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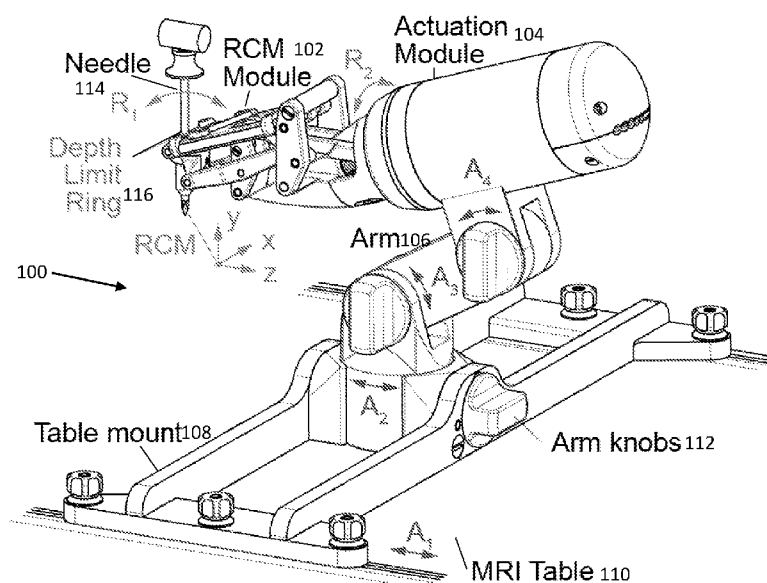
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(54) Title: REMOTE CENTER OF MOTION ROBOT

**FIG. 3**

(57) **Abstract:** An embodiment in accordance with the present invention provides a remote center of motion robot. The RCM here is a parallelogram bar type RCM mechanism with a novel joint arrangement. The novel joint arrangement facilitates the mounting of the medical instrument and offers improved clearance relative to the patient. Moreover, the robot was built to guide a bone biopsy cannula, needle, or drill. Even though exact interventional values are unknown, it is expected that the forces exerted laterally on the needle-guide are higher than those encountered for slender needle insertion into soft tissue. For this, the RCM has been built with novel structure to enhance stiffness.





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REMOTE CENTER OF MOTION ROBOT**GOVERNMENT SUPPORT**

[0001] The present invention was made with government support under 1R01CA172244 awarded by the National Institutes of Health. The government has certain rights in the present invention.

CROSS REFERENCE TO RELATED APPLICATION

[0002] This application claims the benefit of U.S. Provisional Patent Application No. 62/331,729 filed on May 4, 2016, which is incorporated by reference, herein, in its entirety.

FIELD OF THE INVENTION

[0003] The present invention relates generally to medical devices. More particularly, the present invention relates to a remote center of motion robot.

BACKGROUND OF THE INVENTION

[0004] Image-guided interventions (IGI) may be performed based on pre-acquired images, but using the imager at the time of the intervention to directly (DIGI) guide the procedure improves quality control. These often require special devices such as medical robots to help the physician and improve accuracy. Compatibility of robotic devices with the imaging equipment has been a challenging engineering task, especially with the magnetic resonance (MR) environment.

[0005] The highest class of compatibility of devices with the MR environment is MR Safe, according to the American Society for Testing and Materials standard ASTM F2503-13. In the United States compliance to this standard is mandated by the Food and Drug Administration (FDA) for clinical use. These are devices “that poses no known hazards

resulting from exposure to any MR environment. MR Safe items are composed of materials that are electrically nonconductive, nonmetallic, and nonmagnetic”.

[0006] Traditional active robotic components are not MR Safe. All current MR Safe robots are pneumatically actuated, either with special pneumatic cylinders, turbines, or stepper
5 motors. These were commonly powered through long hoses by pneumatic valves, either voice-coil type located outside the MRI room (ACR Zone III), or piezoelectric type valves that may be located in the MR scanner room (ACR Zone IV). Position encoders have been typically done with the classic code-wheel quadrature encoding built with fiber optic sensors, that emit an optical signal through a flexible fiber and recapture it back form another fiber.
10 The fiber sensors were not built for the MR, but a good fit of industrial harsh environment sensors (wet, corrosive, explosive).

[0007] Therefore, it would be advantageous to provide a remote center of motion robot that is MR safe.

SUMMARY OF THE INVENTION

15 [0008] The foregoing needs are met, to a great extent, by the present invention, wherein in one aspect a magnetic resonance (MR) safe robot includes a remote center of motion (RCM) mechanism having a non-collinear architecture. An instrument for use with the MR safe robot is aligned between a top joint and an RCM point of the RCM mechanism.

[0009] In accordance with an aspect of the present invention, the RCM mechanism takes
20 the form of a parallelogram structure. A link and screw mechanism is configured for driving the RCM mechanism. The RCM mechanism can include a spatial structure. The RCM includes a first set of joints A, A₁, and A₂ and a second set of joints B, B₁, and B₂. A first distance between A and A₁ is less than a distance between B and B₁ and a second distance

between A_1 and A_2 is less than a second distance between B_1 and B_2 . A support arm is configured to attach laterally to a table and provide rotation about a vertical axis located at a center of the table. The MR safe robot can include a needle-guide. The needle-guide includes a protruding surface that is positively engaged by a fixture, and a pin of the needle-guide that is latched within the fixture. The needle-guide can be engaged and detached from the fixture through a bag. A ring is configured to be placed over a needle, such that the ring allows for a depth of needle insertion to be preset. A device to preset a position of the ring includes a motor to set a depth position and copy it onto the position of the ring. A remote device is configured for setting a depth of needle insertion.

[0010] In accordance with another aspect of the present invention, an actuation module for use with a magnetic resonance (MR) safe robot includes two coaxially aligned motors. A first of the two coaxially aligned motors is configured to drive a mechanical transmission. A second of the two coaxially aligned motors is configured to pass its output through a bore of the first of the two coaxially aligned motors.

[0011] In accordance with yet another aspect of the present invention, the actuation module includes a modular robot structure and a driving mechanism module. The actuation module can also include a kinematic arrangement and a remote center of motion (RCM) mechanism. The RCM mechanism is driven by a link and screw mechanism.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The accompanying drawings provide visual representations, which will be used to more fully describe the representative embodiments disclosed herein and can be used by those skilled in the art to better understand them and their inherent advantages. In these drawings, like reference numerals identify corresponding elements and:

[0013] FIGS. 1A-1C illustrate different types of 1-DoF parallelogram RCM types.

[0014] FIG. 2 illustrates a kinematic diagram of the RCM mechanism and an actuation schematic for a robot, in accordance with the present invention.

[0015] FIG. 3 illustrates a perspective view of a manipulator design according to an
5 embodiment of the present invention.

[0016] FIGS. 4A-4D illustrate perspective views of an RCM module detached from an actuation base.

[0017] FIG. 5 illustrates a partially sectional view of a depth driver to preset a depth for needle insertion, according to an embodiment of the present invention.

10 [0018] FIG. 6 illustrates an image view of the device according to an embodiment of the present invention.

[0019] FIG. 7 illustrates a schematic diagram the robotic system showing placement of MR safe, conditional and unsafe components.

DETAILED DESCRIPTION

15 [0020] The presently disclosed subject matter now will be described more fully hereinafter with reference to the accompanying Drawings, in which some, but not all embodiments of the inventions are shown. Like numbers refer to like elements throughout. The presently disclosed subject matter may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments
20 are provided so that this disclosure will satisfy applicable legal requirements. Indeed, many modifications and other embodiments of the presently disclosed subject matter set forth herein will come to mind to one skilled in the art to which the presently disclosed subject matter pertains having the benefit of the teachings presented in the foregoing descriptions and the associated Drawings. Therefore, it is to be understood that the presently disclosed subject

matter is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims.

[0021] An embodiment in accordance with the present invention provides a remote center of motion robot (RCM). The RCM here is a parallelogram bar type RCM mechanism with a novel joint arrangement. The novel joint arrangement facilitates the mounting of the medical instrument and offers improved clearance relative to the patient. Moreover, the robot was built to guide a bone biopsy cannula, needle, or drill. Even though exact interventional values are unknown, it is expected that the forces exerted laterally on the needle-guide are higher than those encountered for slender needle insertion into soft tissue. For this, the RCM has been built with novel structure to enhance stiffness.

[0022] The present invention is directed to a new robotic system for direct image-guided interventions. A manipulator of the present invention uses a pneumatic step motor actuation and is entirely made of electrically nonconductive, nonmetallic, and nonmagnetic materials. Accordingly, the manipulator is MR Safe based on the scientific rationale (ASTM F2503-13). The robot is also compatible with all types of medical imaging equipment, and may operate next to the patient within the gantry with no mutual interference.

[0023] The manipulator orients a needle-guide with 2 degrees of freedom (DoF) about a fulcrum point located below the guide using an innovative remote center of motion (RCM) parallelogram type mechanism. In addition, the depth of manual needle insertion is preset with a 3rd DoF located aside of the manipulator. The manipulator includes registration markers for image-to-robot registration. Based on the images, the registration markers may be used to guide needles, drills, or other slender instruments on target. For this versatility, special consideration was given to the kinematic accuracy and the structural stiffness, which are documented experimentally. The manipulator of the present invention includes a Remote Center of Motion (RCM) kinematic structure. The RCM kinematic structure allows a medical

instrument to pivot about a fulcrum point that is located remotely from the mechanism, typically placed at the skin entry point/port of numerous minimally invasive interventions/operations.

[0024] Basic mechanical RCM mechanisms present 2 rotary DoF that intersect at the fulcrum (RCM) point. However, only one of these requires special kinematics, because the second can be simply implemented with a revolute joint whose axis passes the fulcrum. Because only one requires special kinematics, some RCM mechanisms are considered as 1-DoF planar mechanism that implements the actual remote revolute axis.

[0025] FIGS. 1A-1C illustrate schematic diagrams of different 1-DoF parallelogram RCM types. The 1-DoF mechanism of prior RCM mechanisms is schematically represented in FIG. 1A. This is a 6-bar linkage with 8 joints. Here, several of the links and joints are redundant. For example, the kinematics of the mechanism is identical if either link A_1A_2 , or A_1B_2 , or both A_2B_2 and B_1B_2 are removed. Therefore, the mechanism uses at least 2 parallelogram 4-bar structures to implement a virtual parallelogram OAA_1O_1 , which makes link AB rotate about the remote center of motion (RCM) point O. The remote axis of rotation is normal to the plane of the mechanism at the RCM point O. The use of the redundant parallelogram requires precise manufacturing, but improves structural stiffness. Each of the letters represents a joint and links are listed by their combination of letters.

[0026] The end-effector tool/instrument (I) is attached (G, guide) to the link AB and passes the RCM point O. As shown in FIG. 1A, for this RCM type, the points A, B, and O are colinear. Because the instrument (I) must cross the RCM point O, this should be angled relative to AB as shown in the figure, either in the RCM plane or another. The instrument I may be placed parallel to AB if it is in a parallel plane that clears the interference. An example of a robot with this arrangement is the other RCM robot for MRI. Another option is to place the instrument I in a parallel plane to clear the interference.

[0027] A variation of the 1-DoF parallelogram RCM mechanism is illustrated in FIG. 1B. Here, the vertical links $O_1A_1B_1$ and $O_2A_2B_2$ have been “bent” so that the three joints are non-collinear. As such, the virtual parallelogram is OBB_1O_1 , which makes the RCM point O non-collinear with AB. This arrangement give more flexibility in mounting the instrument.

5 With this, the instrument may be mounted parallel to AB and in the same plane ($OI \parallel AB$), as shown in FIG. 1B. Finally, the non-collinear joint arrangement can also be applied to links AA_1A_2 and BB_1B_2 . As shown in FIG. 1C, this helps to further displace the RCM point in the other direction. A variation of this with link $O_2A_2B_2$ straight, $O_1A_1B_1$ and AA_1A_2 bent and non-redundant $A_1A_2B_2B_1$ parallelogram can also be used for an RCM.

10 [0028] For a bone biopsy application, the objective has been to create a structurally stiff robot, to withstand as much as possible the lateral forces exerted by the procedure needle/drill. Because these forces are unknown these are unknown, the design goal was to create the structure as stiff as possible within the MR safe and operation constraints. A possible solution involves small RCM link sizes and a low OA/OB ratio, and the use of a
15 redundant RCM parallelogram.

[0029] FIG. 2 illustrates a kinematic diagram of the RCM mechanism and an actuation schematic for a robot, in accordance with the present invention. As illustrated in FIG. 2 the robot 10 includes an actuation module 12 and an RCM module 14. The actuation module 12 includes motor1 16 and motor2 18, in the embodiment illustrated in FIG. 2. However, any
20 suitable number of motors known to or conceivable by one of skill in the art could also be used. A harmonic drive 20 is also included. The RCM module 14 of the present invention uses a vertically, non-collinear joint arrangement, the redundant parallelogram, relatively short distance to the RCM point, and the needle-guide centered on the joint B. The non-collinear arrangement enabled the bottom joint A to be located aside of the needle-guide. The
25 advantages of this unique arrangement will be described further herein.

[0030] The parallelogram mechanism generates the primary RCM rotation R_1 . This is driven by a spinning-screw (J, revolute joint L) sliding-nut (K) drive, linked with revolute joints to B_1 . The other RCM rotation R_2 is implemented by rotating the base of the parallelogram mechanism about an axis that passes the RCM point (coaxial with OO_1O_2 for convenience), as shown in FIG. 2. The 2-DoF are actuated by motors located in the actuation module 12 which includes a harmonic drive 20 for R_2 .

[0031] FIG. 3 illustrates a perspective view of a manipulator design according to an embodiment of the present invention. The manipulator was designed, analyzed, and manufactured with the Creo (PTC, Inc., Needham, MA) software. The manipulator 100 includes the 2-DoF RCM module 102, the actuation module 104, a passive arm 106 with 3 degrees of adjustment (DoA), and a mount 108 that latches onto the channels of the MRI table 110, as illustrated in FIG. 3. The initial position of the robot and respectively its RCM joint can be adjusted with 4-DoA and locked by sliding the base on the table channels (A_1) and by adjusting the positions of the arm (A_{2-4}), and locking arm knobs 112 by tightening them. The needle 114 includes a depth limiting ring 116.

[0032] For versatility, the manipulator is constructed with a modular structure, so that the actuation module could be reused to drive other mechanisms. The actuation module includes two coaxially placed pneumatic stepper motors ($\varnothing 70$ mm x 25 mm, $4^\circ/\text{step}$, 2 encoder counts/step) and a harmonic drive (49:1 transmission ratio) driven by one of the motors, as illustrated in FIG. 2.

[0033] FIGS. 4A-4D illustrate perspective views of an RCM module detached from an actuation base. FIGS. 4A-4C illustrate isometric and orthogonal views and FIG. 4D illustrates a needle-guide and latching mechanism, according to an embodiment of the present invention. The RCM module 200 detached from the actuation base is shown in FIG. 4A. As illustrated in FIG. 4A the RCM module 200 includes a coupling 202 for connecting the RCM

module 200 to the actuation module (not shown). A set of 4 registration markers 204 has been built into the BB₂ link of the RCM module, as shown in FIG. 4A. These are made of glass tubes, currently filled with Radiance[®] MRI imaging liquid (Beekley, Bristol, CT). The guide is centered on the top joint B by designing the RCM mechanism with a wide structure on both sides of the guide. Joint B is therefore implemented by two coaxial joints BB on the sides, as shown in the RCM module 200 of FIG. 4B. If a collinear RCM mechanism were used, the spacing between the bottom joints AA would have been similar, and the angular clearance with respect to the patient would have been γ_1 . However, the non-collinear design, enabled the two joints A to be located closer, increasing the clearance to γ_2 (40°) $>$ γ_1 (20°).

In the other direction, clearance with respect to the patient is increased by angling the entire RCM module 200 with angle α (20°), as shown in the RCM module 200 of FIG. 4C. The range of the R₁ rotation is -50° to $+30^\circ$ implemented with a custom ACME $\varnothing 10 \times 2$ mm pitch screw. The step size varies between $0.029 - 0.044^\circ/\text{step}$ depending on the position of the RCM mechanism. The R₂ rotation is unrestricted by the joint, but effectively bounded by the interference with the clinical site ($\pm\gamma_2 = \pm 40^\circ$). Its resolution is $0.082^\circ/\text{step}$.

[0034] For sterilization purposes, the entire device is covered with a sterile bag 206 (Universal Medical EZ-3030). The only component to be sterilized is the needle-guide 208, which can be easily detached by pressing a button 210, as illustrated in FIG. 4D. This includes a pin 212 that pierces the bag and attaches to link AB, which has a concave structure that follows the geometry of the needle-guide 208 to provide a secure and stiff attachment, when the latch 212 of the button engages the pin 214. A rubber spring 216 allows depression of the button to engage the pin 214.

[0035] Various needles with diameters up to 10 mm can be manipulated by the robot by adjusting the bore size of the needle-guide. The needle used in the design, illustrated in FIG. 3, is the Invivo 15100 (Schwerin, Germany) MRI bone biopsy set with a cannula diameter of

4.9 mm. However, any suitable needle known to or conceivable by one of skill in the art can also be used.

[0036] While the needle is manually inserted through the guide, the maximum depth of insertion may be pre-adjusted by the robot. A depth limiter consisting of a rubber O-ring is placed on the barrel of the needle, as shown in FIGS. 3, 5, and 6. The needle is inserted through the guide until the ring bottoms on the top surface of the guide. To simplify the construction of the manipulator, a separate device, with 1-DoF, is used to adjust the location of the ring on the needle barrel, implementing a remote DoF.

[0037] FIG. 5 illustrates a partially sectional view of a depth driver to preset a depth for needle insertion, according to an embodiment of the present invention. The depth driver 300 or depth presetting device includes a third pneumatic stepper motor 302 equipped with a central nut 304 (ACME Ø19 x 4.5 mm pitch). The nut 304 drives a screw 306 with 3 flat sides 308 at 120° that slide on 6 rollers 310 that implement a prismatic joint. The motor 302 adjusts the location of a needle limiter 312 attached to the screw 306. The limit ring 314 is initially placed on the needle 316 close to the point, and the needle 316 is inserted in the device until its point bottoms on the needle limiter 312. During this motion the limit ring 314 slides on the barrel of the needle 316 up to the depth position 318 that is to preset. The maximum depth of adjustment is 100mm with a preset depth of 0.05 mm/step. A set of 4 registration markers has been built into the BB₂ link of the RCM module as shown in FIG. 4A and FIG. 6. These are made of glass tubes filled with an MR imaging liquid.

[0038] FIG. 6 illustrates an image view of the device according to an embodiment of the present invention. The manipulator and depth presetting device including the motors and encoders are entirely built of electrically nonconductive, nonmetallic, and nonmagnetic materials. These are plastics such as ABS, Acetal Copolymer, Delrin, Nylon 6, Peek 1000, Polycarbonate, Polyetherimide (Ultem 1000), Polyimide, Polyethersulfone (Radel), PTFE

(Teflon), rubber, composites such as Garolite, Torlon Polyamide-imide, glass, and high-alumina ceramic. In addition to mechanical property considerations, material selection included high electrical resistivity and dielectric strength considerations. The links of the RCM are built of Garolite and Ultem, the pins of the joints are made of Garolite rods, with “tight” Delrin bushings. The needle-guide, which is the only part that comes in direct contact with the patient was built of material with ISO-10993 biocompatible certification, specifically of Radel BL033. The robot 400 includes the actuation module 402 and the RCM module 404. A support arm 406 holds up the actuation module and couples it to the MRI table or other surface. The MRI markers 408 are described in further detail above. The biopsy needle 410 and needle guide 412 are positioned at the distal end of the RCM module 404.

[0039] FIG. 7 illustrates a schematic diagram the robotic system showing placement of MR safe, conditional and unsafe components. The Robot Controller is a PC (Microsoft Corp.) and equipped with a motion control card (MC4000, PMDI, Victoria, BC, Canada). Any other suitable computing device known to or conceivable by one of skill in the art could also be used. The Controller is MR-Unsafe and must remain outside the ACR (American College of Radiology) Zone IV (scanner room), in the ACR Zone III (control room or equipment room).

[0040] An electro-pneumatic and electro-optical Interface to the three pneumatic stepper motors is located in the scanner room (ACR Zone IV) but outside the 0.5 mTesla (5 Gauss) line. The interface is nonmagnetic but uses electricity. For each of the 3 axes, it includes a pneumatic stepper motor driver, 3 piezoelectric valves (Hoerbiger PS10021-641A, Germany), and 2 fiber optic sensors (D10 Expert, Banner Engineering, Minneapolis, MN). The 2 robot axes have no limit switches (hardware stop used to home), but an additional fiber optic sensor is used to home the depth driver. The interface also includes an emergency button and status LEDs.

[0041] The Depth Driver is conveniently mounted on top of the Interface box. The Interface is connected with 3m long hoses to the robot and with DB25 cables (through RF Shield) to the Controller. Motion control, safety, and robot kinematics are implemented on the Robot controller PC under C++ (Visual Studio 2015, Microsoft Corp.) using libraries of the MCC. Safety features include a watchdog, emergency stop buttons, and visual alerts. The watchdog (built on hardware and software) checks the state of several components of the system at 6Hz, disabling power to the pneumatic valves of the electro-pneumatic interface, should a faulty condition occur.

[0042] Images are transferred over the network in DICOM format (Digital Imaging and Communications in Medicine) to the Image Registration & Navigation controller implemented on another PC. Image-to-robot registration of the set of markers of the RCM is used to register the robot and MRI spaces. While our previous imaging programs were based on the Amira Visualization software (Visage Imaging, San Diego, CA). New for this robot, C++ programs were developed using the open source VTK and ITK toolkits and the GDCM open library for DICOM processing. A CAD model of the markers in the robot coordinate system is superimposed over the MR image of the markers to derive the registration matrix. This enables the conversion of points between the two coordinate systems.

[0043] Bench tests of the robot have been completed for motion precision, accuracy, and structural stiffness. A Polaris optical tracker (NDI, Canada) was used to measure the actual location of a passive marker placed on a rod attached to the needle-guide. Under careful measurement conditions, the accuracy of this optical tracker is as low as 0.055 mm. Experimental results showed an angular accuracy of 0.177° and a precision of 0.077° . For a 50mm deep target, the positioning accuracy is 0.155mm and the precision is 0.067mm. The stiffness of the mechanical structure has been measured with a force gauge and a micrometer which showed a structural stiffness of 34.5N/mm at the needle-guide.

[0044] The robot includes high contrast MRI markers for registration (filled with MR-Spots contrast, Beekley, Bristol, CT). A custom image-to-model registration algorithm and image-guided control software was developed. Initial tests were conducted in a Siemens MAGNETOM Tim4G scanner. Images of a gelatin mockup were acquired together with the robot. These initial tests showed no apparent image artifacts or problems in operating the robot within the MRI.

[0045] The movement and actuation of the present invention can be carried out using a computer, non-transitory computer readable medium, or alternately a computing device or non-transitory computer readable medium incorporated into the robotic device or the imaging device.

[0046] A non-transitory computer readable medium is understood to mean any article of manufacture that can be read by a computer. Such non-transitory computer readable media includes, but is not limited to, magnetic media, such as a floppy disk, flexible disk, hard disk, reel-to-reel tape, cartridge tape, cassette tape or cards, optical media such as CD-ROM, writable compact disc, magneto-optical media in disc, tape or card form, and paper media, such as punched cards and paper tape. The computing device can be a special computer designed specifically for this purpose. The computing device can be unique to the present invention and designed specifically to carry out the method of the present invention. The computing device can also take the form of an operating console computer for the imaging device or the robotic device. The operating console for the imaging device or the robotic device is a non-generic computer specifically designed by the manufacturer. It is not a standard business or personal computer that can be purchased at a local store. Additionally, the console computer can carry out communications with the scanner through the execution

of proprietary custom built software that is designed and written by the manufacturer for the computer hardware to specifically operate the hardware.

[0047] The many features and advantages of the invention are apparent from the detailed specification, and thus, it is intended by the appended claims to cover all such features and
5 advantages of the invention which fall within the true spirit and scope of the invention.

Further, since numerous modifications and variations will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

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What is claimed is:

1. A robot comprising:

a remote center of motion (RCM) mechanism having a parallelogram structure with non-collinear joints; and

5 wherein an instrument for use with the robot is aligned between a joint and the RCM point of the RCM mechanism.

2. The robot of claim 1, where the parallelogram structure includes redundant parallelogram components.

- 10 3. The robot of claim 1 further comprising a link and screw mechanism configured for driving the RCM mechanism.

4. The robot of claim 1 further comprising the RCM mechanism having a spatial structure.

- 15 5. The robot of claim 3 further comprising a first set of joints A, A₁, and A₂ and a second set of joints B, B₁, and B₂ wherein a first distance between A and A₁ is less than a distance between B and B₁ and a second distance between A₁ and A₂ is less than a second distance between B₁ and B₂.

6. The robot of claim 1 further comprising a support arm configured to attach to a table and provide rotation about a vertical axis.

- 20 7. The robot of claim 1 further comprising a needle-guide.

8. The robot of claim 6 further comprising the needle-guide having a protruding surface that is positively engaged by a fixture, and a pin of the needle-guide that is latched within the fixture, whereby the needle-guide can be engaged and detached from the fixture through a bag.

9. The robot of claim 7 further comprising a ring configured to be placed over a needle, such that the ring allows for a depth of needle insertion to be preset.

10. The robot of claim 9 further comprising a device to preset a position of the ring wherein the device comprises a motor to set a depth position and copy it onto the position of the ring.

11. The robot of claim 10 further comprising a remote device configured for setting a depth of needle insertion.

12. The robot of claim 1 wherein the robot is configured to be safe for use with magnetic resonance (MR)

13. An actuation module for use with a robot comprising:

two coaxially aligned motors;

wherein a first of the two coaxially aligned motors is configured to drive a mechanical transmission; and

wherein a second of the two coaxially aligned motors is configured to pass its output through a bore of the first of the two coaxially aligned motors.

14. The actuation module of claim 13 further comprising a modular robot structure and a driving mechanism module.

15. The actuation module of claim 13 further comprising a kinematic arrangement and a remote center of motion (RCM) mechanism.

16. The actuation module of claim 15 further comprising the RCM mechanism being driven by a link and screw mechanism.

17. The actuation module of claim 13 further comprising a harmonic drive.

18. The actuation module of claim 13 further comprising an adjustable mounting system.

19. The actuation module of claim 18 wherein the adjustable mounting system is configured to couple to an MRI table.

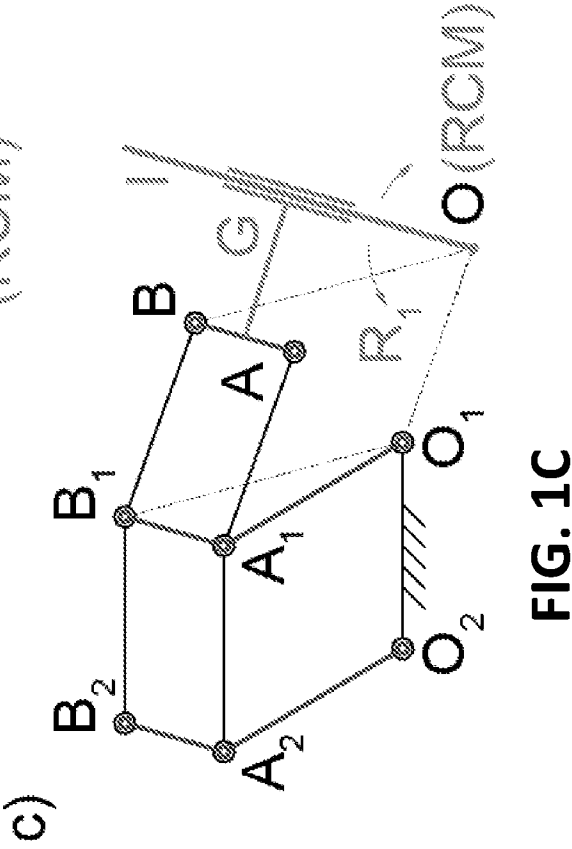
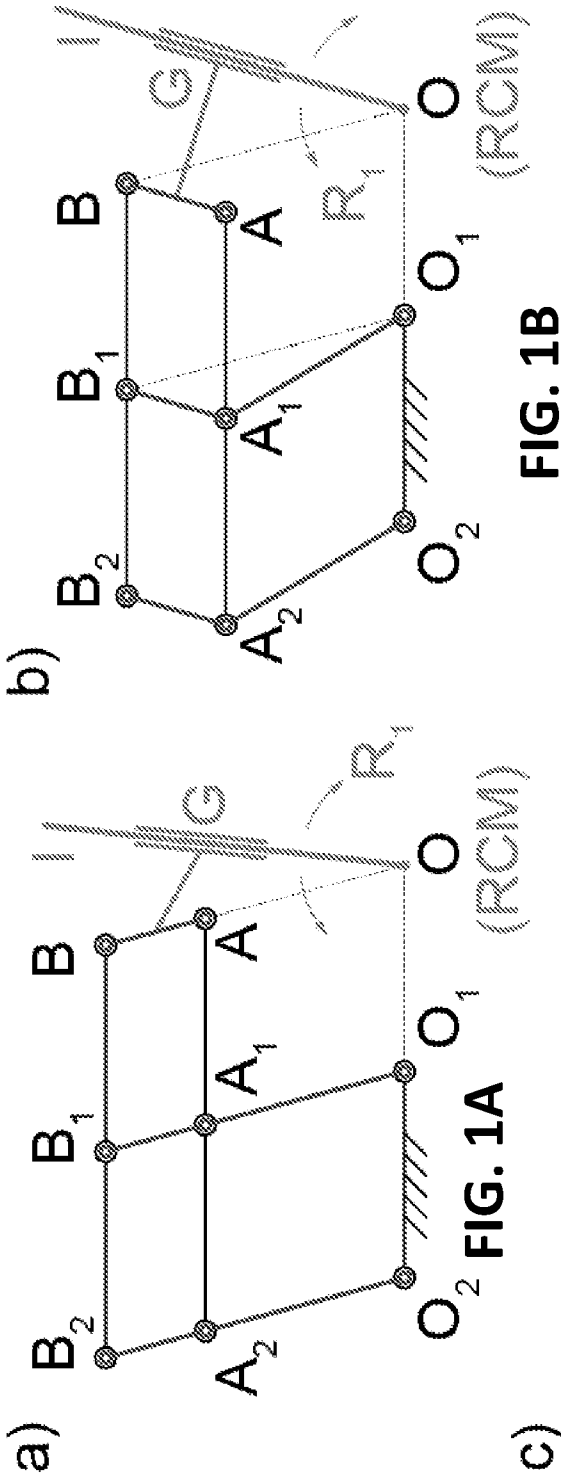
20. A device comprising:

a needle-guide having a protruding surface;

5 a fixture that positively engages the protruding surface of the needle-guide;

and

a pin of the needle-guide that is latched within the fixture, whereby the needle-guide can be engaged and detached from the fixture through a bag.



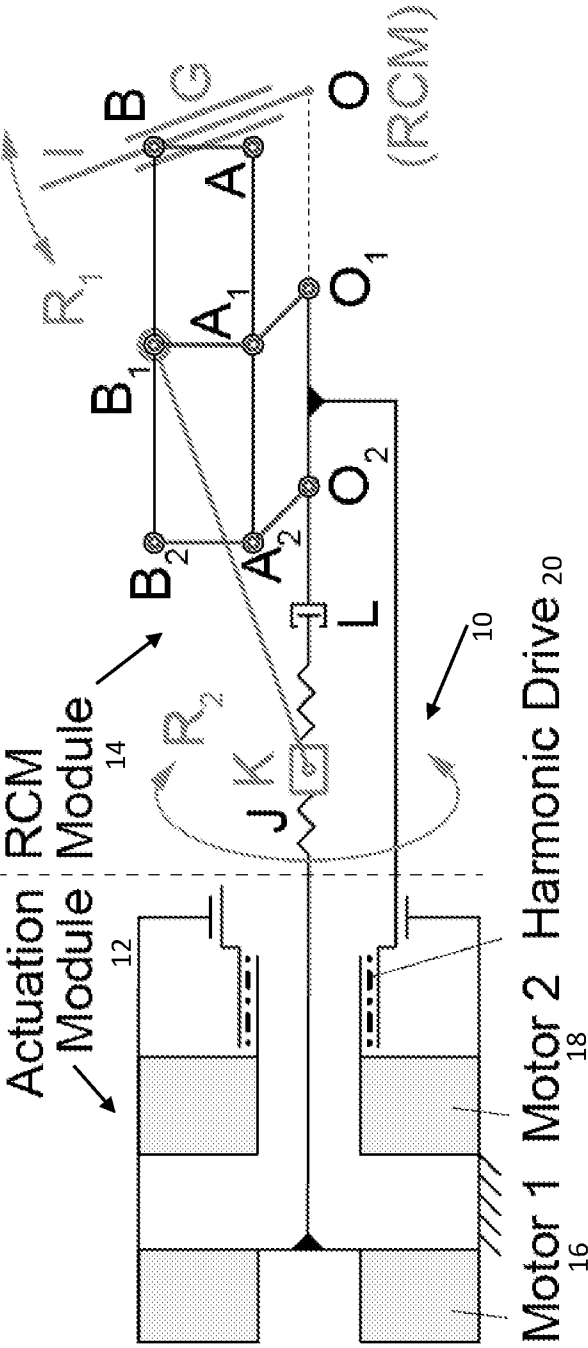
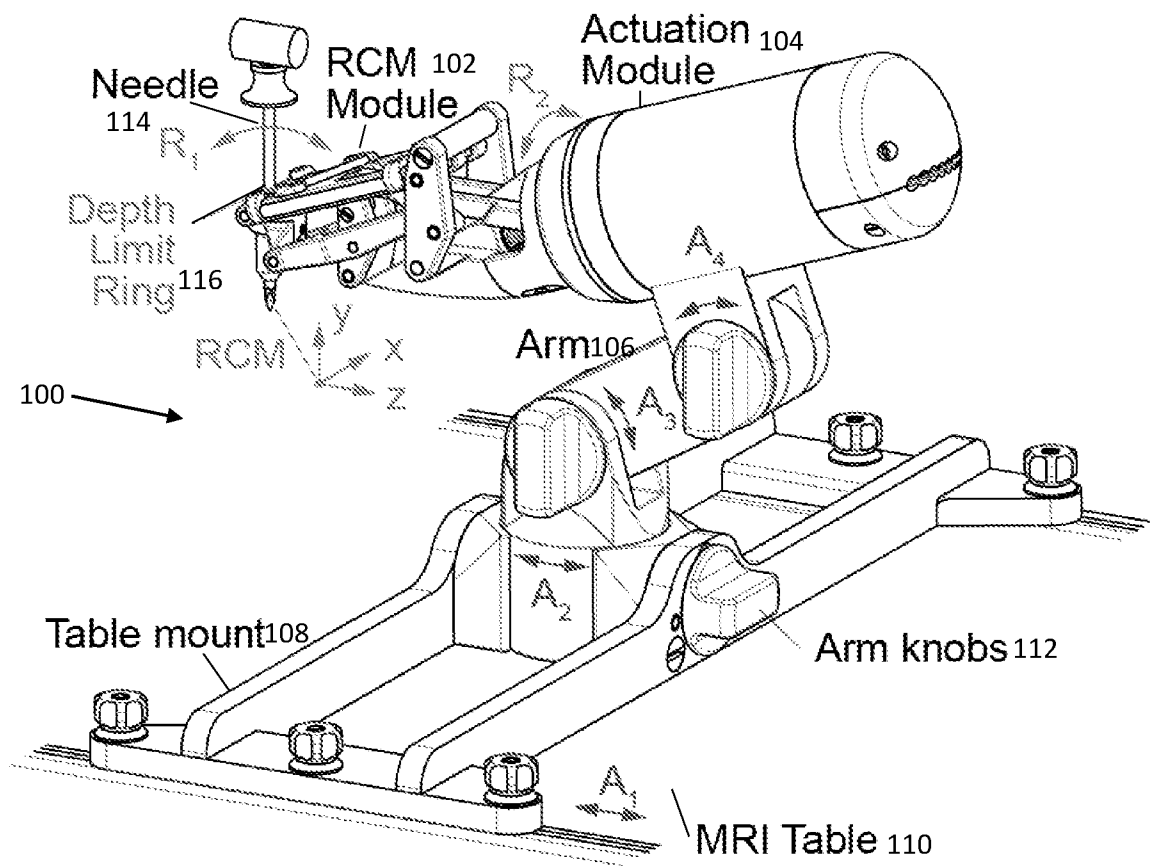
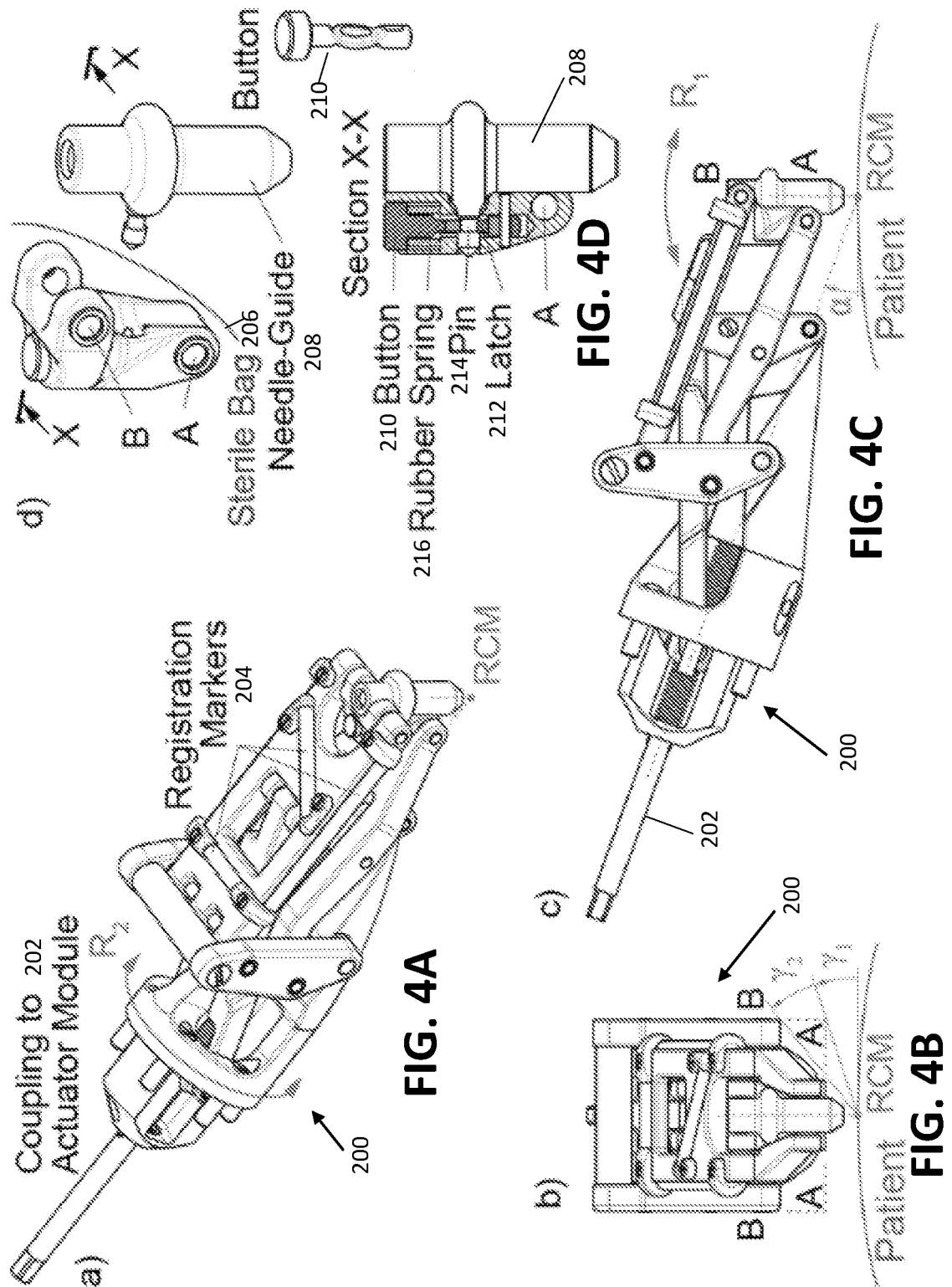


FIG. 2

**FIG. 3**



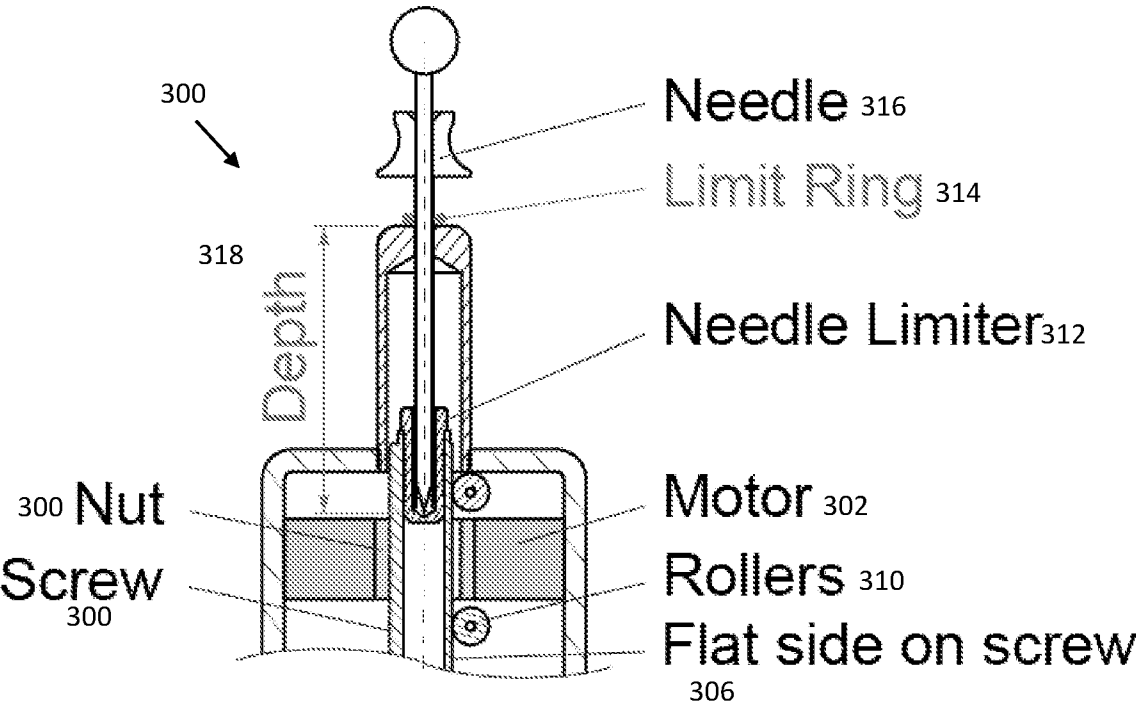
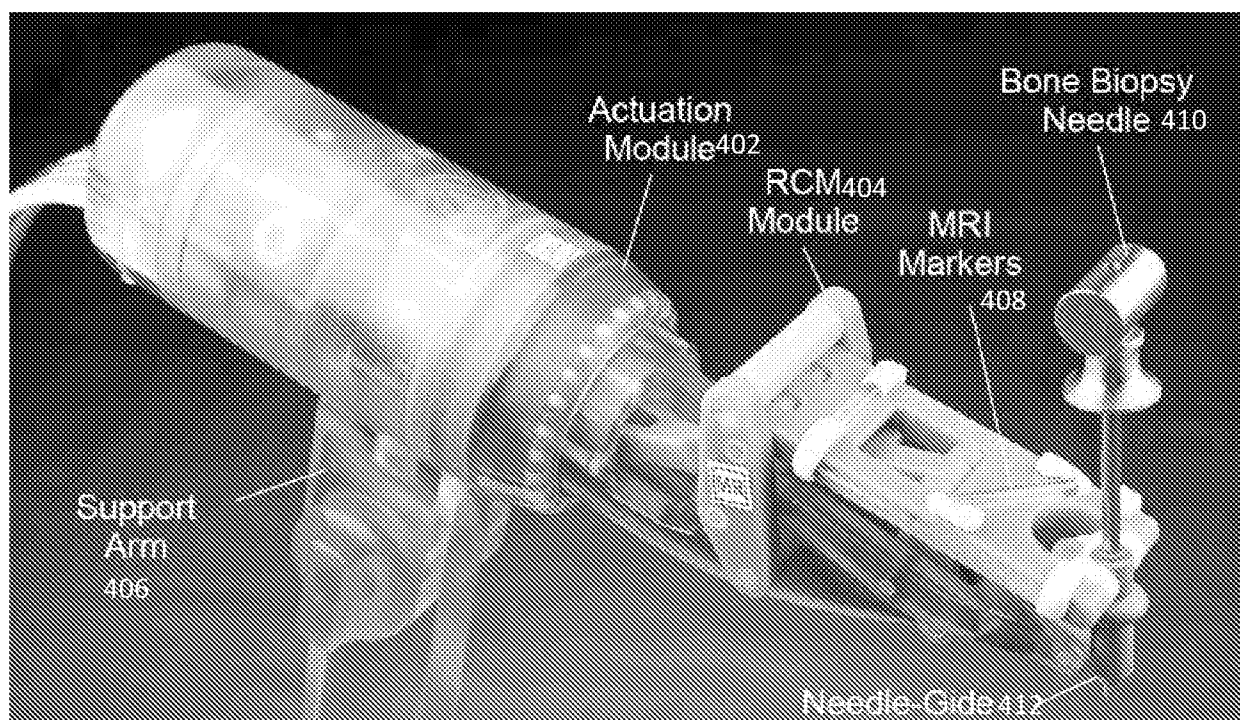
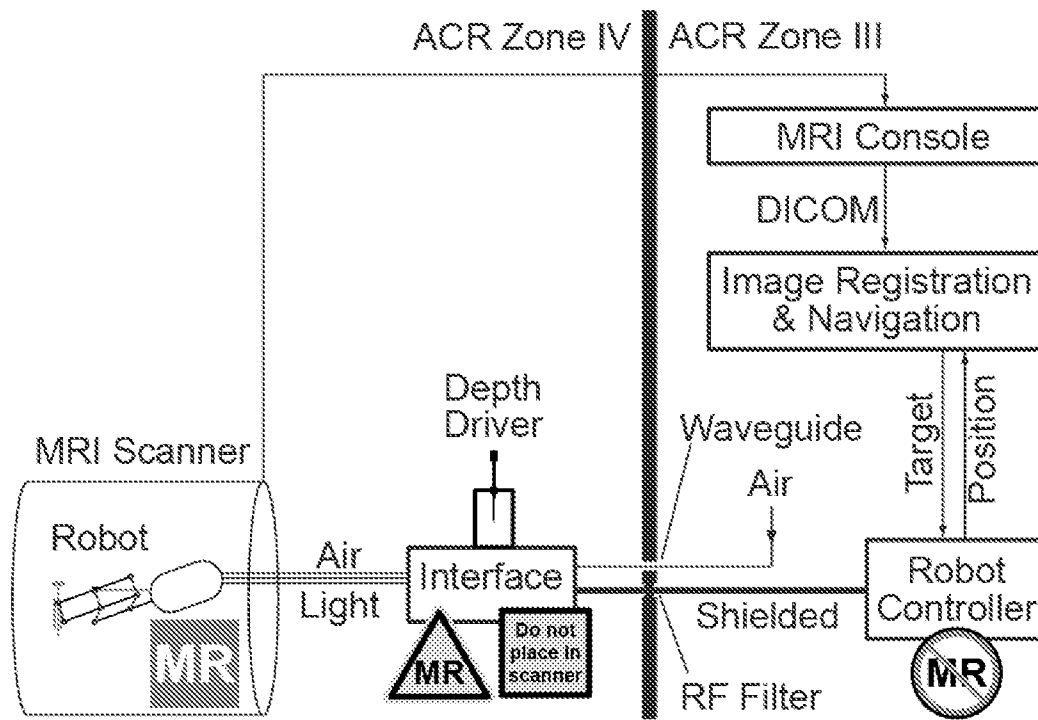


FIG. 5

**FIG. 6**

7/7

**FIG. 7**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2017/030958

A. CLASSIFICATION OF SUBJECT MATTER		
<i>A63B 34/35 (2016.01)</i> <i>A61B 34/30 (2016.01)</i> <i>A61B 90/11 (2016.01)</i>		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols)		
B25J 9/00, 9/08, 13/00, 19/00, A61B 34/00-34/37, 90/00, 90/10, 90/11		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DWPI, EAPATIS, PATENTSCOPE		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GIJBELS A. et al. Design and realisation of a novel robotic manipulator for retinal surgery. 2013 IEEE/RSJ International Conference on Intelligent Robots and System (IROS) November 3-7, 2013. Tokyo, Japan	1, 2, 4, 7, 20
Y		3, 8, 12
A		5, 6, 9-11, 13-19
A	RU 139309 U1 (OBSHESTVO S OGRANICHENNOI OTVETSTVENNOSTIYU "EIDOS-MEDITSINA") 10.04.2014	13-19
	US 6296614 B1 (RICK L. PRUTER) 02.10.2001	
X		20
Y		8
☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search		Date of mailing of the international search report
14 August 2017 (14.08.2017)		24 August 2017 (24.08.2017)
Name and mailing address of the ISA/RU: Federal Institute of Industrial Property, Berezhkovskaya nab., 30-1, Moscow, G-59, GSP-3, Russia, 125993 Facsimile No: (8-495) 531-63-18, (8-499) 243-33-37		Authorized officer S. Omarova Telephone No. 8 499 240 25 91

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2017/030958

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	BOCTOR Emad M. et al. Virtual remote center of motion control for needle placement robots [online] 29.03.2003 [retrieved on 2017-07-31]. Retrieved from the Internet: <URL: http://research.vuse.vanderbilt.edu/MEDLab/sites/default/files/papers/BoctorVirtualMICCAI03.pdf >, par. 2	12
Y	RU 2004229 C1 (SKRINNIK ALEKSEI MIKHAILOVICH) 15.12.1993, col. 3, lines 42-50	3