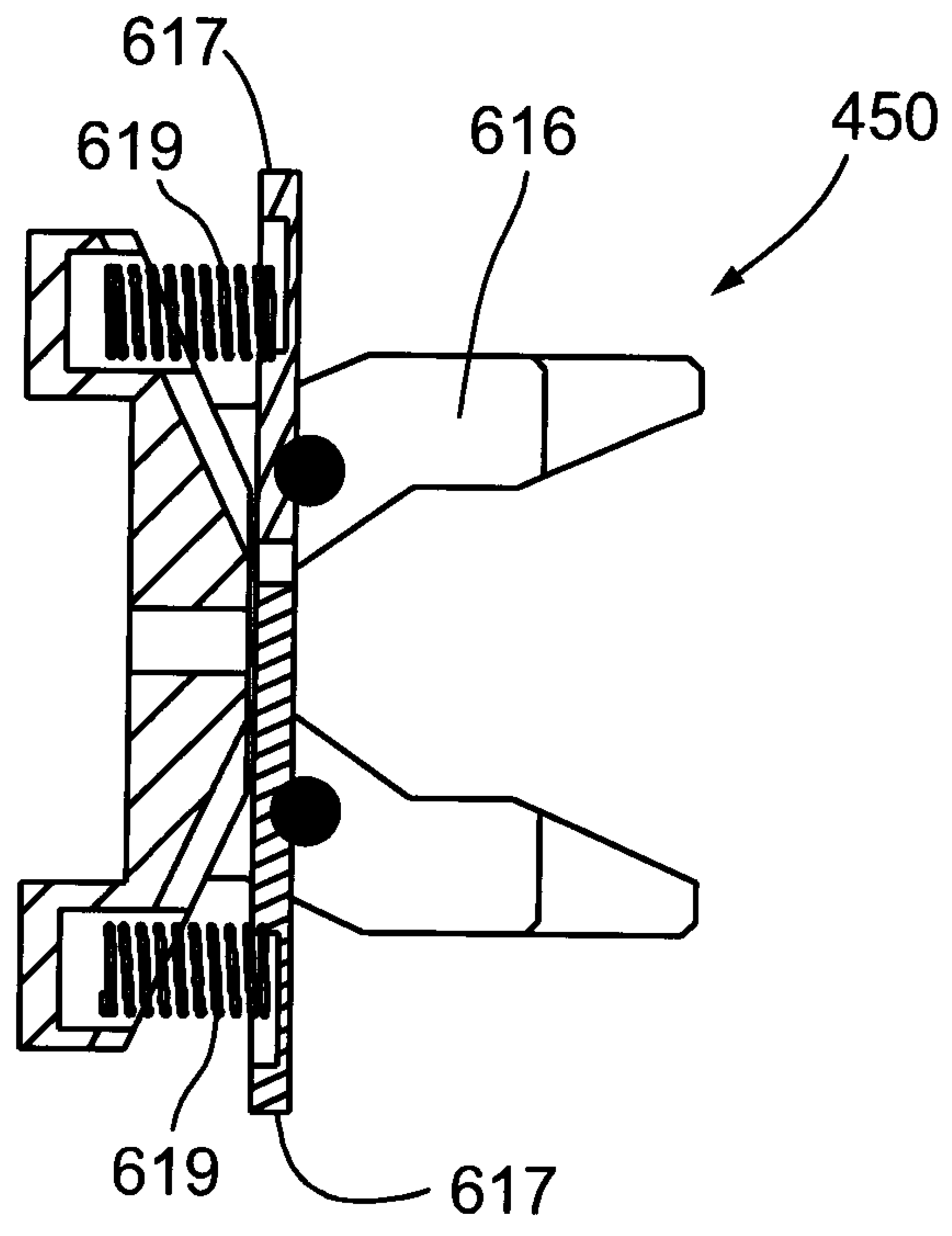


FIG. 29b

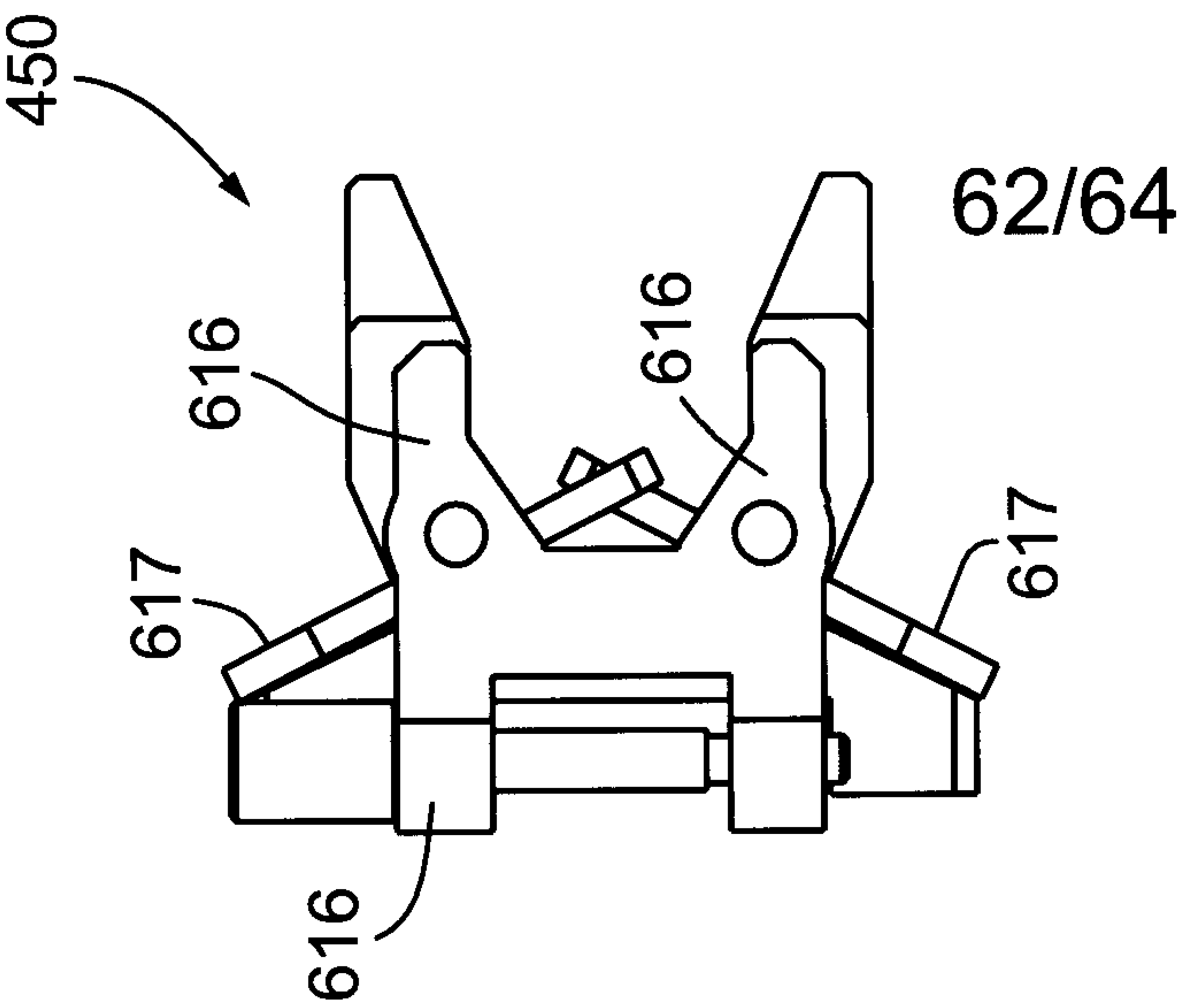


FIG. 29e

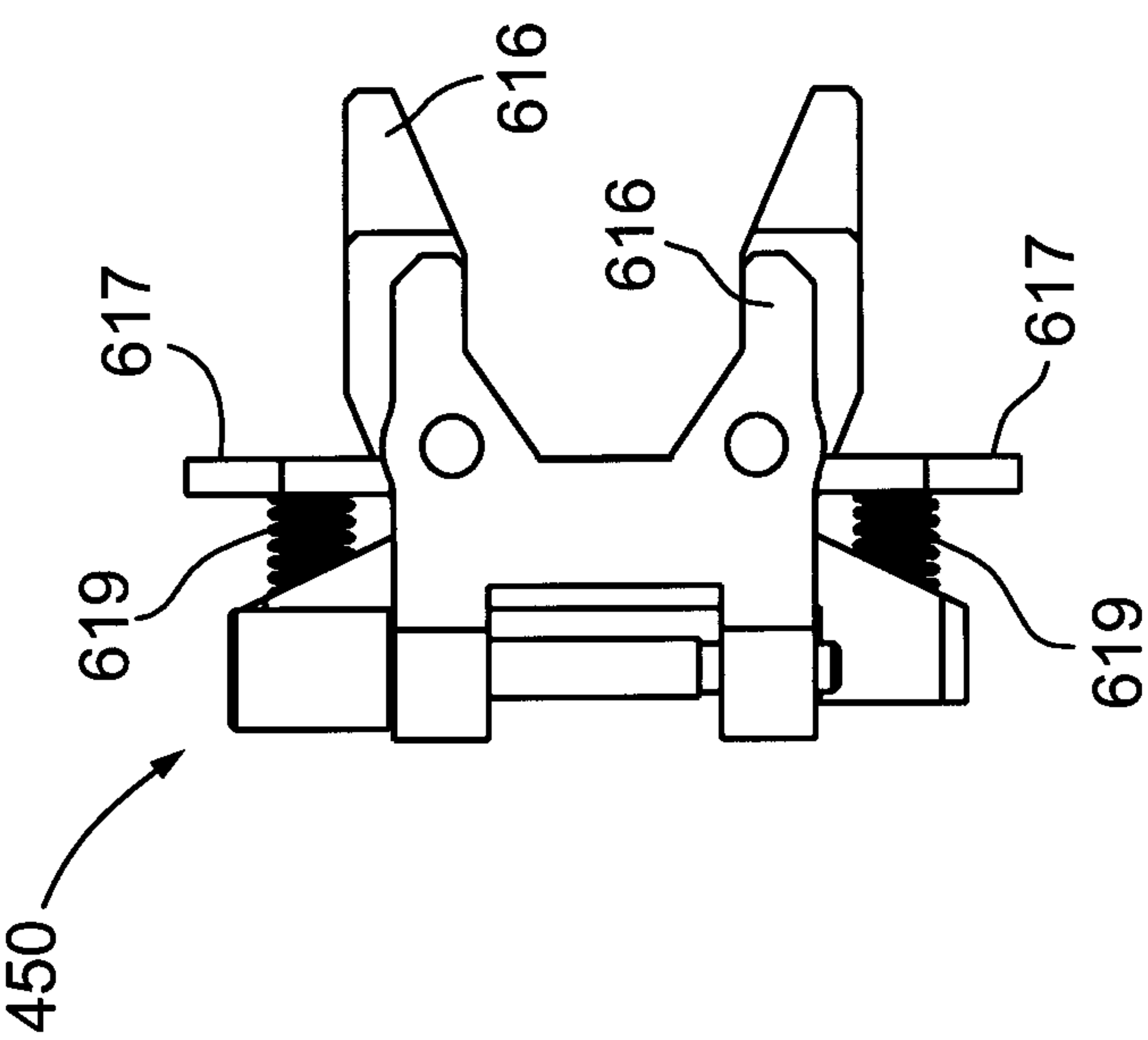


FIG. 29d

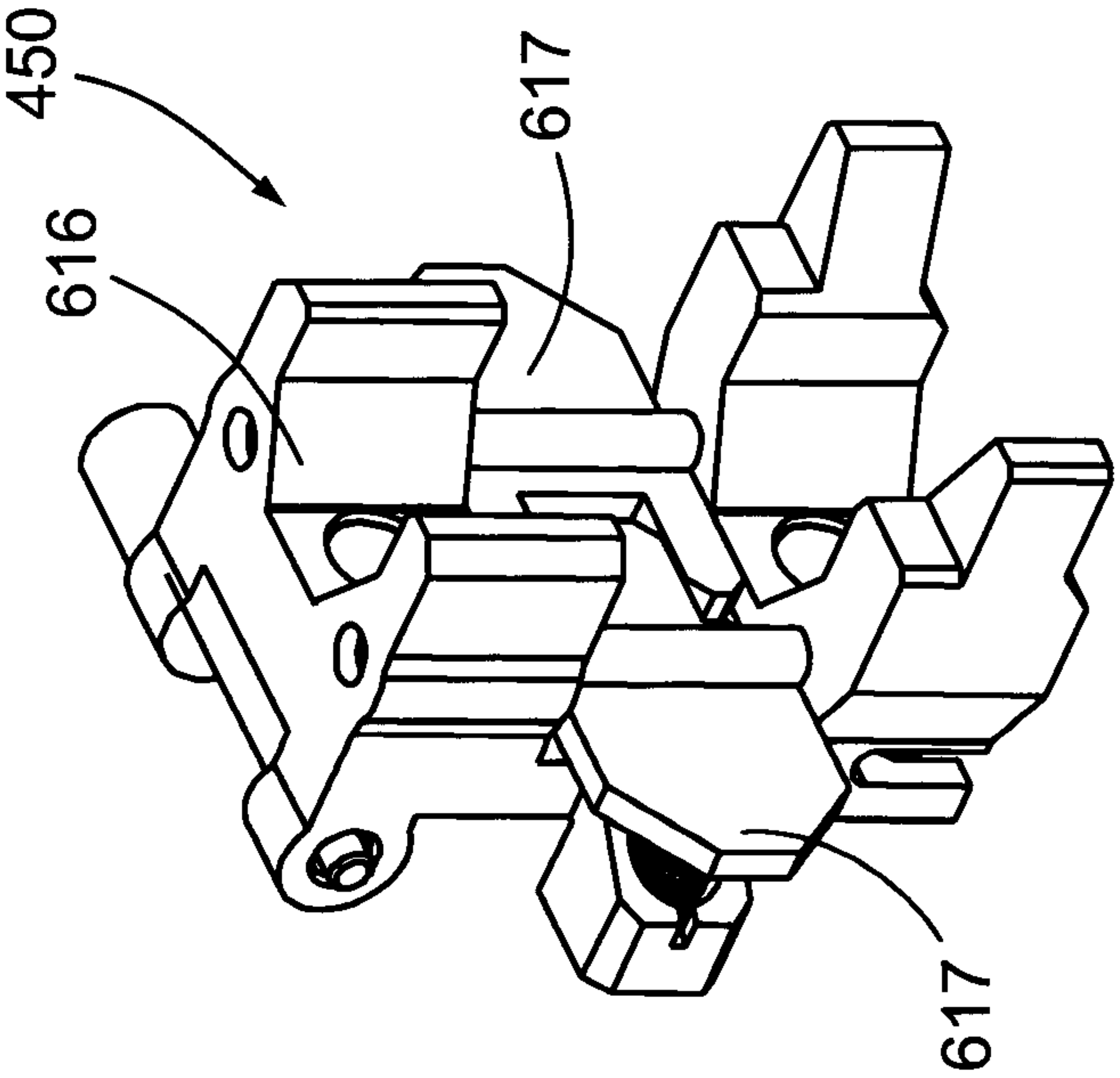


FIG. 29c

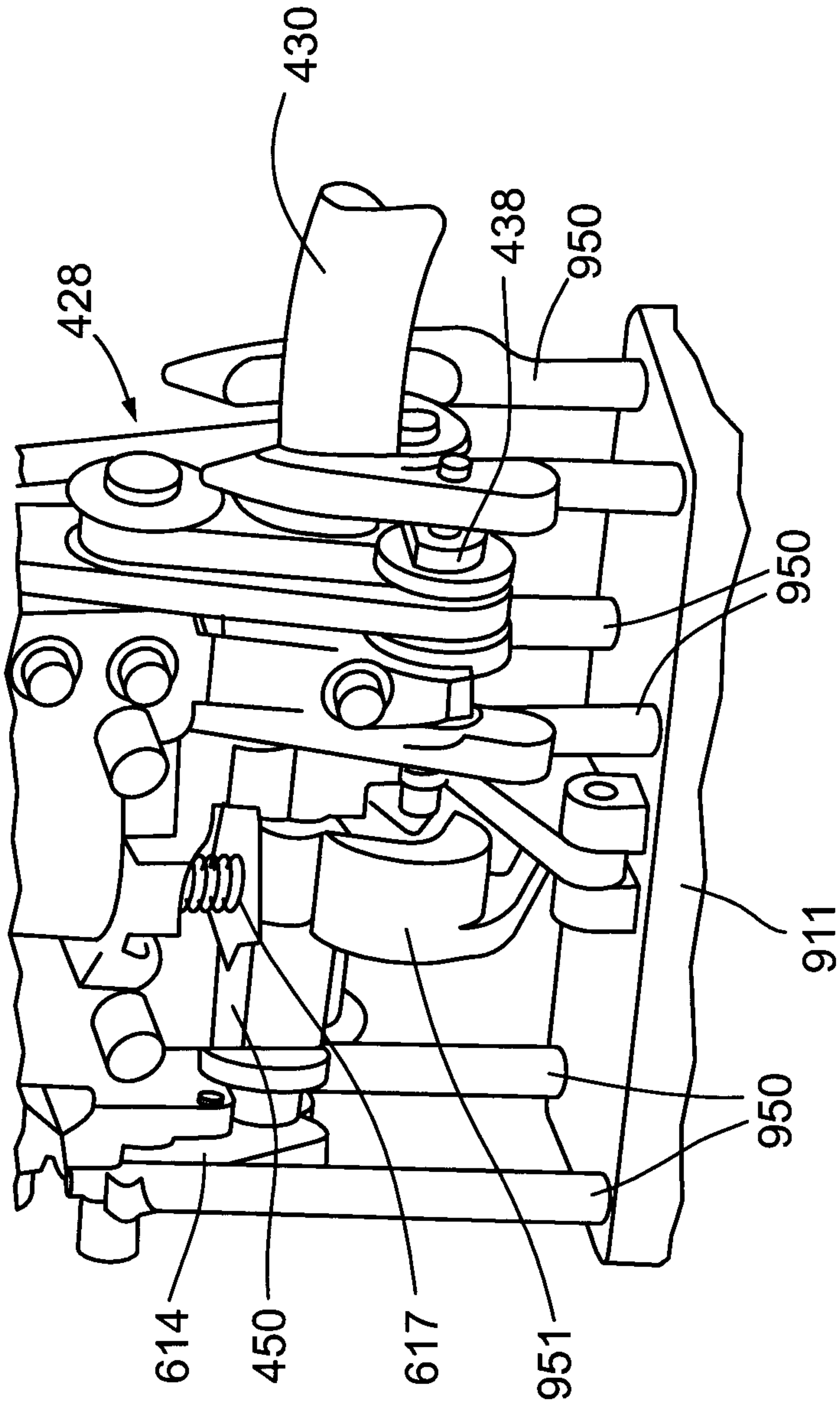


FIG. 29f

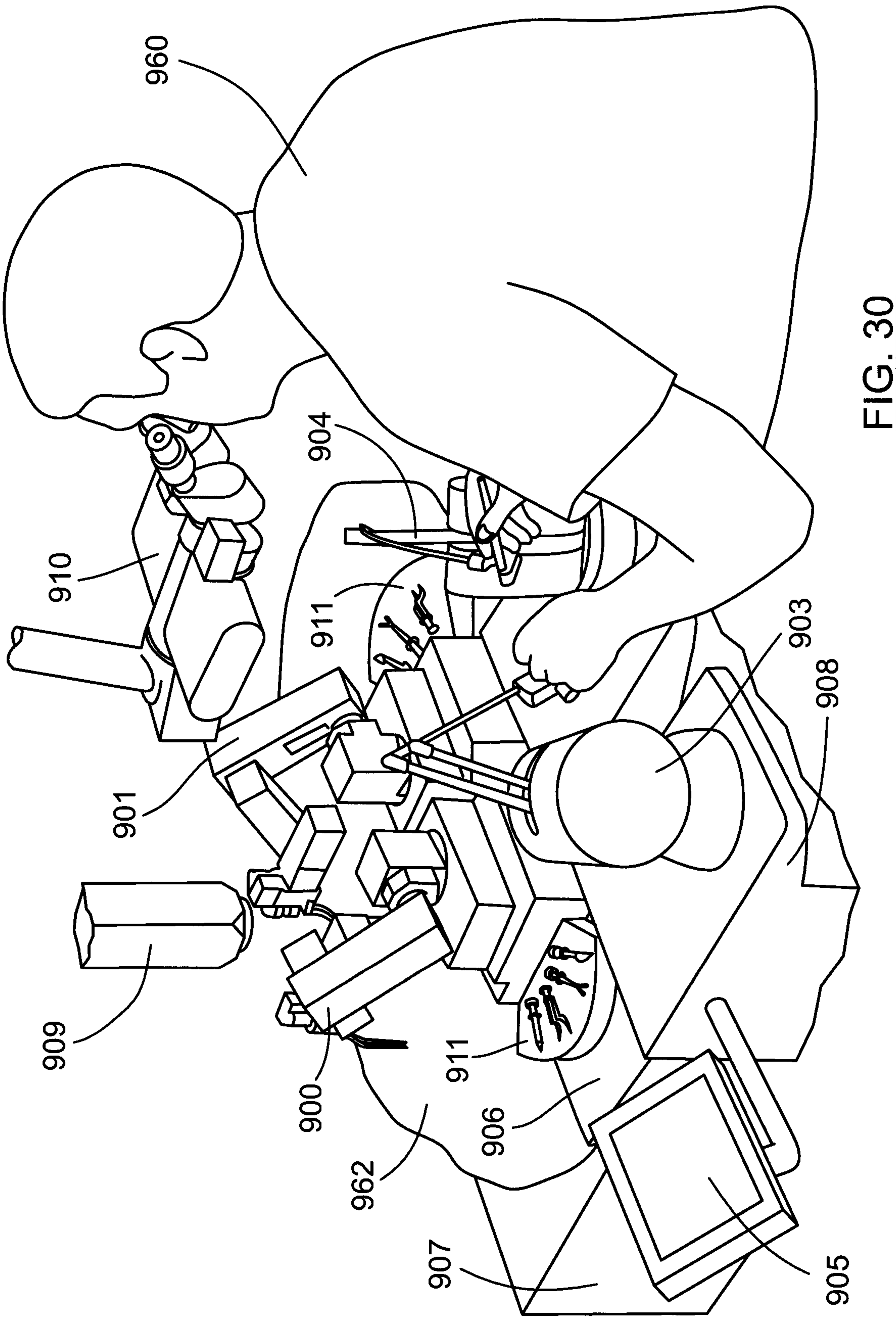
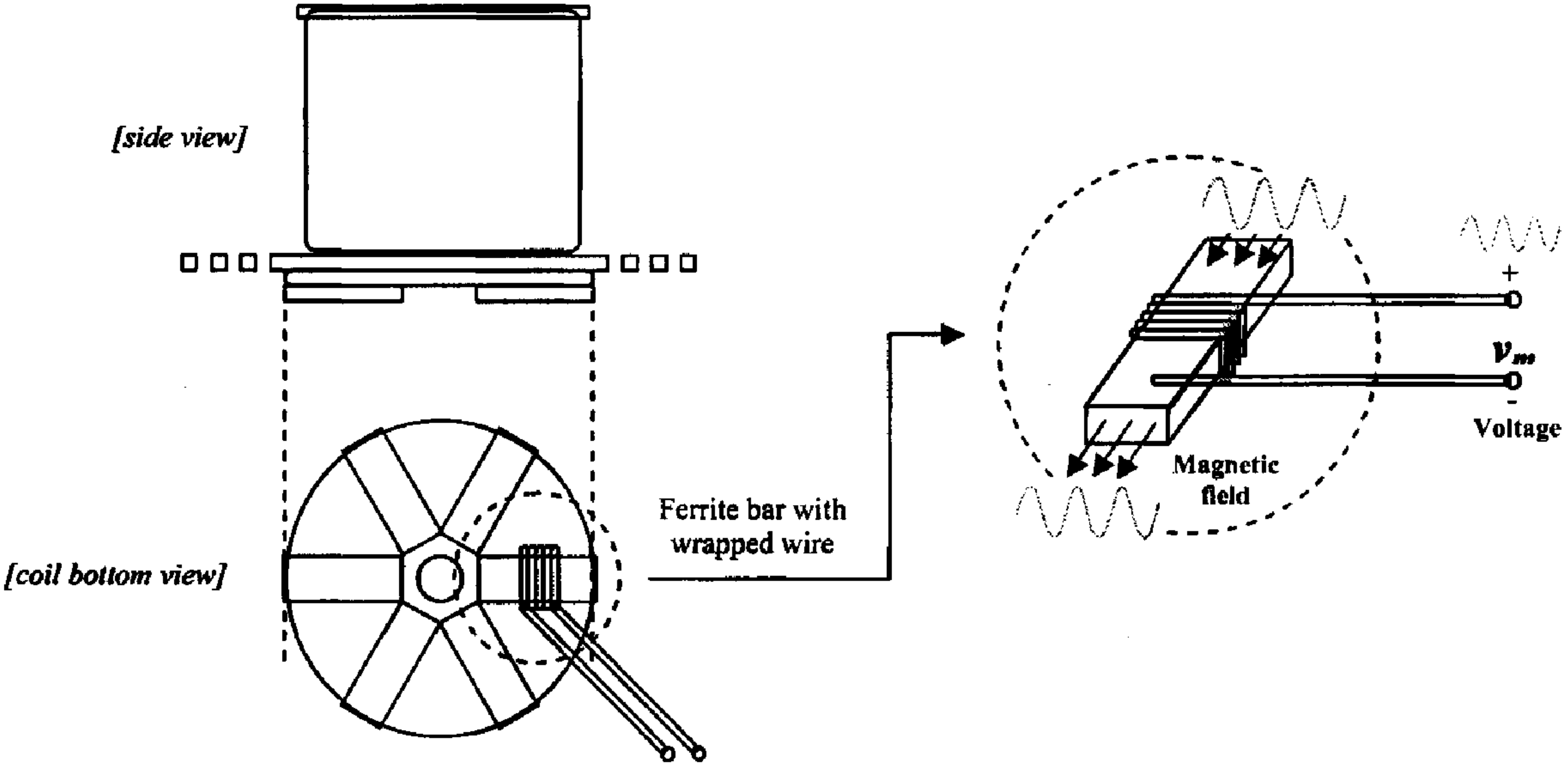


FIG. 30



[side view]
[coil bottom view]
Ferrite bar with wrapped wire
+
v_m
-
Voltage
Magnetic field