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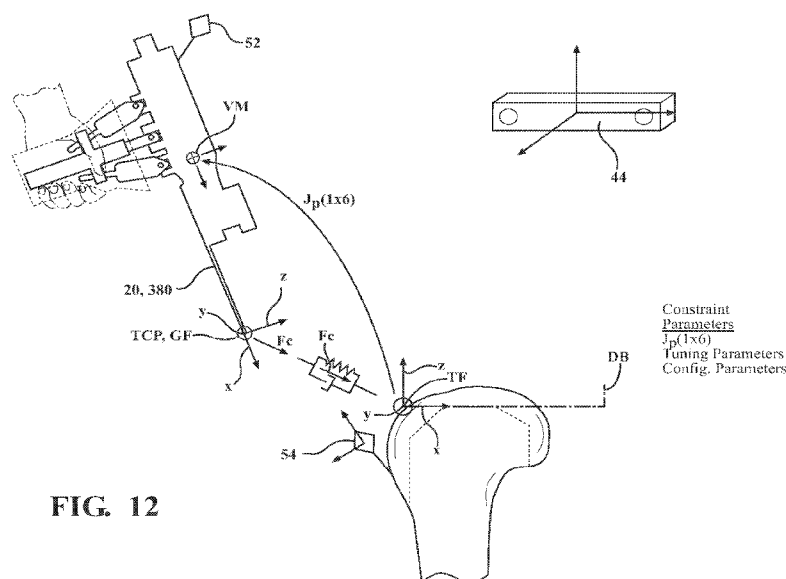


FIG. 12

(57) Abstract: The teachings generally provide for a hand-held medical robotic system for use with a surgical tool, the system comprising an instrument comprising a hand-held portion, a tool support coupled to the hand-held portion, and an actuator assembly operatively interconnecting to move the tool support in a plurality of degrees of freedom to place the surgical tool and a localizer. The system additionally comprises a control system configured to determine a state of the surgical tool and determine a position and/or orientation of a reference coordinate system relative to a known coordinate system, activate a guided mode based on a first relationship criteria between the state of the surgical tool and the reference coordinate system, and deactivate the guided mode based on a second relationship criteria between the state of the surgical tool and the reference coordinate system, wherein the first relationship criteria and the second relationship criteria are different.



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SYSTEMS AND METHODS FOR GUIDING MOVEMENT OF A HAND-HELD MEDICAL ROBOTIC INSTRUMENT

BACKGROUND

[0001] Physical cutting guides are used to constrain surgical tools when resecting tissue from a patient. In some cases, physical cutting guides constrain such surgical tools for the purpose of preparing joints to accept replacement implants. The time required to position and secure a physical cutting guide to the patient can represent a significant portion of the overall time required to perform a surgical procedure.

[0002] Navigation systems (also referred to as tracking systems) can be used to properly align and secure jigs, as well as track a position and/or orientation of a surgical tool used to resect tissue from a patient. Tracking systems typically employ one or more trackers associated with the tool and the tissue being resected. A display can then be viewed by a user to determine a current position of the tool relative to a desired cut path of tissue to be removed. The display may be arranged in a manner that requires the user to look away from the tissue and surgical site to visualize the tool's progress. This can distract the user from focusing on the surgical site. Also, it may be difficult for the user to place the tool in a desired manner.

[0003] Robotically assisted surgery typically relies on large robots with robotic arms that can move in six degrees of freedom (DOF). These large robots may be cumbersome to operate and maneuver in the operating room.

[0004] There is a need for systems and methods to address one or more of these challenges.

SUMMARY

[0005] The present teachings may include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the devices and methods.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Advantages of the present disclosure will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings.

[0007] Figure 1 is a perspective view of a robotic system.

[0008] Figure 2 is a perspective view of a robotic instrument being used to cut one or more planes on a femur and a tibia to receive a total knee implant.

[0009] Figures 3A-3C are illustrations of various pitch orientations of the robotic instrument.

[0010] Figures 4A-4C are illustrations of various roll orientations of the robotic instrument.

[0011] Figures 5A-5C are illustrations of various z-axis translation positions of the robotic instrument.

[0012] Figure 6 is a front perspective view of the robotic instrument illustrating one particular pose of a tool support relative to a hand-held portion.

[0013] Figure 7 is a block diagram of a control system, and also illustrates various software modules.

[0014] Figure 8 is a rear perspective view of the robotic instrument.

[0015] Figure 9 is an exploded view showing a body of the tool support and associated joint connections to a plurality of actuators.

[0016] Figure 10 illustrates various regions in which the robotic instrument is used.

[0017] Figures 11 is a block diagram of particular modules operable by the control system.

[0018] Figures 12 is an illustration of guide constraints and virtual forces.

[0019] Figure 13 illustrates output of a boundary generator for a surgical procedure on a femur.

[0020] Figure 14 illustrates the virtual boundaries based on the planned surgical implant.

[0021] Figure 15 is a top down view of a saw blade and a portion of patient anatomy relative to certain virtual boundaries.

[0022] Figure 16 illustrates a portion of the navigation system relative to the patient anatomy and a surgical robotic instrument, and the potential transform calculations.

[0023] Figure 17A-17E is a block diagram of various portions of the control system.

[0024] Figure 18 and 19 illustrate another application of guide constraints to attract the tool to a target plane.

[0025] Figure 20 illustrates how stiffness of the guide constraint may vary with the distance.

[0026] Figure 21 shows an illustration of a joint centering constraint and associated virtual forces.

[0027] Figure 22A-22C illustrate one example of actuator control with respect to joint centering behavior.

[0028] Figure 23 is a perspective view of the instrument illustrating the range of motion of the tool as controlled in view of a Cartesian space.

[0029] Figure 24 is a perspective view of one example of the hand-held robotic instrument.

[0030] Figure 25 shows a sample constraint equation.

[0031] Figures 26 and 27 show a sample forward dynamics algorithm for carrying out a virtual simulation.

[0032] Figure 28 shows an example set of steps carried out by the control system to solve constraints, perform forward dynamics, and determine a commanded pose

[0033] Figures 29A-29D illustrate movements of the tool in response to application of guide constraints to attract the tool to a target position and target orientation

[0034] Figure 30A and 30B show a schematic view of a robotic instrument performing a cut with respect to the guide behavior.

[0035] Figure 31 is a block diagram of a control system.

[0036] Figure 32 is a schematic illustration of a control implementation for a robotic surgical system using a distance parameter.

[0037] Figures 33A-33C is a schematic illustration of a control implementation for a robotic surgical system using a virtual object.

[0038] Figure 34 is a schematic illustration of a control implementation for a robotic system using a boundary.

[0039] Figure 35 is a schematic illustration of a control implementation for a robotic system using two boundaries.

[0040] Figures 36A and 36B are schematic illustrations of a control implementation for a robotic system using two different distance parameters.

[0041] Figure 37 is an illustration of an exemplary user interface including a plurality of cut icons.

[0042] Figure 38 is an illustration of an exemplary user interface showing a first region and a second region of bone.

[0043] Figures 39A-39C are schematic illustrations of a control implementation for a robotic system for transitioning the system to a home state.

[0044] Figure 40 is a schematic illustration of a control implementation for a robotic system for transitioning the instrument to a home state, including use of a virtual object.

[0045] Figure 41 is a schematic illustration of a control implementation for a robotic system for transitioning the instrument to a home state, including use of a virtual object.

[0046] Figure 42 is a graph depicting a plurality of velocity thresholds based on time for use with controlling a robotic system.

[0047] Figure 43 is a graph depicting a function of a tuning parameter based on time for use with controlling a robotic system.

[0048] Figure 44 is another example of a portion of the navigation system relative to the patient anatomy and a surgical robotic instrument, and the potential transform calculations related to a target trajectory.

[0049] Figure 45 is a front perspective view of a sterilization container.

[0050] Figures 46A and 46B show the instrument operating in a sterilization mode to move the instrument to a sterilization pose.

[0051] Figures 47A and 47B show the instrument being installed in a void of the sterilization container to facilitate a sterilization process.

[0052] Figures 48A and 48B show a lid of the sterilization container being installed over a base of the sterilization container to facilitate a sterilization process.

[0053] Figures 49A-49B show the instrument operating in a sterilization mode to move the instrument to another sterilization pose.

[0054] Figure 50 shows an instrument having a guidance array.

[0055] Figure 51 shows a sterilization container defining a second void configured to receive the guidance array.

[0056] Figure 52 shows the sterilization container with the guidance array received in the second void.

[0057] Figure 53 shows a representation of a pointer instrument contacting bone.

[0058] Figure 54 shows an exemplary display of the robotic system with an indicator.

DETAILED DESCRIPTION

OVERVIEW

[0059] Referring to Figure 1, a robotic system 10 is illustrated. The robotic system 10 is shown performing a total knee procedure on a patient 12 to resect portions of a femur F and tibia T of the patient 12 so that the patient 12 can receive a total knee implant IM. The robotic system 10 may be used to perform other types of surgical procedures, including procedures that involve hard/soft tissue

removal, or other forms of treatment. For example, treatment may include cutting tissue, drilling holes, coagulating tissue, inserting implants, ablating tissue, stapling tissue, suturing tissue, or the like. In some examples, the surgical procedure involves knee surgery, hip surgery, shoulder surgery, spine surgery, and/or ankle surgery, and may involve removing tissue to be replaced by surgical implants, such as knee implants, hip implants, shoulder implants, spine implants, such as pedicle screws, and/or ankle implants. The robotic system 10 and techniques disclosed herein may be used to perform other procedures, surgical or non-surgical, and may be used in industrial applications or other applications where robotic systems are utilized. Aspects of planning an axis and various boundaries for spine surgery are described in WO2021062373, which is hereby incorporated by reference.

[0060] Referring to Figures 1 and 2, the robotic system 10 includes an instrument 14. In some examples, a user manually holds and supports the instrument 14 (as shown in Figure 1). In some other examples, the user may manually hold the instrument 14 while the instrument is being at least partially, or fully, supported by an assistive device, such as a passive arm (e.g., linkage arm with locking joints, weight-balancing arm), an active arm, and/or the like. As best shown in Figures 1 and 2, the instrument 14 comprises a hand-held portion 16 for being supported by the user .

[0061] The instrument 14 may be freely moved and supported by a user without the aid of a guide arm/assistive device, e.g., configured to be held by a human user while effecting physical removal of material or cutting of material such that the weight of the tool is supported solely by a hand or hands of the user during the procedure. Put another way, the instrument 14 may be configured to be held such that the user's hand is supporting the instrument 14 against the force of gravity. The instrument 14 may weigh 8 lbs. or less, 6 lbs. or less, 5lbs. or less, or even 3lbs. or less. The instrument 14 may have a weight corresponding to ANSI/AAMI HE75:2009.

[0062] In implementations where the weight of the instrument configured to be supported by the user without the aid of a guide arm or assistive device, the hand-held portion has no rigid reference to earth and moves relative to earth during control of the actuator assembly. This can be contrasted with robotic arms that feature bases that are coupled to tables, carts, imagers, or other components that remain static during a procedure. Because the hand-held portion of the instrument may move relative to earth, the pose of the hand-held portion is dynamic and may need to be accounted for during control of the hand-held robotic instrument to achieve optimal performance, including to achieve optimal range of motion, optimal balance and center of gravity relative to the user's hands, and optimal feel to a user to avoid providing sensations that may distract the user from positioning the hand-held portion

in an ideal manner to complete the procedure. This is due to the fact that the control system of the instrument cannot assume that the base aka hand-held portion is in a fixed location when calculating the navigation transforms between the various moving/conformable components of the system, including but not limited the tool, the tool platform, the actuator assembly, and/or the hand-held portion.

[0063] Another complexity introduced for hand-held medical robotic instruments that are configured to have their weight supported by a user without use of a guide arm or assistive device is that reaction forces transmitted through the kinematic chain of the instrument are ultimately transmitted solely to the user's hand(s), as opposed to being transmitted, at least in part, to the guide arm/assistive device. Because the user has to bear the reaction forces in a hand-held robotic system, the control system for a hand-held robotic instrument needs to carefully control the actuator assembly so as to ensure that these reactive forces do not compromise the useability of the system. If the control system results in significant reactive forces being applied to the user's hands at undesirable times and/or in undesirable directions, these reactive forces can influence the user's behavior and cause them to move their hand(s), and hence the robotic instrument, to undesirable positions, orientations, and/or poses. For example, if there is a discrepancy between the virtual world and the real world with respect to the bone, the tool, the tool support, and/or the hand-held portion, the discrepancy may lead to the control system controlling the actuator assembly in a way that applies reactive forces to the user's hands.

[0064] The instrument 14 also comprises a tool support 18 for receiving a tool 20. In some examples, when the tool 20 is a saw blade 380, the tool support 18 may be referred to as a blade support. The method for operating the instrument 14 may include a user suspending the weight of the instrument 14 without any assistance from a passive arm or robotic arm. Alternately, the weight of the instrument 14 may be supported through use of a counter-balanced passive arm, assistive device, or active robotic arm, such that the user does not have to support the entire weight of the instrument. In such cases, the user may still grasp the hand-held portion 16 in order to interact with and/or guide the instrument 14. The passive arm and the contents of U.S. Patent No. 9,60,794 to Kang et al. are incorporated herein by reference. Furthermore, the robotic system 10, in some examples, may be free from a robot arm having more than one joint in series.

[0065] The tool 20 couples to the tool support 18 to interact with the anatomy in certain operations of the robotic system 10 described further below. The tool 20 may also be referred to as

an end effector. The tool 20 may be removable from the tool support 18 such that new/different tools 20 can be attached when needed. The tool 20 may also be permanently fixed to the tool support 18. The tool 20 may comprise an energy applicator designed to contact the tissue of the patient 12. In some examples, the tool 20 may be a saw blade, as shown in Figures 1 and 2, or other type of cutting accessory. In such instances, the tool support may be referred to as a blade support. It should be appreciated that in any instance where blade support is referred to, it may be substituted for the term 'tool support' and vice-versa. However, other tools may be contemplated, such as the contents of U.S. Patent No. 9,707,43 to Bozung, which is hereby incorporated herein by reference. In some examples, the tool 20 may be a twist drill bit, a screw driver, a tap, an ultrasonic vibrating tip, a bur, a stapler, a rotary cutting tool, or the like. The tool 20 may comprise the blade assembly and drive motor to cause oscillatory motion of the blade as shown in U.S. Patent No. 9,820,753 to Walen et al. or U.S. Patent No. 10,687,823 to Mac an Tulle et al., hereby incorporated herein by reference. Such driving components may comprise a transmission TM coupled to the drive motor M to convert rotary motion from the drive motor M into oscillating motion of the tool 20.

[0066] The system and methods described in PCT Application No. PCT/US2020/042128, entitled "Robotic Handheld Surgical Instrument Systems and Methods", filed on July 15, 2020, are also hereby incorporated by reference.

[0067] An actuator assembly 400 comprising one or more actuators 21, 22, 23 move the tool support 18 in three degrees of freedom relative to the hand-held portion 16 to provide robotic motion that assists in placing the tool 20 at a desired position and/or orientation (e.g., at a desired pose relative to the femur F and/or tibia T during resection), while the user holds the hand-held portion 16. The actuator assembly 400 may comprise actuators 21, 22, 23 that are arranged in parallel, in series, or a combination thereof. In some examples, the actuators 21, 22, 23 move the tool support 18 in three or more degrees of freedom relative to the hand-held portion 16. In some examples, the actuator assembly 400 is configured to move the tool support 18 relative to the hand-held portion 16 in at least two degrees of freedom, such as pitch and z-axis translation. In some examples, such as shown herein, the actuators 21, 22, 23 move the tool support 18 and its associated tool support coordinate system TCS in only three degrees of freedom relative to the hand-held portion 16 and its associated base coordinate system BCS. For example, the tool support 18 and its tool support coordinate system TCS may: rotate about its y-axis to provide pitch motion; rotate about its x-axis to provide roll motion; and translate along an axis Z coincident with a z-axis of the base coordinate system BCS to provide z-axis

translation motion. The allowed motions in pitch, roll, and z-axis translation are shown by arrows in Figure 2 and in the schematic illustrations of Figures 3A-3C, 4A-4C, and 5A-5C, respectively. Figure 6 provides one example of a pose of the tool support 18 and a pose of the hand-held portion 16 within the range of motion of the instrument 14. In some examples, not shown in the figures, actuators may move the tool support 18 in four or more degrees of freedom relative to the hand-held portion 16.

[0068] The actuator assembly 400 may be arranged as a parallel manipulator configuration. The parallel manipulator configuration, as shown throughout the present application, uses the actuators 21, 22, 23 to support a single platform (i.e. the tool support 18), the actuators 21, 22, 23 controlled and manipulated by the control system 28. The actuators 21, 22, 23, are separate and independent linkages working simultaneously, directly connecting the tool support 18 and the hand-held portion 16. In some examples, such as shown throughout the present application, there is no geometric parallelism required to be a parallel manipulator. Other actuator assembly arrangements are contemplated, such as described in U.S. Patent No. 9,707,43, entitled “Surgical instrument including housing, a cutting accessory that extends from the housing and actuators that establish the position of the cutting accessory relative to the housing” which is incorporated by reference.

[0069] Referring back to Figure 2, a constraint assembly 24 having a passive linkage 26 may be used to constrain movement of the tool support 18 relative to the hand-held portion 16 in the remaining three degrees of freedom. The constraint assembly 24 may comprise any suitable linkage (e.g., one or more links having any suitable shape or configuration) to constrain motion as described herein. In the example shown in Figure 2, the constraint assembly 24 operates to limit motion of the tool support coordinate system TCS by: constraining rotation about the z-axis of the base coordinate system BCS to constrain yaw motion; constraining translation in the x-axis direction of the base coordinate system BCS to constrain x-axis translation; and constraining translation in the y-axis direction of the base coordinate system BCS to constrain y-axis translation. The actuators 21, 22, 23 and constraint assembly 24, in certain situations described further below, are controlled to effectively mimic the function of a physical cutting guide, such as a physical saw cutting guide.

[0070] Referring to Figure 7, an instrument controller 28, or other type of control unit, is provided to control the instrument 14. The instrument controller 28 may comprise one or more computers, or any other suitable form of controller that directs operation of the instrument 14 and motion of the tool support 18 (and tool 20) relative to the hand-held portion 16. The instrument controller 28 may have a central processing unit (CPU) and/or other processors, memory, and storage

(not shown). The instrument controller 28 is loaded with software as described below. The processors could include one or more processors to control operation of the instrument 14. The processors can be any type of microprocessor, multi-processor, and/or multi-core processing system. The instrument controller 28 may additionally, or alternatively, comprise one or more microcontrollers, field programmable gate arrays, systems on a chip, discrete circuitry, and/or other suitable hardware, software, or firmware that is capable of carrying out the functions described herein. The term processor is not intended to limit any embodiment to a single processor. The instrument 14 may also comprise a user interface UI with one or more displays and/or input devices (e.g., triggers, push buttons, foot switches, keyboard, mouse, microphone (voice-activation), gesture control devices, touchscreens, etc.).

[0071] The control system 60 further includes one or more software programs and software modules. The software modules may be part of the program or programs that operate on the navigation controller 36, instrument controller 28, or both, to process data to assist with control of the robotic system 10. The software programs and/or modules include computer readable instructions stored in non-transitory memory 64 on the navigation controller 36, instrument controller 28, or both, to be executed by one or more processors 70 of the controllers 28, 36. The memory 64 may be any suitable configuration of memory, such as RAM, non-volatile memory, etc., and may be implemented locally or from a remote database. Additionally, software modules for prompting and/or communicating with the user may form part of the program or programs and may include instructions stored in memory 64 on the navigation controller 36, instrument controller 28, or both. The user may interact with any of the input devices of the navigation user interface UI or other user interface UI to communicate with the software modules. The user interface software may run on a separate device from the navigation controller 36, and/or instrument controller 28.

[0072] The instrument controller 28 controls operation of the tool 20, such as by controlling power to the tool 20 (e.g., to the drive motor M of the tool 20 that controls cutting motion) and controlling movement of the tool support 18 relative to the hand-held portion 16 (e.g., by controlling the actuators 21, 22, 23). The instrument controller 28 controls a state (e.g., position and/or orientation) of the tool support 18 and the tool 20 with respect to the hand-held portion 16. The instrument controller 28 can control velocity (linear or angular), acceleration, or other derivatives of motion of the tool 20 relative to the hand-held portion 16 and/or relative to the anatomy that is caused by the actuators 21, 22, 23.

[0073] As shown in Figure 2, the instrument controller 28 may comprise a control housing 29 mounted to the tool support 18, and/or the hand-held portion 16 or a combination thereof with one or more control boards 31 (e.g., one or more printed circuit boards and associated electronic components) located inside the control housing 29. The control boards 31 may comprise microcontrollers, field programmable gate arrays (FPGA), drivers, memory, sensors, or other electronic components for controlling the actuators 21, 22, 23 and the drive motor M (e.g., via motor controllers). The instrument controller 28 may also comprise an off-board control console 33 in data and power communication with the control boards 31. The sensors S, actuators 21, 22, 23, and/or drive motor M described herein may feed signals to the control boards 31, which transmit data signals out to the console 33 for processing, and the console 33 may feed control commands (e.g. current commands, torque commands, velocity commands, angle commands, position commands, or a combination thereof, as well as various control and configuration parameters) back to the control boards 31 in order to power and control the actuators 21, 22, 23 and/or the drive motor M. It is contemplated that the processing may also be performed on the control board(s) of the control housing. In some examples, the processing of the control algorithms may be distributed between the console and the control housing. In one example, the position control and velocity control calculations may be in the console and current control may be in the field programmable gate arrays located in the control house. Of course, it is contemplated that no separate control housing is necessary, and/or the processing can be performed in any number of different locations.

[0074] In some versions, the console 33 may comprise a single console for powering and controlling the actuators 21, 22, 23, and the drive motor M. In some versions, the console 33 may comprise one console for powering and controlling the actuators 21, 22, 23 and a separate console for powering and controlling the drive motor M. One such console for powering and controlling the drive motor M may be like that described in U.S. Patent No. 7,422,582, filed on September 30, 2004, entitled, "Control Console to which Powered Surgical Handpieces are Connected, the Console Configured to Simultaneously Energize more than one and less than all of the Handpieces," hereby incorporated herein by reference. Flexible circuits FC, also known as flex circuits, may interconnect the actuators 21, 22, 23 and/or other components with the instrument controller 28. For example, flexible circuits FC may be provided between the actuators 21, 22, 23, and the control boards 31. Other forms of connections, wired or wireless, may additionally, or alternatively, be present between

components. Further, PCT Application No. PCT/US2022/013115 filed January 30, 2022 is incorporated herein by reference.

[0075] Referring briefly back to Figure 1, the robotic system 10 further includes a navigation system 32. One example of the navigation system 32 is described in U.S. Patent No. 9,008,757, filed on September 24, 2013, entitled, “Navigation System Including Optical and Non-Optical Sensors,” hereby incorporated herein by reference. The navigation system 32 tracks movement of various objects. Such objects include, for example, the instrument 14, the tool 20 and the anatomy, e.g., the femur F and tibia T or other bone structures, such as one or more vertebra, the pelvis, scapula, or humerus or combinations thereof. The navigation system 32 tracks these objects to gather state information of each object with respect to a (navigation) localizer coordinate system LCLZ. As used herein, the state of an object includes, but is not limited to, data that defines the position and/or orientation of the tracked object (e.g., coordinate systems thereof) or equivalents/derivatives of the position and/or orientation. For example, the state may be a pose of the object, and/or may include linear velocity data, angular velocity data, and the like.

[0076] The navigation system 32 may include a cart assembly 34 that houses a navigation controller 36, and/or other types of control units. A navigation user interface UI is in operative communication with the navigation controller 36. The navigation user interface UI includes one or more displays 38. The navigation system 32 is capable of displaying graphical representations of the relative states of the tracked objects to the user using the one or more displays 38. The navigation user interface UI further comprises one or more input devices to input information into the navigation controller 36 or otherwise to select/control certain aspects of the navigation controller 36. Such input devices include interactive touchscreen displays. However, the input devices may include any one or more of push buttons, pointer, foot switches, a keyboard, a mouse, a microphone (voice-activation), gesture control devices, and the like. In some examples, the user may use buttons located on the pointer to navigate through icons and menus of the user interfaces UI to make selections, configuring the robotic surgical system 10 and/or advancing through the workflow.

[0077] The navigation system 32 also includes a localizer 44 coupled to the navigation controller 36. In one example, the localizer 44 is an optical localizer and includes a camera unit 46. The camera unit 46 has an outer casing 48 that houses one or more optical sensors 50. The localizer 44 may comprise its own localizer controller 49 and may further comprise a video camera VC. In certain configurations, the localizer may be coupled to the hand-held robotic instrument.

[0078] The navigation system 32 includes one or more trackers. In some examples, the trackers include a pointer tracker PT, a tool tracker 52, a first patient tracker 54, and a second patient tracker 56. In the illustrated example of Figure 1, the tool tracker 52 is firmly attached to the instrument 14, the first patient tracker 54 is firmly affixed to the femur F of the patient 12, and the second patient tracker 56 is firmly affixed to the tibia T of the patient 12. In this example, the patient trackers 54, 56 are firmly affixed to sections of bone. The trackers 52, 54, 56 and pointer tracker are registered to their respective objects (e.g. bone, tool) and the navigation system 32 manually, automatically, or a combination thereof. In some examples, the pointer tracker PT is firmly affixed to a pointer 57 and used for registering the anatomy to one or more coordinate systems, including the localizer coordinate system LCLZ and/or used for other calibration and/or registration functions. In one example, the pointer 57 may be used to register the patient trackers 54, 56 to the bone which the tracker 54, 56 is attached, respectively, and the tool tracker 52 (and optionally 53) to the tool support 18, the tool 20, the hand-held portion 16, or a combination thereof. In some examples, the pointer tracker PT may be used to register the TCP of the instrument 14 to the tracker 52 relative to a tracker coordinate system. This way, if the localizer 44 is moved from position to position, the registration of the instrument 14 is located relative to the tool tracker 52. However, other means of registration of the trackers 52, 54, 56 are contemplated and may be implemented together or separately with the pointer tracker PT. Other tracker locations are also contemplated.

[0079] Throughout this description, various transforms are described, such as ‘bone to tracker’ or ‘instrument TCP to tracker’, i.e., relative to the ‘tracker coordinate system’ rather than to the LCTZ coordinate system. The localizer coordinate system may be used as an intermediate coordinate system during registration and bone prep, since all tracked objects are measured with respect to LCTZ. During registration, ultimately the various localizer-referred poses are combined mathematically and registration results are stored ‘with respect to a tracker’, such that if the camera (i.e., LCTZ) moves, the registration is still valid.

[0080] The tool tracker 52 may be affixed to any suitable component of the instrument 14, and in some versions may be attached to the hand-held portion 16, the tool support 18, directly to the tool 20, or a combination thereof. The trackers 52, 54, 56, PT may be fixed to their respective components in any suitable manner, such as by fasteners, clamps, or the like. For example, the trackers 52, 54, 56, PT may be rigidly fixed, flexibly connected (optical fiber), or not physically connected at all (ultrasound), as long as there is a suitable (supplemental) way to determine the relationship

(measurement) of that respective tracker to the associated object. Any one or more of the trackers 52, 54, 56, PT may include active markers 58. The active markers 58 may include light emitting diodes (LEDs). Alternatively, the trackers 52, 54, 56, PT may have passive markers, such as reflectors, which reflect light emitted from the camera unit 46. Printed markers, or other suitable markers not specifically described herein, may also be utilized.

[0081] Various coordinate systems may be employed for purposes of tracking the objects. For instance, the coordinate systems may comprise the localizer coordinate system LCLZ, the tool support coordinate system TCS, the base coordinate system BCS, coordinate systems associated with each of the trackers 52, 54, 56, PT, one or more coordinate systems associated with the anatomy, one or more coordinate systems associated with pre-operative and/or intra-operative images (e.g., CT images, MRI images, etc.) and/or models (e.g., 2D or 3D models) of the anatomy – such as the implant coordinate system, and a TCP (tool center point) coordinate system. In some examples, the robotic system 10 does not rely on pre-operative and/or intraoperative imaging to create the 2D or 3D models of the target bone. Rather, the robotic system may be used in an imageless system using the pointer tracker PT to register the target anatomy, capturing various anatomical landmarks, which is then processed by the control system 60 to morph a nominal bone model to match the captured data. In other examples, pre-operative and intraoperative imaging is used to image the target area of the patient and then transform the 2D and/or 3D images into a 3D model of the target bone. It is also contemplated that the robotic surgical system 10 may use a combination of imaged and imageless procedures in creating a 3D model of the target surgical area. One exemplary system is described in U.S. Patent No. 8,617,174, which is hereby incorporated by reference. Coordinates in the various coordinate systems may be transformed to other coordinate systems using transformations upon establishing relationships between the coordinate systems, e.g., via registration, calibration, geometric relationships, measuring, etc.

[0082] As shown in Figure 2, in some examples, the TCP is a predetermined reference point or origin of the TCP coordinate system defined at the distal end of the tool 20. The geometry of the tool 20 may be defined relative to the TCP coordinate system and/or relative to the tool support coordinate system TCS. The tool 20 may comprise one or more geometric features, e.g., perimeter, circumference, radius, diameter, width, length, height, volume, area, surface/plane, range of motion envelope (along any one or more axes), etc. defined relative to the TCP coordinate system and/or relative to the tool support coordinate system TCS and stored in the non-volatile memory of the

control boards 31 in the control housing 29 of the instrument 14, the navigation system 32, the instrument controller 28, or a combination thereof. The tool center point (TCP), in one example, is a predetermined reference point and corresponding coordinate system defined at the tool 20. The TCP has a known, or able to be calculated (i.e., not necessarily static), pose relative to other coordinate systems. The TCP coordinate system includes an origin point and a set of axes (e.g. x axis, y axis, z axis) which define the pose of the TCP. By tracking the TCP (or knowing the pose of the TCP), the system 10 may calculate the position and orientation of the instrument 14 based on the pose of the TCP and the known positional relationship between the TCP and the features of the instrument 14. In some examples, the tool 20 has a blade plane (e.g., for saw blades) that will be described for convenience and ease of illustration, but is not intended to limit the tool 20 to any particular form. In other examples, the tool 20 has an axis. Points, other primitives, meshes, other 3D models, etc., can be used to virtually represent the tool 20. The origin point of the TCP coordinate system may be located at the spherical center of the bur 25 of the tool 20, the tip of a drill bit, or at the distal end of the saw blade 27 such that the TCP coordinate system is tracked relative to the origin point on the distal tip of the tool 200. Alternatively, the TCP may be tracked using a plurality of tracked points. The TCP may be defined in various ways depending on the configuration of the tool 20. The instrument may employ the joint/motor encoders, or any other non-encoder position sensing method, so the control system 60 may determine a pose and/or position of the TCP relative to the hand-held portion 16 and BCS. The tool support 18 may use joint measurements to determine TCP pose and/or could employ techniques to measure TCP pose directly. The control of the tool 20 is not limited to a center point. For example, any suitable primitives, meshes, etc., can be used to represent the tool 20. It should be appreciated that the TCP may alternatively be defined as a point, as opposed to a coordinate system. The TCP coordinate system allows calculate any required reference points or geometry aspects of the tool once you have determined the pose of the saw blade or other tool.

[0083] The TCP coordinate system, the tool support coordinate system TCS, and the coordinate system of the tool tracker 52 may be defined in various ways depending on the configuration of the tool 20. For example, the pointer 57 may be used with calibration divots CD in the tool support 18 and/or in the tool 20 for: registering (calibrating) a pose of the tool support coordinate system TCS relative to the coordinate system of the tool tracker 52; determining a pose of the TCP coordinate system relative to the coordinate system of the tool tracker 52; and/or determining a pose of the TCP coordinate system relative to the tool support coordinate system TCS. Other

techniques could be used to measure the pose of the TCP coordinate system directly, such as by attaching and fixing one or more additional trackers/markers directly to the tool 20. In some versions, trackers/markers may also be attached and fixed to the hand-held portion 16, the tool support 18, or both. In instances where the hand-held portion includes a tracker, the pose of the hand-held portion relative to the localizer coordinate system LCTZ may be measured directly. In still other alternatives, the TCP may be defined relative to the tool tracker, using the intermediate tool support coordinate system TCS.

[0084] Since the tool support 18 is movable in multiple degrees of freedom relative to the hand-held portion 16 via the actuators 21, 22, 23, the instrument 14 may employ encoders, hall-effect sensors (with analog or digital output), and/or any other position sensing method, to measure a pose of the TCP coordinate system and/or tool support coordinate system TCS relative to the base coordinate system BCS. In one exemplary configuration, the instrument 14 may use measurements from sensors that measure actuation of the actuators 21, 22, 23 to determine a pose of the TCP coordinate system and/or tool support coordinate system TCS relative to the base coordinate system BCS, as described further below.

[0085] The localizer 44 monitors the trackers 52, 54, 56, PT (e.g., coordinate systems thereof) to determine a state of each of the trackers 52, 54, 56, PT, which correspond respectively to the state of the object respectively attached thereto. The localizer 44 may perform known techniques to determine the states of the trackers 52, 54, 56, PT, and associated objects (such as the tool, the patient, the tool support, and the hand-held portion). The localizer 44 provides the states of the trackers 52, 54, 56, PT to the navigation controller 36. In some examples, the navigation controller 36 determines and communicates the states of the trackers 52, 54, 56, PT to the instrument controller 28.

[0086] The navigation controller 36 may comprise one or more computers, or any other suitable form of controller. Navigation controller 36 has a central processing unit (CPU) and/or other processors, memory, and storage (not shown). The processors can be any type of processor, microprocessor or multi-processor system. The navigation controller 36 is loaded with software. The software, for example, converts the signals received from the localizer 44 into data representative of the position and/or orientation of the objects being tracked. The navigation controller 36 may additionally, or alternatively, comprise one or more microcontrollers, field programmable gate arrays, systems on a chip, discrete circuitry, and/or other suitable hardware, software, or firmware that is

capable of carrying out the functions described herein. The term processor is not intended to limit any embodiment to a single processor.

[0087] Although one example of the navigation system 32 is shown to determine object states, the navigation system 32 may have any other suitable configuration for tracking the instrument 14, tool 20, and/or the patient 12. In another example, the navigation system 32 and/or localizer 44 are ultrasound-based. For example, the navigation system 32 may comprise an ultrasound imaging device coupled to the navigation controller 36. The ultrasound imaging device images any of the aforementioned objects, e.g., the instrument 14, the tool 20, and/or the patient 12, and generates state signals to the navigation controller 36 based on the ultrasound images. The ultrasound images may be 2D, 3D, or a combination of both. The navigation controller 36 may process the images in near real-time to determine states of the objects. The ultrasound imaging device may have any suitable configuration and may be different than the camera unit 46 as shown in Figure 1.

[0088] In another example, the navigation system 32 and/or localizer 44 are radio frequency (RF)-based. For example, the navigation system 32 may comprise an RF transceiver coupled to the navigation controller 36. The instrument 14, the tool 20, and/or the patient 12 may comprise RF emitters or transponders attached thereto. The RF emitters or transponders may be passive or actively energized. The RF transceiver transmits an RF tracking signal and generates state signals to the navigation controller 36 based on RF signals received from the RF emitters. The navigation controller 36 may analyze the received RF signals to associate relative states thereto. The RF signals may be of any suitable frequency. The RF transceiver may be positioned at any suitable location to track the objects using RF signals effectively. Furthermore, the RF emitters or transponders may have any suitable structural configuration that may be much different than the trackers 52, 54, 56, PT shown in Figure 1.

[0089] In yet another example, the navigation system 32 and/or localizer 44 are electromagnetically based. For example, the navigation system 32 may comprise an EM transceiver coupled to the navigation controller 36. The instrument 14, the tool 20, and/or the patient 12 may comprise EM components attached thereto, such as any suitable magnetic tracker, electro-magnetic tracker, inductive tracker, or the like. The trackers may be passive or actively energized. The EM transceiver generates an EM field and generates state signals to the navigation controller 36 based upon EM signals received from the trackers. The navigation controller 36 may analyze the received EM signals to associate relative states thereto. Again, such navigation system 32 examples may have

structural configurations that are different than the navigation system 32 configuration shown in Figure 1.

[0090] The navigation system 32 may have any other suitable components or structure not specifically recited herein. Furthermore, any of the techniques, methods, and/or components described above with respect to the navigation system 32 shown may be implemented or provided for any of the other examples of the navigation system 32 described herein. For example, the navigation system 32 may utilize solely inertial tracking or any combination of tracking techniques, and may additionally or alternatively comprise, fiber optic-based tracking, machine-vision tracking, and the like.

[0091] Referring to Figure 7, the robotic system 10 includes a control system 60 that comprises, among other components, the instrument controller 28 and the navigation controller 36. The control system 60 further includes one or more software programs and software modules. The software modules may be part of the program or programs that operate on the instrument controller 28, navigation controller 36, or a combination thereof, to process data to assist with control of the robotic system 10. The software programs and/or modules include computer readable instructions stored in memory 64 on the instrument controller 28, navigation controller 36, or a combination thereof, to be executed by one or more processors 70 of the controllers 28. The memory 64 may be any suitable configuration of memory, such as non-transitory memory, RAM, non-volatile memory, etc., and may be implemented locally or from a remote database. Additionally, software modules for prompting and/or communicating with the user may form part of the program or programs and may include instructions stored in memory 64 on the instrument controller 28, navigation controller 36, or a combination thereof. The user may interact with any of the input devices of the navigation user interface UI or other user interface UI to communicate with the software modules. The user interface software may run on a separate device from the instrument controller 28 and/or navigation controller 36. The instrument 14 may communicate with the instrument controller 28 via a power/data connection. The power/data connection may provide a path for the input and output used to control the instrument 14 based on the position and orientation data generated by the navigation system 32 and transmitted to the instrument controller 28, as shown as the BUS/COMM connection 37 in Figure 7.

[0092] The control system 60 may comprise any suitable configuration of input, output, and processing devices suitable for carrying out the functions and methods described herein. The control system 60 may comprise the instrument controller 28, the navigation controller 36, or a combination

thereof, and/or may comprise only one of these controllers, or additional controllers. The controllers may communicate via a wired bus or communication network as shown in one example as the BUS/COMM connection 37 in Figure 7, via wireless communication, or otherwise. The control system 60 may also be referred to as a controller. The control system 60 may comprise one or more microcontrollers, field programmable gate arrays, systems on a chip, discrete circuitry, sensors, displays, user interfaces, indicators, and/or other suitable hardware, software, or firmware that is capable of carrying out the functions described herein.

INSTRUMENT

[0093] In one exemplary configuration, the instrument 14 is best shown in Figures 8 and 9. The instrument 14 includes the hand-held portion 16 to be held by the user, the tool support 18 movably coupled to the hand-held portion 16 to support the tool 20, the actuator assembly 400 with the plurality of actuators 21, 22, 23 operatively interconnecting the tool support 18 and the hand-held portion 16 to move the tool support 18 in at least three degrees of freedom relative to the hand-held portion 16, and the constraint assembly 24 having the passive linkage 26 operatively interconnecting the tool support 18 and the hand-held portion 16.

[0094] The hand-held portion 16 comprises a grip 72 for being grasped by the user so that the user is able to manipulate, guide, and/or grasp the instrument 14. The hand-held portion 16 may be configured with ergonomic features such as a grip for a hand of a user to hold, a textured or mixed material coating for preventing a user's hand from slipping when wet and/or bloody. The hand-held portion 16 may include a taper to accommodate users with different hand sizes and contoured to mate with the contours of a user's hand and/or fingers. The hand-held portion 16 also comprises a base 74 to which the grip 72 is attached by one or more fasteners, adhesive, welding, or the like. In the version shown, the base 74 comprises a sleeve 76 having a generally hollow cylindrical shape. Joint supports 77, 78, 79 extend from the sleeve 76. The actuators 21, 22, 23 may be movably coupled to the base 74 at the joint supports 77, 78, 79 via joints described further below.

[0095] The tool support 18 comprises a tool support body 80 to which the tool tracker 52 can be fixed to or removably mounted via one or more tracker mounts fixed to the tool support 18 at one or more mounting locations 82. In one example, the tool tracker 52 is integrated with the tool support 18. In another example, the tool tracker 52 is removably mounted at the one or more mounting locations 82. The tool 20 is removably coupled to the tool support 18 in the version shown. In particular, the tool support 18 comprises a tool coupler, such as head 84 to which the tool 20 is

mounted, as described in U.S. Patent No. 9,820,753 to Walen et al., incorporated herein by reference. The head 84 may be configured to utilize an oscillating-style of saw blade, as well as a sagittal-style saw blade. The drive motor M that drives operation of the tool 20 is disposed in the tool support body 80 (e.g., to drive oscillation of the saw blade in some versions). The tool 20 may be attached to and released from the head 84 in the manner disclosed in U.S. Patent No. 9,820,753 to Walen et al., incorporated herein by reference. As best shown in Figure 9, the tool support 18 also comprises a plurality of actuator mounts 86, 88, 90 at which the actuators 21, 22, 23 are to be movably coupled to the tool support 18 via joints, as described further below. The actuator mounts 86, 88, 90 may comprise brackets, or the like, suitable to mount the actuators 21, 22, 23 such that the tool support 18 is able to move in at least three degrees of freedom relative to the hand-held portion 16.

[0096] The actuators 21, 22, 23, in the version shown, comprise electric, linear actuators that extend between the base 74 and the tool support body 80. When actuated, an effective length of the actuator 21, 22, 23 changes to vary a distance between the tool support body 80 and the base 74 along a corresponding axis of the actuator 21, 22, 23. Accordingly, the control system 60 commands the actuators 21, 22, 23 to work in a coordinated fashion, responding to individual inputs given to each actuator 21, 22, 23, respectively, by the control system 60 to change their effective lengths and move the tool support 18 in at least three degrees of freedom relative to the hand-held portion 16 into the target pose. In the version shown, three actuators 21, 22, 23 are provided, and may be referred to as first, second, and third actuators 21, 22, 23 or front actuators 21, 22, and rear actuator 23. The first, second, and third actuators 21, 22, 23 are adjustable in effective length along a first active axis AA1, a second active axis AA2, and a third active axis AA3 (see Figure 9). The first, second, and third actuators 21, 22, 23 are independently adjustable in effective length to adjust one or more of a pitch orientation, a roll orientation, and a z-axis translation position of the tool support 18 relative to the hand-held portion 16, as previously described. More actuators may be provided in some examples. The actuators may comprise rotary actuators in some examples. The actuators 21, 22, 23 may comprise linkages having one or more links of any suitable size or shape. The actuators 21, 22, 23 may have any configuration suitable to enable movement of the tool support 18 relative to the hand-held portion 16 in at least three degrees of freedom. For example, in some versions, there may be one front actuator and two rear actuators, or some other arrangement of actuators.

[0097] In this version, the actuators 21, 22, 23 are coupled to the base 74 and the tool support body 80 via a plurality of active joints. The active joints include a set of first active joints 92 that

couple the actuators 21, 22, 23 to the tool support body 80 at the actuator mounts 86, 88, 90. In one version, as shown in Figure 9, the first active joints 92 comprises active U-joints. The U-joints comprise first pivot pins 94 and joint blocks 96. The first pivot pins 94 pivotally connect the joint blocks 96 to the actuator mounts 86, 88, 90 via throughbores 98 in the joint blocks 96. Set screws 100 may secure the first pivot pins 94 to the actuator mounts 86, 88, 90. The U-joints may also comprise second pivot pins 104. The joint blocks 96 have crossbores 102 to receive the second pivot pins 104. The second pivot pins 104 have throughbores 103 to receive the first pivot pins 94, such that the first pivot pins 94, the joint blocks 96, and the second pivot pins 104 form a cross of the U-joint. The first pivot pin 94 and the second pivot pin 104 of each U-joint define pivot axes PA that intersect. The second pivot pins 104 pivotally connect a pivot yoke 106 of the actuators 21, 22, 23 to the joint blocks 96. As a result, the actuators 21, 22, 23 are able to move in two degrees of freedom relative to the tool support body 80. Other types of active joints are also contemplated, such as active spherical joints comprising balls with slots that receive pins.

[0098] Referring to Figure 9, the active joints also comprise a set of second active joints 108 coupling the front two actuators 21, 22 to the base 74 of the hand-held portion 16. In the version shown, the second active joints 108 are supported at the joint supports 77, 78. Each of the second active joints 108 comprises a swivel yoke 110 arranged to swivel relative to the base 74 of the hand-held portion 16 about a swivel axis SA. Each swivel yoke 110 has a swivel head 112

[0099] and a post 114 extending from the swivel head 112 to pivotally engage the base 74 at one of the joint supports 77, 78. Nuts 115 threadably connect to one end of the posts 114 to trap the posts 114 in the base 74 while allowing the respective swivel yoke 110 to freely rotate within its respective joint support 77, 78.

[0100] Each of the second active joints 108 comprises a carrier 116 pivotally coupled to one of the swivel yokes 110. The carriers 116 have internally threaded throughbores 117 to receive lead screws 150 of the front two actuators 21, 22, as described further below. Each of the carriers 116 also comprises opposed trunnions 118 that allow the carriers 116 to pivot relative to the swivel yokes 110 about pivot axes PA (see Figure 9) by being seated in pockets in the swivel yokes 110. In some versions, for each of the second active joints 108, the swivel axis SA intersects the pivot axis PA to define a single vertex about which the actuators 21, 22 move in two degrees of freedom.

[0101] Covers are fastened to the swivel heads 112 and define one of the pockets, while the swivel head 112 defines the other pocket. During assembly, the carriers are first positioned with one

of the trunnions placed in the pocket in the swivel head 112, and the cover is then fastened over the other trunnion such that the carrier is captured between the cover and the swivel head 112 and is able to pivot relative to the swivel yoke 110 via the trunnions and pockets. Owing to the configuration of the swivel yokes 110 and the associated carriers, i.e., the carriers ability to swivel about the swivel axes SA and pivot about the pivot axes PA, the second active joints 108 allow two degrees of freedom of movement of the front two actuators 21, 22 relative to the base 74. Other joint arrangements between the front two actuators 21, 22 and the base 74 are also possible.

[0102] The active joints also comprise a third active joint 124 coupling the rear (third) actuator 23 to the base 74 of the hand-held portion 16. In the version shown, the third active joint 124 is supported at the joint support 79. The third active joint 124 comprises a pivot housing 126 fixed to the joint support 79 of the base 74.

[0103] The third active joint 124 comprises a carrier pivotally coupled to the pivot housing 126 via trunnions. Fasteners having pockets attach to either side of the pivot housing 126 via throughbores to engage the trunnions. The fasteners are arranged such that the carrier is able to pivot via the trunnions being located in the pockets after assembly. The carrier has an internally threaded throughbore to receive a lead screw 150 of the rear actuator 23, as described further below. Owing to the configuration of the pivot housing 126 and associated carrier, i.e., the ability of the associated carrier to only pivot about the pivot axis PA (e.g., and not swivel), the third active joint 124 allows only one degree of freedom of movement of the rear actuator 23 relative to the base 74. Other joint arrangements between the rear actuator 23 and the base 74 are also possible.

[0104] Each of the actuators 21, 22, 23 comprises a housing. The housing comprises a canister and a cap threadably connected to the canister. The pivot yokes 106 that form part of the first active joints 92 are fixed to the housings such that the housings and pivot yokes 106 are able to move together relative to the tool support 18 via the first active joints 92. The caps capture annular shoulders of the pivot yokes 106 to secure the pivot yokes 106 to the canisters.

[0105] In some versions, the pivot yokes 106 and canisters comprise one or more alignment features to align each pivot yoke 106 to its respective canister in a predefined, relative orientation. Such alignment features may comprise mating portions, keys/keyways, or the like. During assembly, the pivot yoke 106 may first be secured to the canister in its predefined, relative orientation, and the cap may then be threaded onto the canister (e.g., via mating outer and inner threads) to trap the pivot yoke 106 to the canister at the predefined, relative orientation. This predefined relationship may be

helpful in routing and/or aligning the flex circuits FC, preventing rolling of the pivot yoke 106 relative to the canister, and/or for other purposes.

[0106] Each of the actuators 21, 22, 23 also comprises a motor disposed in each housing. The motor has a casing disposed in the housing and a motor winding assembly disposed within the casing. The motor winding assembly may also be aligned in a predefined, relative orientation to the canister, such as via a set screw or other alignment feature, such as those described above. Each motor also has a rotor fixed to the lead screw 150. The lead screw 150 is supported for rotation in the housing by one or more bushings and/or bearings. The rotor and associated lead screw 150 are configured to rotate relative to the housing upon selective energization of the motor. The lead screws 150 have fine pitch and lead angles to prevent backdriving (i.e., they are self-locking). As a result, a load placed on the tool 20 does not easily back drive the motor. In some examples, the lead screws 150 have an 8-36 class 3 thread that results in a lead of from 0.02 to 0.03 inches/revolution. Other thread types/sizes may also be employed.

[0107] Each of the actuators 21, 22, 23 may be controlled by a separate motor controller. Motor controllers may be wired separately to the actuators 21, 22, 23, respectively, to individually direct each actuator 21, 22, 23 to a given target position. In some examples, the motor controllers are proportional integral derivative (PID) controllers. In some examples, the motor controllers may include cascaded control loops relating to position, velocity, and torque (current). Additionally, and/or alternatively, the motor controller may only include of a torque (current) control loop. In another example, the position control loop may directly feed the torque (current) control loop. Each of these control stages may be implemented as a PID controller, state space controller, and/or utilize alternate or additional control techniques (e.g., velocity feedforward, torque feedforward, etc.). In some cases, the torque (current) control loop is implemented using field-oriented control and space vector modulation. The stages of the control loop could be distributed between various components of the system. In some examples, the position loop and velocity loop are implemented in the instrument controller and the torque control loop is implemented directly in the control boards 31 as part of the control housing 29 on the instrument 14, mitigating the impact of data communication latency from the instrument 14 through the connection to the console 33, since the current control loop does not require any data feedback via the console 33. The position control loop and velocity control loop are not as sensitive to the communication latency and can be implemented in the console 33. In some examples, the motor controllers can be integrated with or form part of the instrument controller 28.

For ease of illustration, the motor controllers shall be described herein as being part of the instrument controller 28.

[0108] A power source provides, for example, 32 VDC power signals to the motors via the console 33. The 32 VDC signal is applied to the motors through the instrument controller 28. The instrument controller 28 selectively provides the power signal to each motor to selectively activate the motors. This selective activation of the motors is what positions the tool 20. The motors may be any suitable type of motor, including brushless DC servomotors, permanent magnet synchronous motors, other forms of DC motors, or the like. The power source also supplies power to the instrument controller 28 to energize the components internal to the instrument controller 28. In some examples, the actuator motor may be a 3-phase, brushless motor. The actuator motor may be a DC motor. The actuator motor may be a permanent magnet synchronous motor. Each of the actuator motors may be configured with a sinusoidal back-EMF, configured to achieve limited mechanical cogging, allowing smooth and particular motion, limiting torque ripple. However, other motor types are contemplated. It should be appreciated that the power source can provide other types of power signals such as, for example, 12 VDC, 24 VDC, 40 VDC, etc. The instrument may use electronic switches, e.g., MOSFETs or GaN FETs to PWM the voltage signals to the 3-phase motor on/off at a high frequency, e.g., typically at a rate of at least 16 kHz, up to 256 kHz or higher.

[0109] In one possible implementation, one or more sensors S (see also Figure 7) transmit signals back to the instrument controller 28 so that the instrument controller 28 can determine a current position and/or angle of the associated actuator 21, 22, 23 (i.e., a measured position). The levels of these signals may vary as a function of the rotational position of the associated rotor. In one implementation, the sensor(s) S may resolve the rotational position of the rotor within a given turn at a high resolution. These sensors S may be Hall-effect sensors that output analog and/or digital signals based on the sensed magnetic fields from the rotor, or from other magnets placed on the lead screw 150 (e.g., the 2-pole magnet A low voltage signal, e.g., 5 VDC, for energizing the Hall-effect sensors may be supplied from the motor controller associated with the motor with which the Hall-effect sensors are associated. In some examples, two Hall-effect sensors are disposed in the housing and spaced 90 degrees apart from each other around the rotor to sense joint position so that the instrument controller 28 is able to determine the position and count incremental turns of the rotor). In some versions, the Hall-effect sensors output digital signals representing incremental counts.). Various types of motors and sensor arrangements are possible. In some examples, the motors are brushless DC

servomotors and two or more internal Hall-effect sensors may be spaced 90 degrees, 120 degrees, or any other suitable spacing from each other around the rotor. The sensors S may also comprise absolute or incremental encoders, which may be used to detect a rotational position of the rotor and to count turns of the rotor. Other type of encoders may be also used as the one or more sensors. The sensors may be placed at any suitable location on the actuator and its surrounding components suitable to determine the position of each actuator as it is adjusted, such as on the housing, nut, screw, etc. In yet another configuration, sensorless motor control may be utilized. In such an implementation, the position of each rotor may be determined by measuring the motor's back-emf and/or inductance. One suitable example may be found in U.S. Patent No. 7,422,582, which is hereby incorporated by reference in its entirety.

[0110] In some examples, the sensors and/or encoders may measure position feedback for joint position control and/or to determine the position of the tool support 18 relative to the hand-held portion 16 when used in conjunction with a kinematic model of the instrument 14. In some examples, the sensors and/or encoders rely on a multi-turn measurement, which accumulates from revolution to the next, used to determine an absolute position of the actuator 21, 22, 23 along its axis and is used in conjunction with the known pitch (i.e. revolutions per inch of the leadscrew). Additionally, or alternatively, the sensors and/or encoders may be used to determine the “electrical angle of the rotor” for use in electronic commutation of the motor. For example, the sensors and/or encoders may be used to determine a rotor position and apply appropriate energization signals to achieve optimal (efficient) torque generation. In this example, the sensors and/or encoders may utilize a single turn or sub-turn (within one electrical revolution) measurement that rolls over each electrical revolution. The number of electrical revolutions is equal to the number of mechanical revolutions divided by the number of magnetic poles of the motor (e.g. number of pole pairs). However, it is contemplated that a sensor-less method be implemented.

[0111] In some examples, output signals from the Hall-effect sensors are sent to the instrument controller 28. The instrument controller 28 monitors the received signals for changes in their levels. Based on these signals the instrument controller 28 determines joint position. Joint position may be considered the degrees of rotation of the rotor from an initial or home position. The rotor can undergo plural 360° rotations. The joint position can therefore exceed 360°. A scalar value referred to as a count is representative of joint position from the home position. The rotors rotate in both clockwise and counterclockwise directions. Each time the signal levels of the plural signals (analog or digital)

undergo a defined state change, the instrument controller 28 increments or decrements the count to indicate a change in joint position. For every complete 360° rotation of the rotor, the instrument controller 28 increments or decrements the value of the count by a fixed number of counts. In some examples, the count is incremented or decremented between 100 and 3,000 per 360-degree revolution of the rotor. In some examples, there are 1,24 positions (counts) per 360-degree revolution of the rotor, such as when an incremental encoder is used to monitor joint position. Internal to the instrument controller 28 is a counter associated with each actuator 21, 22, 23. The counter stores a value equal to the cumulative number of counts incremented or decremented. The count value can be positive, zero or negative. In some versions, the count value defines incremental movement of the rotor. Accordingly, the rotors of the actuators 21, 22, 23 may first be moved to known positions, referred to as their home positions (described further below), with the count values being used thereafter to define the current positions of the rotors.

[0112] As previously described, the carriers have the internally threaded throughbores to threadably receive the lead screws 150 so that each of the lead screws 150 can rotate relative to a corresponding one of the carriers to adjust the effective length of a corresponding one of the plurality of actuators 21, 22, 23 and thereby vary the counts measured by the instrument controller 28. Each of the housings and corresponding carriers are constrained from relative movement in at least one degree of freedom to allow the lead screws 150 to rotate relative to the carriers. More specifically, the lead screws 150 are able to rotate relative to the carriers owing to: the pivot yokes 106 being unable to rotate about the associated active axes AA1, AA2, AA3 (i.e., the pivot yokes 106 are limited from such rotational movement by virtue of the configuration of the first active joints 92); and the carriers being unable to rotate about the associated active axes AA1, AA2, AA3 (i.e., the carriers are limited from such rotational movement by virtue of the configuration of the second active joints 108 and the third active joint 124).

[0113] Stops 152, such as threaded fasteners and shoulders formed on the lead screws 150, are fixed to the lead screws 150. The stops 152 are sized to abut the carriers 116 at ends of travel of each lead screw 150.

[0114] As previously described, the actuators 21, 22, 23 are actively adjustable in effective length to enable movement of the tool support 18 relative to the hand-held portion 16. One example of this effective length is labeled “EL” on the third actuator 23. Here, the effective length EL is measured from the pivot axis PA to a center of the associated first active joint 92. As each actuator

21, 22, 23 is adjusted, the effective length EL changes, by varying how far the lead screw 150 has been threaded into or out of its associated carrier and thereby changing the distance from the center of the associated carrier to the center of the associated first active joint 92. The actuators 21, 22, 23 are adjustable between minimum and maximum values of the effective length EL. The effective length EL of each actuator 21, 22, 23 can be represented/measured in any suitable manner to denote the distance between the tool support 18 and the hand-held portion 16 along the active axes AA1, AA2, AA3 that changes to cause various movements of the tool support 18 relative to the hand-held portion 16.

[0115] The constraint assembly 24 works in concert with the actuators 21, 22, 23 to constrain the movement provided by the actuators 21, 22, 23. The actuators 21, 22, 23 provide movement in three degrees of freedom, while the constraint assembly 24 constrains movement in three degrees of freedom. In the version shown, the constraint assembly 24 comprises the passive linkage 26, as well as a passive linkage joint 156 that couples the passive linkage 26 to the tool support 18.

[0116] In one version, as shown in Figure 9, the passive linkage joint 156 comprises a passive linkage U-joint. The U-joint comprises a first pivot pin 158 and a joint block 160. The first pivot pin 158 pivotally connects the joint block 160 to a passive linkage mount 162 of the tool support body 80 via a throughbore 164 in the joint block 160. A set screw 166 may secure the first pivot pin 158 to the passive linkage mount 162. The U-joint also comprises a second pivot pin 170. The joint block 160 has a crossbore 168 to receive the second pivot pin 170. The second pivot pin 170 pivotally connects a passive linkage pivot yoke 172 of the passive linkage 26 to the joint block 160. The second pivot pin 170 has a throughbore 171 to receive the first pivot pin 158, such that the first pivot pin 158, the joint block 160, and the second pivot pin 170 form a cross of the U-joint. The first pivot pin 158 and the second pivot pin 170 define pivot axes PA that intersect. As a result, the passive linkage 26 is able to move in two degrees of freedom relative to the tool support body 80. Other types of passive linkage joints are also contemplated, such as a passive linkage spherical joint comprising a ball with slot that receives a pin.

[0117] The passive linkage 26 comprises a shaft 174 fixed to the passive linkage pivot yoke 172. The passive linkage 26 also comprises the sleeve 76 of the base 74, which is configured to receive the shaft 174 along a constraint axis CA. The passive linkage 26 is configured to allow the shaft 174 to slide axially along the constraint axis CA relative to the sleeve 76 and to constrain movement of the

shaft 174 radially relative to the constraint axis CA during actuation of one or more of the actuators 21, 22, 23.

[0118] The passive linkage 26 further comprises a key to constrain rotation of the shaft 174 relative to the sleeve 76 about the constraint axis CA. The key fits in an opposing keyway in the shaft 174 and sleeve 76 to rotationally lock the shaft 174 to the sleeve 76. Other arrangements for preventing relative rotation of the shaft 174 and sleeve 76 are also contemplated, such as an integral key/slot arrangement, or the like. The passive linkage 26 operatively interconnects the tool support 18 and the hand-held portion 16 independently of the actuators 21, 22, 23. The passive linkage is passively adjustable in effective length EL along the constraint axis CA during actuation of one or more of the actuators 21, 22, 23. The sleeve 76, shaft 174, and key 176 represent one combination of links for the passive linkage 26. Other sizes, shapes, and numbers of links, connected in any suitable manner, may be employed for the passive linkage 26.

[0119] In the version shown, the passive linkage joint 156 is able to pivot about two pivot axes PA relative to the tool support 18. Other configurations are possible, including robotic hand-held instruments that do not include a passive linkage.

[0120] Also, in the version shown, the first active joints 92 and the passive linkage joint 156 define pivot axes PA disposed on a common plane. Non-parallel pivot axes PA, parallel pivot axes PA disposed on different planes, combinations thereof, and/or other configurations, are also contemplated.

[0121] In some versions, the head 84 of the tool support 18 is arranged so that the tool 20 is located on a tool plane TP (e.g., blade plane) parallel to the common plane when the tool 20 is coupled to the tool support 18. In some examples, the tool plane TP is spaced from the common plane CP by 2.0 inches or less, 1.0 inches or less, 0.8 inches or less, or 0.5 inches or less.

[0122] In the version shown, the actuators 21, 22, 23 are arranged such that the active axes AA1, AA2, AA3 are in a canted configuration relative to the constraint axis CA in all positions of the actuators 21, 22, 23, including when in their home positions. Canting the axes AA1, AA2, AA3 generally tapers the actuator arrangement in a manner that allows for a slimmer and more compact base 74 and associated grip 72. Other configurations are contemplated, including those in which the active axes AA1, AA2, AA3 are not in the canted configuration relative to the constraint axis CA. Such configurations may include those in which the actuator axes AA1, AA2, AA3 are parallel to each other in their home positions.

[0123] Further configurations of the actuators, active joints, and constraint assembly are possible. It is contemplated that the control techniques described may be applied to other mechanical configurations not mentioned, in particular those for controlling a tool or saw blade relative to a hand-held portion in one or more degrees of freedom. In some versions, the constraint assembly may be absent and the tool support 18 of the instrument 14 may be able to move in additional degrees of freedom relative to the hand-held portion 16. For example, the instrument may include linear actuators, rotary actuators, or combinations thereof. The instrument may include 2, 3, 4, 5, 6 or more different actuators arranged parallel, in series, or in combinations thereof.

VISUAL GUIDANCE

[0124] As shown in Figure 10, a guidance array 200 may be optionally coupled to the tool support 18. Additionally, or alternatively, the guidance array 200 could be optionally attached to the hand-held portion 16, or other portion of the instrument 14. In the version shown, the guidance array 200 comprises at least a first visual indicator 201, a second visual indicator 202, and a third visual indicator 203. Each of the visual indicators 201, 202, 203 comprises one or more illumination sources coupled to the instrument controller 28. In some versions, the illumination sources comprise one or more light emitting diodes (e.g., RGB LEDs), which can be operated in different states, e.g., on, off, flashing/blinking at different frequencies, illuminated with different intensities, different colors, combinations thereof, and the like. In the version shown in Figure 10, each of the visual indicators 201, 202, 203 comprises upper portion and lower portion 204, 206 (upper segment 204; lower segment 206). It is further contemplated that the each of the visual indicators 201, 202, 203 may be divided into more than two portions 204, 206, such as three or more, four or more, or even ten or more portions. For example, each of the visual indicators 201, 202, 203 may be divided into three portions, with each portion including one or more LEDs. The visual indicators 201, 202, 203 may have generally spherical shapes with the upper and lower portions 204, 206 comprising hemispherical, transparent or translucent domes that can be separately controlled/illuminated as desired. It is contemplated that the visual indicators 201, 202, 203 may have a shape other than a sphere such as a cylinder, a ring, a square, a polygon, or any other shape capable of conveying visual cues to a user. One or more light emitting diodes may be associated with each dome. The visual indicators 201, 202, 203 may be fixed via one or more mounting brackets 205 to the tool support 18 or to the hand-held portion 16.

[0125] In some examples, where no guidance array is used, the visual indicators 201, 202, 203 may comprise separate portions of a display screen, such as separate regions on a LCD, or LED

display mounted to the tool support 18 or the hand-held portion 16. The display screen may also be included as part of the navigation system, in addition or as an alternative to having a display screen mounted to the instrument.

[0126] Alternatively still, visual guidance in the second mode may be provided with a mechanical guide coupled to the hand-held portion, the blade support, or both.

[0127] In some configurations, there may be one, two, three, or four portions of the display screen, each corresponding to a different visual indicator. Each portion of the display screen may correspond to a different visual graphic. As described below, each of the visual indicators (or portions of the display screen) may be based on actuator information. In some cases, a single visual indicator may be based on actuator information from two or more actuators. Furthermore, as described throughout, the visual indicator may be used in a first mode indicating where the user should position the tool and a second mode where the visual indicator indicates where the user should position the hand-held portion.

[0128] For example, the visual indicator 201, 202, 203 may be configured to output a first indication (a first visual graphic) based on a first commanded position of the first actuator 21, 22, 23 and a second indication (second visual graphic) based on a second commanded position of the first actuator 21, 22, 23, wherein the first indication is different than the second indication, and the first commanded position is different from the second commanded position. As described above, the visual indicator 201, 202, 203 may be controlled based on any suitable type of actuator information. In other words, the visual graphics displayed on the display screen may be based on the commanded position, the previous commanded position, a simulated commanded position, a current measured position, a previous measured position, available travel, an actuator limit (such as a hard or soft stop), a distance needed from current position to commanded position, or a combination thereof.

[0129] In some configurations, the instrument controller 28 is configured to control illumination of the upper and lower portions 204, 206 such that the upper and lower portions 204, 206 are operated in different states to indicate the direction of desired movement of the tool 20. It is further contemplated that the instrument controller 28 may be configured to control illumination of multiple portions in different states or with different indications. For example, the different states may indicate to the user: (1) how the user should move the hand-held portion 16 to place the tool 20 (e.g., saw blade) at a desired pose (e.g., on a desired cutting plane/desired cutting trajectory); or (2) how the user should move the hand-held portion 16 such that the actuators 21, 22, 23 move in a preferred direction,

such as closer to their home positions while the control system 60 simultaneously works to keep the tool 20 at the desired pose, as will be described further below.

[0130] In the first mode, the guidance array or display screen (on the instrument or in part of the navigation system) may be used when the instrument is far enough from the bone that the guide constraints are inactive and joint centering constraints are active. In this configuration, the user desires to use the visual indicators to achieve a good initial alignment of the blade/tool/hand-held portion to be near the center of the joint travel when entering the resection zone/region and enabling the guide constraints so that there is limited abrupt movement on the blade support/tool support and actuators when the guide constraint(s) are first enabled, and to ensure that, when enabled, the actuators will be able to ‘reach’ the target plane or target trajectory or other target virtual object.

[0131] In the second mode, because each of the actuators has only a limited range of motion/travel, it is often important for the user to position the hand-held portion such that the actuators can reach the target plane, target trajectory, or other target object. If one of the actuators reaches its joint limit, the control system must not let it move any more in that direction and in this case the system will not be able to align the blade to the cut plane (and the control system would typically deactivate the saw drive motor to prevent improper resection) or the system will not align the tool to the planned trajectory. Accordingly, it may be important to give the user continual feedback so that they can position the hand-held portion appropriately, such that the actuator assembly can reach the target plane or target trajectory. Without continual feedback, the user will not realize how close they are operating to the limits of range of motion until the blade ultimately lifts off the plane since one of the motors has reached the joint limits and the saw blade drive motor is deactivated which may annoy to the user, lengthens the surgical procedure, etc. The goal is to give intuitive, live handle alignment feedback to minimize/reduce the occurrence of any actuator reaching its joint limits. The guidance array, display screen, or mechanical guide may be suitable for this purpose.

[0132] During some modes of operation, the instrument controller 28 is configured to automatically control/adjust the guidance array 200 (e.g., change states thereof) to visually indicate to the user desired changes in pitch orientation, roll orientation, and z-axis translation of the tool 20 to achieve the desired pose of the tool 20 while the user moves the tool 20 via the hand-held portion 16. In some versions, the guidance array 200 is coupled to the tool support 18 or to the hand-held portion 16 in a way that intuitively represents the plane of the tool 20. For example, since three points define a plane, the three visual indicators 201, 202, 203 may generally represent the plane of the tool 20. In

some cases, each of the indicators 201, 202, 203 corresponds to one of the points P1, P2, P3 having a known position relative to the plane of the tool 20 (e.g., located in the tool plane and defined in the TCP coordinate system, the tool support coordinate system TCS, or defined in any other suitable coordinate system). Points associated with the visual indicators 201, 202, 203 could be defined at other suitable locations in the plane of the tool 20 or at locations having a known relationship to the plane of the tool 20.

[0133] Collectively, the guidance array 200, using the one or more visual indicators 201, 202, 203 may be located and their states controlled to visually indicate to the user desired changes in movement (e.g. amount of travel) to change pitch, roll, and translation of the tool 20, and by extension, desired changes in pitch, roll, and translation of the tool support coordinate system TCS to achieve a desired pose. More specifically, the instrument controller 28 is configured to illuminate the guidance array 200 in a manner that enables the user to distinguish between a desired change in pitch orientation, a desired change in roll orientation, and a desired change in translation. The instrument controller 28 may be configured to illuminate the guidance array 200 or control the display screen in a manner that enables the user to indicate an amount of travel required to move the tool 20 to a desired plane. A desired plane may be a plane or a plane segment. The changes in pitch, roll, and translation are, for example, relative to the target plane TP.

[0134] In another configuration, the guidance array 200, using the one or more visual indicators 201, 202, 203 may be located and their states controlled to visually indicate to the user desired changes in movement (e.g. amount of travel) to change pitch, roll, and translation of the hand-held portion 16 and by extension, desired changes in pitch, roll, and translation of the base coordinate system BCS to achieve a desired pose. More specifically, the instrument controller 28 is configured to illuminate the guidance array 200 or display screen in a manner that enables the user to distinguish between a desired change in pitch orientation, a desired change in roll orientation, and a desired change in translation. The instrument controller 28 is configured to illuminate the guidance array 200 in a manner that enables the user to indicate an amount of travel required to move the hand-held portion 16 so that the tool 20 is on a desired plane or target trajectory. The changes in pitch, roll, and translation are, for example, relative to target plane TP.

[0135] The instrument controller 28 may switch operation of the guidance array 200 and/or visual indicators 201, 202, 203 (or display screen) from a mode where the guidance array/visual indicators indicate desired changes in movement of the tool 20 to indicate desired changes in

movement of the hand-held portion 16 based on an input signal, such as activation of an input device (e.g. footswitch, trigger, mouse click or touch screen press on navigation UI 38, etc.). Alternatively, the instrument controller 28 may be configured to switch between these modes based on the position of the tool 20 and the position of a reference location of bone in a known coordinate system, such as trackers 54, 56. A reference location may be a point, surface, or volume in the coordinate system used to locate the instrument 14 relative a target state, such as a target object. In one particular implementation, the reference location is a planned entry 71a of the bone. For example, the reference location may be a surface of a bone, a point within a bone, an imaginary or virtual point within the known coordinate system, a volume in the coordinate system, or a combination thereof. The position and/or orientation of the reference location is known with respect to the patient tracker through registration and suitable planning steps. The instrument controller 28 may switch modes/operate differently based on a distance parameter computed between two objects, such as a distance between the tool and a reference location. A distance parameter may be a distance (e.g., how far apart two objects are), magnitude (the direction of the distance relative to one object), or both. In some examples, the instrument controller 28 may switch modes when the distance parameter has a direction away from bone and a magnitude greater than a first threshold value. Other visualizations and guidance systems and methods are contemplated, such as described in PCT Application PCT/US2021/014205 filed January 20, 2021, and PCT Application PCT/US2022/013108 filed January 20, 2022.

CONTROLS OVERVIEW

[0136] Referring to Figures 7 and 11, a behavior controller 186 and a motion controller 188 may be run on the instrument controller 28 and/or the navigation controller 36. The control system 60 computes data that indicates the appropriate instruction for the plurality of actuators. In one implementation, the behavior controller 186 functions to output the next commanded position and/or orientation (e.g., pose) for the tool relative to the hand-held portion. During operation, the tool 20 is effectively moved toward the target state using the plurality of actuators. These effects may be generated in one or more degrees of freedom to move the tool 20 toward the target state. Thus, the target state may be defined such that the tool 20 is being moved in only one degree of freedom, or may be defined such that the tool 20 is being moved in more than one degree of freedom. Accordingly, the target state may comprise a target position, target orientation, or both, defined as a target coordinate system TF (also referred to as a target frame TF). The target coordinate system TF may be defined with respect to the coordinate system of an anatomy tracker or target bone(s), however, other

coordinate systems may be used. As shown in Figure 12, the target position may comprise one or more position components with respect to x, y, and/or z axes of the target coordinate system TF with respect to a reference coordinate system, such as the anatomy tracker or bone, e.g., a target x position, a target y position, and/or a target z position. In some cases, the target position is represented as the origin of the target coordinate system TF with respect to a reference coordinate system, such as the anatomy tracker or bone. It should be appreciated that the reference coordinate system and the patient coordinate system may be the same or different. In some instances, the reference coordinate system may be identical to the reference coordinate system. The target orientation may comprise one or more orientation components with respect to the x, y, and/or z axes of the target coordinate system TF with respect to a reference coordinate system, such as the anatomy tracker or bone, e.g., a target x orientation, a target y orientation, and/or a target z orientation. In some cases, the target orientation is represented as the orientation of the x, y, and z axes of the target coordinate system TF with respect to a reference coordinate system, such as the anatomy tracker or bone. Target pose means a combination of the one or more position components and the one or more orientation components. In some cases, the target pose may comprise a target position and target orientation in less than all six degrees of freedom of the target coordinate system TF. For example, in one specific configuration, the target pose may be defined by a single position component and two orientation components. In some cases, the target position and/or target orientation may also be referred to as starting position and/or starting orientation. In another configuration, the target pose may be defined as an axis anchored relative to the known coordinate system.

[0137] Referring to Figure 11, the target state is an input to the behavior controller 186. The target state may be a target position, target orientation, or both where the tool 20 is adjusted to a target plane or target trajectory. In some cases, only the position of the TCP is output from the behavior controller 186, while in other cases, the position and orientation of the tool 20 is output. In some examples, the commanded pose output of the behavior controller 186 may include position, orientation, or both. In some examples, output from a boundary generator 182 and one or more sensors, such as an optional force/torque sensor S, may feed as inputs into the behavior control 186 to determine the next commanded position and/or orientation for the tool relative to the hand-held portion. The behavior controller 186 may process these inputs, along with one or more virtual constraints described further below, to determine the commanded pose.

[0138] The motion controller 188 performs motion control of the plurality of actuators. One aspect of motion control is the control of the tool support 18 relative to the hand-held portion 16. The motion controller 188 receives data from the behavior controller 186, such as data that defines the next commanded pose. Based on these data, the motion controller 188 determines a commanded joint position of each of the plurality of actuators coupled to the tool support 18 (e.g., via inverse kinematics) so that the tool 20 is positioned at the commanded pose output by the behavior controller. In other words, the motion controller 188 processes the commanded pose, which may be defined in Cartesian space, into commanded joint positions of the plurality of actuators coupled to the tool support 18, so that the instrument controller 28 can command the actuators 21, 22, 23 accordingly, to move the tool support 18 to commanded joint positions corresponding to the commanded pose of the tool relative to the hand-held portion. In one version, the motion controller 188 regulates the joint positions of the plurality of actuators and continually adjusts the torque that each actuator 21, 22, 23 outputs to, as closely as possible, ensure that the actuators 21, 22, 23 lead the instrument to assume the commanded pose. Alternately, and/or additionally, the motion controller 188 can output the commanded joint positions to a separate set of motor controllers (e.g., one for each actuator 21, 22, 23), which handle the joint-level position control. In some examples, the motion controller 188 (or motor controllers) may use feed-forward control to improve the dynamic tracking and transient response. In such a case, in addition to commanded joint positions, the motion controller 188 may also compute feed-forward joint velocities (or rather commanded joint velocities) and potentially feed-forward joint torques (and/or motor currents). This data is then used within the control loop of the motor controllers to more optimally drive the actuators 21, 22, 23.

[0139] It should be appreciated that while position control is described in detail, similar control implementations may be used with joint angle control. Furthermore, the motion controller may use joint angle control and joint position control. In some examples, joint angle may be interchanged with joint position. Depending on the joint type, actuator type, or both on the instrument, joint angle, joint position, or both may be used. For example, the motion controller may determine a commanded joint angle based on the commanded pose for one or more actuators.

[0140] Referring to Figure 7, the software employed by the control system 60, and run on the instrument controller 28 and/or the navigation controller 36 may include a boundary generator 182. The boundary generator 182 is a software program or module that generates a virtual boundary 184 for constraining movement and/or operation of the tool 20. The virtual boundary 184 may be one-

dimensional, two-dimensional, three-dimensional, and may comprise a point, line, axis, trajectory, plane, or other shapes, including complex geometric shapes. The virtual boundary could also be a plane or line defined perpendicular to a planned trajectory. In some embodiments, the virtual boundary 184 is a surface defined by a triangle mesh. The virtual boundaries 184 may also be referred to as virtual objects. The virtual boundaries 184 may be defined with respect to an anatomical model AM, such as a 3-D bone model, in an implant coordinate system. The anatomical model AM is associated with the real patient anatomy by virtue of the anatomical model AM being mapped to the patient's anatomy via registration or other process.

[0141] The virtual boundaries 184 may be represented by pixels, point clouds, voxels, triangulated meshes, other 2D or 3D models, combinations thereof, and the like. U.S. Patent Publication No. 2018/0333207 and U.S. Patent No. 8,898,43 are incorporated by reference, and any of their features may be used to facilitate planning or execution of the surgical procedure. One example of a system and method for generating the virtual boundaries 184 is described in U.S. Patent No. 9,119,655, entitled, "Surgical Manipulator Capable of Controlling a Surgical Instrument in Multiple Modes," the disclosure of which is hereby incorporated by reference. In some examples, the virtual boundaries 184 may be generated offline rather than on the instrument controller 28 or navigation controller 36. Thereafter, the virtual boundaries 184 may be utilized at runtime by the instrument controller 28.

[0142] There are a variety of options for how the location and/or shape of the boundary can be determined, including the boundary that provides the posterior protection. As mentioned, the boundary could be 'implant specific', a predefined shape that is stored in a database based on the type/size of implant for each of its planar cuts, with its pose relative to the bone being adjusted based on surgeon input as part of the implant positioning workflow (i.e., the boundaries may be defined in the implant coordinate system and moves with the implant placement). Alternatively, the boundary could be 'patient-specific', i.e., computed automatically or manually based on pre-operative imaging, such as a CT scan. The boundary could be 'drawn' by the user (via touch screen or mouse) as an overlay superimposed on a representation of bone (real or generated) on the GUI, either pre-operatively or intraoperatively. Another option is that the boundary is a fixed shape that is placed or generated interactively by the surgeon. For example, it may be desirable to have the user use a navigated pointer to select (by putting the pointer tip against the bone in the corresponding location) the desired cutting depth at which to place the posterior protection boundary. In cases where two boundaries are generated

or created, the more proximal boundary – the re-enable boundary’ could be automatically generated by applying a position offset (e.g., to move

[0143] The anatomical model AM and associated virtual boundaries 184 are registered to the one or more patient trackers 54, 56. Thus, the anatomical model AM (and associated real patient anatomy) and the virtual boundaries 184 fixed to the anatomical model AM can be tracked by the patient trackers 54, 56. The virtual boundaries 184 may be implant-specific, e.g., defined based on a size, shape, volume, etc. of an implant and/or patient-specific, e.g., defined based on the patient’s anatomy. The implant-specific virtual boundaries may have a particular size boundary, e.g., a 1:1 implant specific boundary to the specific implant used. In other cases the boundary may be larger or smaller than the actual dimension of the implant (e.g. 2:1, 1:2, etc.). The implant-specific boundary for the particular implant may be arbitrarily shaped. In some examples, the implant-specific boundary may be offset past the implant size by a fixed or configured amount. The virtual boundaries 184 may be boundaries that are created pre-operatively, intra-operatively, or combinations thereof. In other words, the virtual boundaries 184 may be defined before the surgical procedure begins, during the surgical procedure (including during tissue removal), or combinations thereof. In any case, the control system 60 obtains the virtual boundaries 184 by storing/retrieving the virtual boundaries 184 in/from memory, obtaining the virtual boundaries 184 from memory, creating the virtual boundaries 184 pre-operatively, creating the virtual boundaries 184 intra-operatively, or the like. In other words, one or more virtual boundaries may be obtained from the planned pose of the implant, and planned size, shape, volume, etc. of the implant. The implant coordinate system and the anatomical model coordinate system may be considered interchangeable throughout this description.

[0144] The virtual boundaries 184 may be used in various ways. For example, the control system 60 may: control certain movements of the tool 20 to stay inside the boundary; control certain movements of the tool 20 to stay outside the boundary; control certain movements of the tool 20 to stay on the boundary (e.g., stay on a point, trajectory, and/or plane); control certain operations/functions of the instrument 14 based on a relationship of the instrument 14 to the boundary (e.g., spatial, velocity, etc.), and/or control energization to the drive motor M of the instrument 14. Other uses of the boundaries 184 are also contemplated. With reference to Figure 13, in one potential implementation, the virtual boundary 184 may comprise a generally planar mesh located distally of the cut, a distal boundary DB. This virtual boundary 184 may be associated with the 3-D bone model. This virtual boundary may be used to control the saw drive motor M. In other examples, the boundary

generator 182 provides virtual boundaries 184 for purposes of controlling the plurality of actuators. In this example, the virtual boundaries may be used for generating constraints that affect the movement of the virtual mass and virtual saw blade/tool in the virtual simulation. In such an implementation, the virtual boundaries may establish a virtual cutting guide (e.g., a virtual saw cutting guide). Virtual boundaries 184 may also be provided to delineate various operational/control regions as described below for either control of the saw driver motor or for control of the plurality of actuators. The virtual boundaries 184 may be one-dimensional (1D), two-dimensional (2D), three-dimensional (3D), and may comprise a point, line, axis, trajectory, plane (an infinite plane or plane segment bounded by the anatomy or other boundary), volume or other shapes, including complex geometric shapes.

[0145] Referring to Figures 10 and 14, the pose of the implant (IM) may be planned relative to the femur F in the implant coordinate system. This planned pose of the implant may be then defined relative to the one of the patient trackers 54, 56 through various navigation transforms, and the pose of the implant may be the basis of planned virtual objects, such as the target plane (TP), or the virtual boundaries. The target plane may be a representation of what cut(s) need to be made relative to bone to achieve the planned implant pose. In other words, the target plane (TP) may be aligned with the plane where the planned implant intends to contact bone. In some examples, the location of the target planes (TP) may need to be adjusted to account for the thickness of the saw blade. In one example, at the distal tip of the saw blade, the TCP coordinate system may be placed at a point half the thickness of the saw blade at the saw blade's center. The location of the cutting plane may be adjusted by the saw blade's half-thickness in a direction based on which side of the saw blade is against the bone during a particular cut. By cutting along the target plane, the resulting bone that will be removed from the femur will allow for the planned implant to seat on the bone properly. The target plane TP may take the form of a target state as will be described below. Alternatively, the target plane TP may be generated as a form of the virtual boundary that may be used to control the plurality of actuators.

[0146] The control system 60 will ultimately function to keep the tool 20 on the desired cutting plane in some versions. The virtual boundary 184 that may be used control the plurality of actuators may also be a volumetric boundary, such as one having a thickness equal to and/or slightly larger than a blade thickness to constrain a saw blade to stay within the boundary and on the desired cutting plane. Therefore, the desired cutting plane can be defined by a virtual planar boundary, a virtual volumetric boundary, or other forms of virtual boundary. In some examples, the cutting slot in the virtual boundary 184 needs to be offset to account for the saw blade thickness, so that a slot boundary

(corresponding to the side of the saw blade which contacts bone for that cut) is aligned with the final desired implant-bone surface, and the other boundary is offset by the full blade thickness. In another example, a slightly larger thickness is used for the slot boundary, causing the vertical centerline of the cutting slot to be offset by the saw blade half thickness. Virtual boundaries 184 may also be referred to as virtual objects. The virtual boundaries 184 may be defined with respect to an anatomical model AM in an implant coordinate system, such as a 3D bone model (see Figure 10, which illustrates the anatomical model AM being virtually overlaid on the actual femur F due to their registration). In other words, the points, lines, axes, trajectories, planes, volumes, and the like, that are associated with the virtual boundaries 184 may be defined in a coordinate system that is fixed relative to a coordinate system of the anatomical model AM such that tracking of the anatomical model AM (e.g., via tracking the associated anatomy to which it is registered) also enables tracking of the virtual boundary 184.

[0147] The anatomical model AM is registered to the first patient tracker 54 such that the virtual boundaries 184 become associated with the anatomical model AM and associated coordinate system. The virtual boundaries 184 may be implant-specific, e.g., defined based on a size, shape, volume, etc. of an implant and/or patient-specific, e.g., defined based on the patient's anatomy. The implant-specific boundaries may be larger or smaller than the physical dimensions of the implant. The virtual boundaries 184 may be boundaries that are created pre-operatively, intra-operatively, or combinations thereof. In other words, the virtual boundaries 184 may be defined before the surgical procedure begins, during the surgical procedure (including during tissue removal), or combinations thereof. The virtual boundaries 184 may be provided in numerous ways, such as by the control system 60 creating them, receiving them from other sources/systems, or the like. The virtual boundaries 184 may be stored in memory for retrieval and/or updating.

[0148] In some cases, such as when preparing the femur F for receiving the total knee implant IM (see Figure 1), the virtual boundaries 184 comprise multiple planar boundaries that can be used to delineate multiple cutting planes (e.g., five cutting planes) for the total knee implant IM, and are associated with a 3D model of the distal end of the femur F and/or a cutting plane based on the 3D model of the tibia. These multiple virtual boundaries 184 and/or target planes can be activated, one at a time, by the control system 60 to control the plurality of actuators to cut one plane at a time. Each of these cutting planes may be a target plane for the control system. Example virtual boundaries 184 is shown in Figure 13, for illustrative purposes. While Figure 13 shows that the target planes are aligned with the implant boundaries, it should be appreciated that this is a schematic representation, and the

target planes may be slightly offset from the planned implant boundaries. Other shapes and arrangements are possible. Figure 13 illustrates a series of cuts with the desired target plane of each. Each of the distal ends of the femurs show an entry portion that provides access to the femur. The entry portion continues into a cutting slot defined along one of the five target cutting planes TP, 73a-73e. In other cases, the virtual boundaries may be a planned trajectory for insertion of a rotary tool into bone, such as for insertion of a drill bit or tap, into bone, such as into a femur or vertebra. Again, the multiple virtual trajectories may be active one at a time to control the plurality of actuators to drill one trajectory at a time.

[0149] In cases wherein the virtual boundaries are used to control the saw drive motor (or other drive motor) and referring to Figures 13 and 15, the virtual boundaries 184 may represent boundaries that can be used delineate in-plane cutting depths or widths for the saw (DB, LB) or tool when preparing a knee for receiving a total knee implant or other surgical procedure. The in-plane cutting depths or widths for the saw (DB, LV) may be features of a 3D boundary model rather than distinct boundaries. Those distal boundaries DB may be generally perpendicular to the target cutting plane or target trajectory, and may be optionally contoured to the patient's anatomical features (distal face of the femur, ligaments, arteries, soft tissue, etc.). This may avoid inadvertent cutting of a critical structure. The virtual boundaries 184 used to control the drive motor may include one or more lateral boundaries (LB). These lateral boundaries (LB) may serve to prevent cutting beyond a target depth in a lateral direction. In some examples, the cutting slot defined by the depth boundaries and lateral boundaries in the 3D boundary may be used for a secondary error mitigation feature, such as to turn off the drive motor M if the saw blade does not sufficiently stay on plane (in the case of sudden fast motion of the instrument and/or bone or as a mitigation against another system malfunction) or tool does not stay on the trajectory. The boundaries for controlling the saw drive motor may be selectively activated based on the selected target plane. Similarly, the boundaries for control the tool drive motor may be activated based on the selected target axes.

[0150] In some cases, the virtual boundaries that delineate cutting depths may be based on a pose of a planned virtual object, such as a fixed boundary offset, such as 5 mm plane offset and perpendicular to each planned cut plane (TP) or target trajectory. Referring again to Figure 13, where the 5 TPs are aligned with each plane where the planned implant is intended to contact bone, the distal boundaries DB are implemented as perpendicular to the TP for each cut, and offset a predetermined distance from the distal end of plane where the planned implant will contact bone. In some versions,

the control system 60 evaluates whether the saw blade will violate the depth boundary DB by more than a threshold amount, and may command the instrument controller 28 to cease operation of the drive motor M. In some examples, the instrument controller 28 may not cease operation of the drive motor M, but rely on user-controlled starting, stopping, and/or speed control of the drive motor M.

[0151] Referring to Figs. 35 and 53, in certain cases, the location of the one or more boundaries, such as DB in Figure 35, can be set using a pointer PT or other instrument. During the bone registration process, the system can prompt a user to position the pointer PT or other instrument to set a location for the boundary. The control system 60 can use the localizer 44 to determine a position of the pointer PT and set the boundary DB based on the determined position. The boundary can be used by the control system 60 to control tool drive motor M, such as the saw drive motor. The boundary 35 can be associated with one of the target planes TP, and may be configured as a three-dimensional object, such as a rectangular prism that intersects the target plane TP. The method can include positioning the pointer PT to contact a surface of the tibia T to define the boundary DB. Of course, the pointer PT could be positioned to contact other anatomical structures to define boundaries for other desired boundaries. Alternatively still, the pointer PT need not necessarily contact the patient's anatomy in particular instances in order to set the desired boundary.

[0152] The application may prompt a user to digitize the point to represent the allowable posterior depth for bone resection, and engage a control surface, such as button on the pointer PT, when the pointer PT is appropriately positioned. The selected boundary may show up as a line on the image of the bone on the proposed cut surface at the depth corresponding to the point that is elected by the user. Referring to Fig. 35, the control system 60 may model this boundary using a rectangular box DB whose front surface is aligned with the selected point. If the box DB is penetrated by the saw blade 20 or other tool by more than a defined threshold, the control system 60 turns off the saw drive motor. In some implementations, the control system 60 may actually place the boundary DB more conservatively, such as more anterior, than the selected point to account for mechanical tolerances in the blade mechanism or turn off delay for the drive motor M. The boundary DB may be positioned at least 0.25, at least 0.5, or at least 1 mm more anterior than the selected point. Alternatively, the front edge of the boundary DB may be positioned between 0.1 and 1.5 mm more anterior than the selected point.

[0153] The application may allow a user to disable the one or more boundaries associated with control of the drive motor M through interaction with the user interface UI, such as by engaging an

icon to turn off. This may allow users to do the bulk removal of bone first with the boundary enabled by default, and then disabling the drive motor boundary, and remove the remaining bone.

[0154] In some cases, the instrument controller 28 controls a motor parameter of the drive motor M at a first value and a second value, such that the first value is different than the second value and the instrument controller 28 may change operation from the first value to the second value based on the position of the tool 20 and the position of a reference location associated with bone, such as the virtual boundary, or based on a computed distance parameter.

[0155] As the tool 20 proceeds into a cut or hole of the bone, the instrument controller 28, using navigation data of the tool 20 relative to the reference location or based on the pose of the tool associated with the bone, may allow activation of the drive motor M. Further, the instrument controller 28 may turn off the drive motor M based on whether the tool 20 has reached a certain pose, distance parameter value or position relating to the reference point or boundary associated with the bone. In some cases, the user may find difficulty in perceiving the depth of the tool 20 within the bone while performing the surgical procedure because of limited line of sight due to soft tissue, unremoved bone, and other surgical apparatuses used in the procedure. The user may also have difficulty perceiving the depth of the tool 20 because of adjacent anatomy applying pressure onto the saw blade 20 or tool. By controlling the drive motor M based on the pose or position of the tool 20, the user may be able to control with more accuracy the depth of the cut.

[0156] In some examples, when the instrument controller 28 changes the operating mode by changing a parameter of the drive motor M, the instrument 14, the input device, the navigation system 32, the instrument controller 28, or a combination thereof may provide an audible indication, a tactile indication, or both that the mode has been changed. In one instance, the input device may be a footswitch, and when the mode of the instrument is changed, controlling the speed of the drive motor M, the footswitch may vibrate. In another example, when the mode and/or control behavior is changed speeding up or slowing down the drive motor M, a user may perceive an audible indication such as the motor speed of the drive motor M changing volume, pitch, vibration, or a combination thereof, indicating that the mode and/or control behavior of the instrument has changed.

[0157] As described above, the instrument controller 28 and/or the navigation controller 36 track the state of the tool 20, such as the position and/or orientation of the saw blade relative to the virtual boundaries 184. In one example, it can be described as monitoring the state of the TCP is measured relative to the virtual boundaries 184 for purposes of controlling the tool drive motor M. In

other words, the control system may control the saw drive motor M based on the state of the TCP measured relative to the virtual boundaries 184, such as slowing down or stopping the saw drive motor M when any aspect of the instrument virtual model VM violates the virtual boundary 184 by more than a threshold amount. In some examples, the pose of the tool (TCP coordinate system) may be utilized to evaluate whether any aspects of the tool 20 would violate the virtual boundary 184 by more than a threshold amount. The instrument controller 28 may have a model of the blade (e.g., a CAD model or a simplified model using geometric primitives) that may be evaluated for violations of the virtual boundary 184. In some examples, the extents of the tool 20 may be modeled with an array of discrete spheres, placed around the periphery of a swept volute of the tip of the tool 20, with the diameters of the spheres matching the thickness of the tool 20, the locations defined with respect to the TCP coordinate system. Further, the virtual boundary 184 may be an open-ended surface or a closed surface. When the virtual boundary 184 is configured as a closed surface, the virtual boundary 184 may function as a “keep out” boundary where the instrument 14 may be actuated “outside” of the virtual boundary but shut off after crossing the virtual boundary by a threshold amount. Similarly, the closed surface virtual boundary may function as a “keep in” boundary, where the instrument 14 may only operate within the virtual boundary 184, shutting off the instrument 14 when the instrument “leaves” the virtual boundary 184 by more than a threshold amount.

[0158] In another example, the state of the TCP is measured relative to the virtual boundaries 184 for purposes of determining forces to be applied to a virtual rigid body model via a virtual simulation so that the tool 20 remains in a desired positional relationship to the virtual boundaries 184 (e.g., not moved beyond them). The results of the virtual simulation are processed when controlling the plurality of actuators coupled to the tool support 18. The boundary generator 182 may be implemented on the instrument controller 28. Alternatively, the boundary generator 182 may be implemented on other components, such as the navigation controller 36.

[0159] The boundary generator 182, the behavior controller 186 and motion controller 188 may be sub-sets of a software program 378. Alternatively, each may be software programs that operate separately and/or independently in any combination thereof. The term “software program” is used herein to describe the computer-executable instructions that are configured to carry out the various capabilities of the technical solutions described. For simplicity, the term “software program” is intended to encompass, at least, any one or more of the boundary generator 182, behavior controller 186, and/or motion controller 188. The software program 378 can be implemented on the instrument

controller 28, navigation controller 36, or both, or may be implemented in any suitable manner by the control system 60.

[0160] A clinical application 190 may be provided to handle user interaction. The clinical application 190 handles many aspects of user interaction and coordinates the surgical workflow, including pre-operative planning, implant placement, registration, bone preparation visualization, and post-operative evaluation of implant fit, etc. The clinical application 190 is configured to output to the displays 38. The clinical application 190 may run on its own separate processor or may run alongside the navigation controller 36. In one example, the clinical application 190 interfaces with the boundary generator 182 after implant placement is set by the user, and then sends the virtual boundary 184 and/or tool plane TP returned by the boundary generator 182 to the instrument controller 28 for execution. The instrument controller 28 executes the target plane TP or target trajectory as described herein. The instrument controller 28 may also process the virtual boundaries 184 to generate corresponding virtual constraints as described further below.

[0161] Turning to Figure 16, the exemplary control is described with respect to the various transforms. The TCP is located by tracking the tool 20 with the tool tracker 52 (TT) with respect to the localizer coordinate system LCLZ (LCLZ-TT transform), and determining a transform between tool tracker 52 and the TCP of the tool 20 (TT-TCP transform), such as the saw blade, using registration data or calibration data. Similarly, the patient is tracked using the patient tracker (shown as 54), resulting in the transform from the localizer coordinate system LCLZ to the patient tracker coordinate system (LCLZ-PT transform).

[0162] As described with respect to Figure 11, through a bone registration process, a transform from bone to the patient tracker 54, 56 is established (bone to patient tracker). Through the implant planning process, a bone to implant/anatomical model transform is determined (bone to IM transform). Then, a patient tracker 54 to planned implant (patient tracker to IM) transform is computed. The planned implant (IM) may be related to the target plane (IM to TP transform), given the locations of the planar sections of the chosen implant component and size, or may be related to a target trajectory (see Figure 44, described further below). Referring again to Figure 16, a transform is then computed between the patient tracker 54, 56 and each planned virtual object, such as each target plane (PT-TP transform), or such as each target trajectory (PT – trajectory transform) using the combination of registration data and planning information.

[0163] The position and/or orientation of the tool support 18, and therefore TCP, may be related to the tool tracker 52 (tool support to tool tracker transform, computed via registration or calibration process). As described above, in some implementations, a transform between the hand-held portion 16 and the TCP (BCS-TCP) is computed based on the positions of each actuator. The transform between BCS and TCP is utilized to relate the various coordinate systems back to the hand-held portion 16, since the commanded pose may be determined relative to the BCS for certain control implementations. Conceptually, the commanded pose, is an update to the BCS to TCP transform which results in the TCP being aligned with the planned virtual object (the target plane TP) in this example. As an alternative, the pose of the hand-held portion 16 may be determined directly in some instances by using a hand-held portion tracker 53 coupled directly to the hand-held portion 16. This may eliminate the need to utilize the TCP coordinate system and perform a transform between BCS and TCP based on the positions of each actuators.

[0164] An initial pose of the TCP with respect to the base coordinate system BCS can be determined based on a known geometric relationship between the tool support and the hand-held portion 16 when the actuators 21, 22, 23 are at their home position/center point or other predetermined position. Additionally, and/or alternately, the initial pose may be “seeded” into the virtual simulation by measuring the initial pose using the encoders and computing forward kinematics to get a measured pose of the TCP with respect to BCS, using that pose to initialize the virtual simulation. This relationship changes when the actuators 21, 22, 23 are adjusted and the associated changes can be determined based on the kinematics of the robotic system 10 (e.g., which establishes a dynamic transformation between these coordinate systems). Thus, the robotic system 10 knows the pose of the tool 20, such as in the home position and its relation to the pose of the hand-held portion 16. Accordingly, when the tool 20 is moved by the user and its pose is tracked using the tool tracker 52, the robotic system 10 also tracks the pose of the hand-held portion 16 and its base coordinate system BCS. In some examples, as a result of prior calibration processes, the position of the tool 20 relative to the tool support 18 is assumed to be known. After the home position/center point and maximum travel of each of the actuators 21, 22, 23 is established, control is based on the position and/or orientation data from the navigation controller 36 and the measured position data of the actuator(s). The home position could also be computed in other manners. When all of the actuators are in their home positions, this collectively defines the home state of the instrument. The home state may involve a pose of the hand-held portion relative to a pose of the tool support, i.e., defined in cartesian space,

or the home state of the instrument may be defined in actuator space (position) or joint space (angles) of the plurality of actuators and/or joints.

[0165] Since both the patient tracker 54, 56 and the tool tracker 52 are each reported by the localizer 44 with respect to the localizer coordinate system LCLZ, providing LCLZ-to-PT and LCLZ-to-TT, these transforms may be processed together to determine a transformation between the tool tracker 52 and the patient tracker 54, 56 (TT-to-PT). From there, a base coordinate system to patient tracker (BCS-to-PT) transformation can be calculated by the control system 60, computing the location of the patient tracker 54, 56 with respect to the hand-held portion 16. Since the target plane TP with respect to the patient tracker 54, 56 is known, the control system 60 may calculate a base coordinate system BCS to target plane TP (BCS-to-TP) transformation, resulting in the pose of the target plane in the coordinate system of the hand-held portion 16 (BCS). In one example, the BCS-to-TP may be used directly to compute the commanded pose BCS-to-TCP which puts the TCP on the target cutting plane TP, which may then be commanded to the actuators 21, 22, 23 to move the tool 20 to the desired pose. In some examples, the BCS-to-TCP calculation may be used to generate constraints to attract the TCP to TP within a virtual simulation VM. While the target plane transforms are described throughout, it should be appreciated that transforms related to the target trajectory in lieu of the target plane are contemplated herein as well.

[0166] In some examples, digital filters may be applied to the input data received from the localizer directly to the input data received from the forward kinematics (e.g., motion controller 188 directly), or to any intermediate combination of the previously described transforms. In some examples, a moving average filter may be used, although other digital filtering techniques may be applicable.

[0167] The instrument controller 28 may control the one or more actuators 21, 22, 23 by sending command signals to each actuator 21, 22, 23 to adjust the tool 20 towards a target state in at least one degree of freedom. The instrument controller 28 may send command signals to each actuator 21, 22, 23 to move the actuators 21, 22, 23 from a first set of positions to a set of commanded positions which will place the tool 20 into the target state. In some examples, the commanded position may be determined by the instrument controller 28 in conjunction with the navigation system 32 based on the pose of hand-held portion 16 and a target state in a known coordinate system (i.e. defined relative to the patient tracker 54, 56), such as the pose of the virtual object (target cut plane or target trajectory), and send a signal to the actuators 21, 22, 23 to adjust to the commanded position.

[0168] The second software module is a motion controller 188. One function of the motion controller 188 is the control of the instrument 14. The motion controller 188 may receive data defining the target state of the saw blade 20, 380, such as the next commanded pose from the behavior controller 186. Based on these data, the motion controller 188 determines the next commanded joint position of the rotors 148 of each actuator 21, 22, 23 (e.g., via inverse kinematics) so that the instrument 14 is able to position the tool 20 as commanded by the behavior control 186, e.g., controlling instrument to the commanded pose. In other words, the motion controller 188 processes the commanded pose, which may be defined in Cartesian space, into actuator positions (such as commanded joint positions) of the instrument 14, so that the instrument controller 28 can command the motors 142 accordingly, to move the actuators 21, 22, 23 of the instrument 14 to commanded positions, such as commanded joint positions corresponding to the commanded pose. In one version, the motion controller 188 regulates the joint position of each motor 142 and continually adjusts the torque that each motor 142 outputs to, as closely as possible, ensure that the motor 142 drives the associated actuator 21, 22, 23 to the commanded joint position. In another version, the instrument controller regulates the joint position of each motor 142 and continually adjusts the torque that each motor 142 outputs to, as closely as possible, ensure that the motor 142 drives the associated actuator 21, 22, 23 to the commanded joint position

[0169] The instrument controller 28 may know the entire length that an actuator 21, 22, 23 may adjust the tool support 18 relative to the hand-held portion 16. In some examples, the instrument controller 28 knows the entire length which an actuator 21, 22, 23 is capable of adjusting and may send command signals to the actuators 21, 22, 23 to move a measured distance from position to position (e.g., by commanding a desired amount of linear travel via commanded rotation). A measured position may be a known position, or a distance between the present location of an actuator 21, 22, 23 and the actuator limits. Each position that the actuator 21, 22, 23 moves to may be a measured distance from a positive limit and a negative limit of actuator travel (i.e., a position between two ends of a lead screw). The instrument controller 28 may command the actuators 21, 22, 23 to and from positions as described below. The instrument controller may command the actuator 21, 22, 23 to a position in order to reach the desired adjustment of the tool 20. The instrument controller 28 may control the actuators 21, 22, 23 to linearly move a calculated distance to adjust the tool 20 towards a desired pose. In other examples, such as when absolute encoders are used, the instrument controller may send signals to the actuators 21, 22, 23 to place each actuator 21, 22, 23 into a commanded position based on the known

location of the actuator 21, 22, 23 between the respective actuator travel limits determined by the absolute encoder. Alternately, in one example, an incremental encoder may be used in conjunction with a homing procedure performed during system setup as described in U.S. Patent Publication No. 2017/0156799, which is hereby incorporated by reference. A homing procedure may be used, placing the actuators 21, 22, 23 and the joints at their centered position, and subsequently determines the absolute offsets of the incremental encoders. By determining the offsets of the incremental encoders, the incremental encoders may perform as absolute encoders going forward.

[0170] In some versions, the instrument controller 28, for each actuator 21, 22, 23, determines the difference between a commanded position and a measured position of the actuator. The instrument controller 28 outputs a target current (proportional to a torque of the actuator), changing the voltage to adjust the current at the actuator from an initial current to the target current. The target current effectuates a movement of the actuators 21, 22, 23, moving each actuator 21, 22, 23 towards the commanded joint position, and, as a result, moving the instrument towards the commanded pose. This may occur after the commanded pose is converted to joint positions. In one example, the measured position of each joint may be derived from the sensors S described above, such as an encoder.

[0171] Throughout this description, unless otherwise noted, any instance of pose may be a current commanded pose, a current measured pose, a past measured pose, or a past commanded pose. While each of these poses may be different from one another, due to the frequency of control cycles, the difference in position and/or orientation between these poses may be minimal in each control iteration. Furthermore, any instance of position may be a current commanded position, a current measured position, a past measured position, or a past commanded position.

[0172] Different control methodologies may be used to control the plurality of actuators to place the tool at a desired location, such as target plane or target trajectory, including but not limited to impedance control, admittance control, position control, or a hybrid control using multiple different control implementations. While an admittance control implementation is described in detail, it should be appreciated that other methodologies may be used. In an admittance control mode, the control system accepts force input (virtual or measured) and commands position (or motion) output. For example, for admittance control, the system models a force and/or torque at a particular location on a virtual mass and acts to modify the pose of the virtual mass to achieve the desired target state of the tool. In an impedance control mode, the control system accepts position (or motion) input and commands a force or torque output. For example, the impedance control system measures, senses,

and/or calculates a position (i.e., position, orientation, velocity, and/or acceleration) of the instrument and may apply an appropriate corresponding torque to each of the actuators to achieve the desired target state of the tool. Position control may also be used to control the plurality of actuators towards implementing certain behaviors. It should be appreciated that changes to both the behavior controller and the motion controller would be needed implement these control schemes.

[0173] In some versions, once treatment begins, the instrument controller 28 may mitigate the effects of the user's ability to place the tool 20 away from the desired pose (e.g., outside or off of the virtual boundary 184 or planned virtual object (TP)). For example, in some implementations, as soon as the navigation system 32 provides an indication that the tool 20 is moving off the desired cutting plane or away from the bone by a predetermined distance/orientation, the instrument controller 28 immediately terminates the application of energization signals to the drive motor M, preventing the tool 20 from gouging the bone, and minimizing soft tissue damage. In other examples, the drive motor M may be slowed down or stopped using motor braking, for example, as described in US Patent No. 7,998,157 entitled "Surgical tool system with a powered handpiece and a console, the console able to provide energization signals to the handpiece in either a motor drive mode or a direct drive mode" which is hereby incorporated by reference. In some implementations of this feature, the acceptable misalignment of the tool 20 with the desired pose may vary as the depth of the resection increases.

[0174] The boundary generator 182, behavior controller 186, and motion controller 188 may be sub-sets of a software program. Alternatively, each may be software programs that operate separately and/or independently in any combination thereof. The term "software program" is used herein to describe the computer-executable instructions that are configured to carry out the various capabilities of the technical solutions described.

[0175] Referring now to Figure 12, the target coordinate system TF can be any coordinate system whose origin and axes define the target state, and the target state can be specified with respect to any other coordinate system desired for monitoring the state of the tool 20 relative to the target state of the tool 20. The target state can be tracked in a patient tracker coordinate system (e.g., the coordinate system of the patient tracker 54, 56), the localizer coordinate system LCLZ, the base coordinate system BCS, a virtual mass coordinate system VM, the TCP coordinate system, or the like. The target state may be initially defined with respect to the implant coordinate system (IM) for the patient and may be fixed with respect to the patient's anatomy and fixed relative to the one or more

patient trackers. For purposes of this disclosure, the target state may include the desired pose of the saw blade.

[0176] The current state of the tool 20 may be defined by a guided coordinate system GF (also referred to as a guided frame GF). The guided coordinate system GF may be tied to another coordinate system, or the current state may be transformed to any other coordinate system to enable tracking of the current state relative to the target state. The current state can be tracked in a tracker coordinate system (e.g., the tool tracker coordinate system (TT), the localizer coordinate system LCLZ, the base coordinate system BCS, the virtual mass coordinate system VM, the TCP coordinate system, or the like. In some of the versions described herein, the current state of the tool 20 is initially defined by the TCP coordinate system (e.g., the TCP coordinate system and the guided coordinate system GF are shown as being the same for ease of illustration). Both the guided coordinate system GF and the target coordinate system TF can be transformed to a common coordinate system for tracking purposes. The target state may be defined pre-operatively, intraoperatively, or both.

[0177] As described above, to control the plurality of actuators, a commanded pose is often set. This commanded pose may be a desired relationship between the BCS and the TCP, i.e., a desired relationship between the tool support and the hand-held portion. The commanded pose is determined based on the pose of the hand-held portion 16 in a known coordinate system and a target state in the same coordinated system (e.g. the coordinate system associated with the patient tracker 54, 56), such as a pose of a planned virtual object, e.g., a target pose of the saw blade deduced from the pose of the planned implant. The commanded pose may result in the tool 20 being on the desired plane or aligned with the planned virtual object, such as a planned trajectory. As mentioned above, the instrument controller 28 may convert the commanded pose to a commanded position for each of the plurality of actuators using inverse kinematics, then send command instructions to the actuators 21, 22, 23 to move to a commanded position, thereby changing the relative poses of the tool support 18 and tool 20.

[0178] It is contemplated that the control system 60 may be configured to control other types of instruments and actuator assembly arrangements, such as drills, burs, probes, guides, the like, or a combination thereof. For example, the present teachings may be implemented to control the instrument described in U.S. Patent No. 9,707,43, entitled “Surgical instrument including housing, a cutting accessory that extends from the housing and actuators that establish the position of the cutting accessory relative to the housing” which is incorporated by reference. For example, as shown in Figure 44, an alternative example of the instrument is shown with tool 20 as a drill or a bur. The exemplary

control is described with respect to the various transforms. The TCP is located by tracking the tool 20 with the tool tracker 52 (TT) with respect to the localizer coordinate system LCLZ (LCLZ-TT transform), and determining a transform between tool tracker 52 and the TCP of the tool 20 (TT-TCP transform), such as the drill/bur, using registration data or calibration data. Similarly, the patient is tracked using the patient tracker (shown as 54), resulting in the transform from the localizer coordinate system LCLZ to the patient tracker coordinate system (LCLZ-PT transform).

[0179] As described with respect to Figure 11, through a bone registration process, a transform from bone to the patient tracker 54, 56 is established (bone to patient tracker). Through the implant planning process, a bone to implant/anatomical model transform is determined (bone to IM transform). Then, a patient tracker 54 to planned implant (patient tracker to IM) transform is computed. The planned implant (IM) may be related to the target trajectory (IM to Trajectory transform), given the locations of the chosen implant component. Referring again to Figure 44, a transform is then computed between the patient tracker 54, 56 and each planned virtual object, such as each target trajectory (PT-TTRAJ transform), using the combination of registration data and planning information.

[0180] The position and/or orientation of the tool support 18, and therefore TCP, may be related to the tool tracker 52 (tool support to tool tracker transform, computed via registration or calibration process). As described above, in some implementations, a transform between the hand-held portion 16 and the TCP (BCS-TCP) is computed based on the positions of each actuator. The transform between BCS and TCP is utilized to relate the various coordinate systems back to the hand-held portion 16, since the commanded pose may be determined relative to the BCS for certain control implementations. Conceptually, the commanded pose, is an update to the BCS to TCP transform which results in the TCP being aligned with the planned virtual object (the target trajectory TTRAJ) in this example. As an alternative, the pose of the hand-held portion 16 may be determined directly in some instances by using a hand-held portion tracker 53 coupled directly to the hand-held portion 16. This may eliminate the need to utilize the TCP coordinate system and perform a transform between BCS and TCP based on the positions of each actuators.

[0181] An initial pose of the TCP with respect to the base coordinate system BCS can be determined based on a known geometric relationship between the tool support and the hand-held portion 16 when the actuators 21, 22, 23 are at their home position/center point or other predetermined position. Additionally, and/or alternately, the initial pose may be “seeded” into the virtual simulation by measuring the initial pose using the encoders and computing forward kinematics to get a measured

pose of the TCP with respect to BCS, using that pose to initialize the virtual simulation. This relationship changes when the actuators 21, 22, 23 are adjusted and the associated changes can be determined based on the kinematics of the robotic system 10 (e.g., which establishes a dynamic transformation between these coordinate systems). Thus, the robotic system 10 knows the pose of the tool 20, such as in the home position and its relation to the pose of the hand-held portion 16. Accordingly, when the tool 20 is moved by the user and its pose is tracked using the tool tracker 52, the robotic system 10 also determines the pose of the hand-held portion 16 and its base coordinate system BCS. In some examples, as a result of prior calibration processes, the position of the tool 20 relative to the tool support 18 is assumed to be known. After the home position/center point and maximum travel of each of the actuators 21, 22, 23 is established, control is based on the position and/or orientation data from the navigation controller 36 and the measured position data of the actuator(s).

[0182] Since both the patient tracker 54, 56 and the tool tracker 52 are each reported by the localizer 44 with respect to the localizer coordinate system LCLZ, providing LCLZ-to-PT and LCLZ-to-TT, these transforms may be processed together to determine a transformation between the tool tracker 52 and the patient tracker 54, 56 (TT-to-PT). From there, a base coordinate system to patient tracker (BCS-to-PT) transformation can be calculated by the control system 60, computing the location of the patient tracker 54, 56 with respect to the hand-held portion 16. Since the target trajectory TTRAJ with respect to the patient tracker 54, 56 is known, the control system 60 may calculate a base coordinate system BCS to target trajectory TTRAJ (BCS-to-TTRAJ) transformation, resulting in the pose of the target trajectory in the coordinate system of the hand-held portion 16 (BCS). In one example, the BCS-to-TTRAJ may be used directly to compute the commanded pose BCS-to-TCP which puts the TCP on the target trajectory TTRAJ, which may then be commanded to the actuators 21, 22, 23 to move the tool 20 to the desired pose. In some examples, the BCS-to-TCP calculation may be used to generate constraints to attract the TCP to TTRAJ within a virtual simulation VM.

[0183] The instrument controller 28 may control the one or more actuators 21, 22, 23 by sending command signals to each actuator 21, 22, 23 to adjust the tool 20 towards a target state in at least one degree of freedom. The instrument controller 28 may send command signals to each actuator 21, 22, 23 to move the actuators 21, 22, 23 from a first set of positions to a set of commanded positions which will place the tool 20 into the target state, aligning the tool 20 with the target trajectory. In some examples, the commanded position may be determined by the instrument controller 28 in conjunction

with the navigation system 32 based on the pose of hand-held portion 16 and a target state in a known coordinate system (i.e. defined relative to the patient tracker 54, 56), such as the pose of the virtual object (target trajectory), and send a signal to the actuators 21, 22, 23 to adjust to the commanded position. Other control systems and methods are contemplated, such as described in PCT application PCT/US2021/49440 filed September 8, 2021.

VIRTUAL CONSTRAINTS

[0184] In some implementations, the control system uses one or more virtual constraints to compute the commanded pose. Generally, virtual constraints are restrictions and/or enhancements on the motion of rigid bodies in certain directions that are considered by the control system 60, along with other motion-related information, as part of a virtual simulation. Each virtual constraint may be considered to act along a particular direction, called the direction of the constraint. These one-direction constraints can be combined to produce multi-degree-of-freedom constraints that may, for example, work to align or repel two coordinate systems from each other in the virtual simulation. A virtual constraint can both restrict motion or enhance motion in a certain direction. A constraint ‘restricts’ the motion not in a directional sense (attract/repel) but rather than it doesn’t allow free (unconstrained) motion but influences it in a certain way based on the relative motion or pose of two tracked objects/coordinate systems in the virtual simulation. The active virtual constraints are all added into a constraint solver where the constraint solver determines a set of parameters which account for each virtual constraint and compute a force. This resulting force may be represented as a 6-DOF force/torque vector which represents a balance or equilibrium of the various virtual constraints, each acting along potentially separate constraint directions. It should be noted in the present teachings that the term “force” is used, it may refer to a generalized force/torque vector, in which components of linear force and/or rotational torques are specified in one or more degrees of freedom. For example, “force” may refer to a single force in a single direction, a single torque about a single axis, or any combination thereof, e.g., a 6-DOF force/torque vector in a given coordinate system defining a force consisting of x, y, and z components and a moment consisting of torque components about an x, y, and z axis.

[0185] In some examples, each virtual constraint does not have an equal force, and, depending on the location of the rigid bodies being acted upon by the virtual constraint, may be adjusted so that the virtual constraint is flexible. For example, depending on the location of the instrument 14 relative to the patient anatomy and the target cutting plane or target trajectory, the virtual constraint may be

adjusted so that the virtual constraint is flexible. The virtual constraints are not infinitely rigid, but instead each of the virtual constraints has tuning parameters to adjust the stiffness of the virtual constraints, e.g., by incorporating spring and damping parameters into the virtual constraints. Such parameters may include a constraint force mixing parameter (C) and an error reduction parameter (ϵ). The virtual force may then be applied to a virtual rigid body (representing the tool 20 or blade support 18) in the virtual simulation. The 6-DOF forward dynamics computation is performed to determine the resulting motion of the virtual rigid body. The simulation is conducted over a time-step and the result is utilized as the commanded pose.

[0186] The values of the tuning parameters may be greater (e.g., stiffer) for position constraints than for orientation constraints, or vice versa. Thus, the computation of the virtual constraints leads to direct control of the motion parameter of the tool support moving relative to the hand-held portion. The tuning parameters can be determined as described, for example, in PCT Application No. PCT/US2020/053548, entitled “Systems and Methods For Guiding Movement Of A Tool,” filed on September 30, 2020, which is hereby incorporated herein by reference.

[0187] The states of the virtual constraints may be controlled during operation of the instrument. For example, the states of the virtual constraints may change based on a relationship between a first state and a second state (e.g. the current state and the target state of the tool). For example, the state may be configured as a function of a distance parameter between a position of the tool and a position of the reference location such that the state varies during use. In another example, the state may be configured as a function of an angle parameter between a position of the tool and a position of the reference location such that the state varies during use. The state of each virtual constraint may be an active state, an inactive state, including a first value for a tuning parameter, and/or including a second value for a tuning parameter. In some examples, the value of the state may be defined by a look-up table. Thus, certain constraints may be activated and/deactivated based on the state of the tool.

[0188] In instances where the tool is a saw blade, the state of the saw blade relative to the target states of the saw blade for the plurality of cutting planes may include determining angles between a current orientation of the saw blade and a plurality of target orientations of the saw blade, determining distances between a current position of the saw blade and a plurality of target positions of the saw blade, or determining both the angles and the distances. Determining the current state of the saw blade relative to the target state of the saw blade may also include determining a location of a

plane defined by the saw blade relative to a plurality of cutting planes in the known coordinate system. Thus, if the saw blade is positioned adjacent to a particular target cutting plane, the state of one or more virtual constraints may be altered and the control system may further be updated to update the target pose to reflect the chosen cutting plane. Similar techniques may be implemented for controlling the instrument when a rotary cutting tool is used to align with one or more target trajectories.

[0189] A virtual constraint may be activated when with a user input device, or when the robotic system 10 automatically activates the virtual constraints. Additionally, or alternatively, the user may be able to manually set the virtual constraints (e.g., change one or more parameters of the virtual constraints, activate/deactivate the virtual constraints, etc., via one or more of the user interfaces UI). The user may employ the clinical application 190 for this purpose. The virtual constraints may also be triggered when certain surgical steps are being performed, e.g., cutting a desired section of tissue, etc.), or when the robotic system 10 detects or otherwise recognizes certain conditions.

[0190] In one example, referring to Figure 10, the states of the virtual constraints may be changed depending on which region the tool is located in relative to the planned cut or surgical site. These regions may be defined by a virtual object 184 (see spherical object depicted) in one or more known coordinate systems.

[0191] In one example of changing the states of the virtual constraints, the spring and damping parameters may be adjusted during operation. In some versions, values for the tuning parameters may change based on a relationship between the current state and the target state of the tool. For example, the tuning parameters may be configured to increase in stiffness the closer the tool 20 gets to the target state, or the tuning parameters may decrease in stiffness as the tool 20 approaches the target state. The tuning parameters may be different for different constraints. For example, the virtual constraints may comprise a first virtual constraint that has a first value for a tuning parameter and a second virtual constraint that has a second value for the tuning parameter, the first value being greater than the second value so that the resulting virtual forces and/or torques embodied in the constraint force F_c are adapted to move the tool more strongly as a result of the first virtual constraint as compared the second virtual constraint. The values of the tuning parameters may be greater (e.g., stiffer) for position constraints than for orientation constraints, or vice versa.

[0192] The tuning parameters may also be set to: remain constant regardless of the distance/angle from the current state of the tool to the target state of the tool; rise/fall exponentially with distance; vary linearly with distance between the current state and the target state; vary with

constraint direction; vary as a function of time; take gravitational effects into account; or combinations thereof. Referring to Figures 18-20, a tuning parameter for one constraint associated with one degree of freedom may be set based on a relationship associated with another degree of freedom, e.g., the stiffness of an y-axis constraint may change based on the distance along the x-axis between the current state and the target state. The tuning parameters may also vary depending on the direction in which the tool 20 needs to move to reach the target state, e.g., more stiff when moving in one direction along the x-axis versus the opposite direction along the x-axis. The tuning parameters can also be scaled depending on the constraint force F_c that is ultimately computed based on the virtual constraints, such as by increasing/decreasing the stiffness depending on the magnitude of the constraint force F_c , or any components thereof. Fixed values for one or more virtual forces could also be added into the virtual simulation in some cases. The tuning parameters for the virtual constraints may be: set preoperatively; set intraoperatively; updated intraoperatively; and combinations thereof. The tuning parameters and their values, their correlation to a particular relationship, and the manner in which they may be scaled, may be stored in one or more look-up tables in any suitable memory in the control system 60 for later retrieval.

[0193] Changing the stiffness of one or more tuning parameters of one or more constraints as a function of time and distance may provide advantageous actuator behavior in response to one or more events. For example, in the event of a line of sight of to a tracker being temporarily interrupted, by slowly increasing the stiffness once the tracker comes back into line of sight of the camera, this can minimize abrupt and intense actuator movements in the user's hand, which can be distracting for the user. Instead, once the tracker of the instrument comes back into line of sight, the stiffness can be slowly increased. This control of the tuning parameters based on a function of time and distance may also be useful when the hand-held instrument transitions between different control regions, as described below. As described above, the one or more virtual constraints may be activated automatically. Additionally, or alternatively, the user may be able to manually set the virtual constraints (e.g., change one or more parameters of the virtual constraints, activate/deactivate the virtual constraints, etc., via one or more of the user interfaces UI). The user may employ the clinical application 190 for this purpose. The virtual constraints may also be triggered when certain surgical steps are being performed, e.g., cutting a desired section of tissue, etc.), or when the robotic system 10 detects or otherwise recognizes certain conditions.

[0194] Each virtual constraint also has configuration settings. The configuration settings may comprise: information regarding the tuning parameters, such as the constraint force mixing parameter (C) and the error reduction parameter (ϵ); upper and/or lower force limits; and/or upper and lower constraint distance offsets. The upper and lower force limits refer to limits on the forces computed for each virtual constraint that are ultimately solved by the constraint solver 189 to produce the constraint force F_c , as described further below. The virtual constraints may be two-sided constraints (e.g., the forces computed to satisfy the constraints can be positive or negative), and may apply attractive forces in either direction regardless of which side of the target coordinate system TF the guided coordinate system GF is located (in each degree of freedom). The force limits can be set high in positive and negative directions (e.g., -100,000/+100,000 Newtons) or at any desired limit. Alternately, a virtual constraint may be a one-sided constraint (e.g., the forces computed to satisfy the constraint can only act in one direction, i.e., can only either be positive or negative, depending on the direction configured by the force limits). Further, constraints may be configured to be “attractive,” applying forces towards meeting the constraint criteria, or “repellant,” applying forces away from meeting the constraint criteria. The upper and lower constraint distance offsets dictate when the constraint is active. With respect to the virtual constraints, the upper and lower constraint distance offsets can be set so that the constraint is active any time the current state is different than the target state.

[0195] If the control system receives a higher force associated with one or more of the virtual constraints, the higher force can lead to higher rates of acceleration for the rigid bodies being affected by the virtual constraints in the simulation. The output of the virtual simulation as the commanded pose of the tool, commanding the actuators 21, 22, 23 accordingly, causing the higher forces and higher acceleration seen in the virtual simulation to result in a higher acceleration of the tool support 18 relative to the hand-held portion 16. The higher force may be based on the value computed for that particular constraint, the values of the tuning parameters, or combinations thereof. For example, the virtual constraints may comprise a first virtual constraint that has a first value for a tuning parameter and a second virtual constraint that has a second value for the tuning parameter, the first value being greater than the second value so that the resulting virtual forces and/or torques embodied in the constraint force F_c are adapted to move the tool more strongly as a result of the first virtual constraint as compared the second virtual constraint.

[0196] Figures 11 and 17A-17E are control diagrams of processes carried out to execute computation of the commanded pose using the one or more virtual constraints. Figure 11 is a simplified

control diagram and Figures 17A-17E are more in-depth. In these versions, the behavior controller 186 may be connected with a constraint generator 384. The constraint generator 384 may include a boundary handler 389, which sends boundary constraints to the behavior controller 186, and a guide handler 385, which sends guide constraints to the behavior controller 186. The behavior controller 186 may include a constraint solver 189, and a virtual simulator 388. A motion constraint handler 390 sends joint center constraints, kinematic motion constraints, workspace constraints, and joint limit constraints to the behavior controller 186 to be added into the constraint solver 386 and virtual simulator 388. In some examples, the motion constraint handler 390 is part of the motion controller 188. The virtual simulator (indicated as sim in Figure 11 and virtual forward dynamics in Figures 17A-E) may simulate the virtual dynamics on the tool 20 based on the constraint forces and potentially additional forces, including damping, inertial, and external sensed forces. The constraint generator 384, constraint solver 189, and virtual simulator 388, each comprise executable software stored in a non-transitory memory of any one or more of the aforementioned controllers and implemented by the control system 60. The constraint forces may be applied to a virtual mass coordinate system VM in which a virtual simulation is carried out on the virtual rigid body model of the tool 20 so that the forces and torques can be virtually applied to the virtual rigid body in the virtual simulation to ultimately determine how those forces and torques (among other inputs) would affect movement of the virtual rigid body, as described below. The virtual forces and torques that can be applied to the virtual rigid body in the virtual simulation are adapted to move the tool 20 toward the target state. The virtual forces and torques influence overall movement of the tool 20 towards the virtual object, i.e., a target state.

[0197] In one example, as shown in Figure 11, the behavior controller 186 does not utilize an external force sensor input to the virtual simulation. The use of virtual-constraints based control provides for some advantageous outcomes, even in the absence of an external force sensor. The constraint system and modeling of virtual forces in a virtual simulation allows you to easily blend together constraints tied to different outcomes with ease. The constraint system also allows you to tune parameters for each constraint in an intuitive way. Furthermore, the use of velocity constraints provides for a higher responsiveness (e.g., higher stiffness) for a given sample rate given its improved numerical stability over other numerical integration or simulation methods. As described, however, the use of an external force sensor or other approximation for external force, such as current-based estimation of external force, may be used with the systems and methods described herein.

GUIDE CONSTRAINTS

[0198] One type of virtual constraints are referred to herein as guide constraints. The guide constraints are defined to ultimately influence movement of the tool 20 toward the target state. The guide constraints, as described further below, have configurable spring and damping properties so that the guide constraints are not infinitely stiff. More specifically, in some versions, the guide constraints are defined as “soft constraints” such that they do not completely prevent motion that violates them, such as motion resulting from forces and torques applied by other constraints in opposite directions to the target state.

[0199] One or more guide constraints may be used by the control system 60 to guide the tool support 18, including up to three guide constraints associated with the target position and up to three guide constraints associated with the target orientation. As described in more detail below, the control system 60 operates to calculate the constraint force F_c that satisfies, or attempts to satisfy, the guide constraints (and other virtual constraints, if used). The constraint force F_c incorporates the virtual forces and torques therein to move the tool 20 to the target state. Each of the guide constraints are considered one-dimensional, virtual constraints. The control system may utilize a plurality of one-degree of freedom constraints to align a guided frame to a target frame. As noted previously, the guide constraints are “two-sided” constraints in that guide constraints may apply attractive forces in either direction regardless of which side of the target coordinate system TF the guided coordinate system GF is located (in each degree of freedom). In some versions, the guide constraints are velocity impulse constraints in which forces and/or torques are calculated to apply a virtual impulse to an object in the virtual simulation to cause a change in the object’s velocity in accordance with desired constraint parameters. In some versions, the constraints are similar to those used in the impulse modeling described in U.S. Patent No. 9,119,655, incorporated herein by reference.

[0200] In Figure 12, guide constraints GC associated with a target pose in at least one degree of freedom is illustratively represented as being defined in the target coordinate system TF. The constraint force F_c that is ultimately calculated as a result of these guide constraints GC (and other active virtual constraints) is illustrated as comprising a force that incorporates virtual spring and damping properties that guides the TCP of the tool 20 to the target pose. The guide constraint may be based on the pose of the guided coordinate system GF (e.g., defined with respect to the virtual mass coordinate system VM) and the pose of the target coordinate system TF (e.g., defined with respect to the patient tracker(s)). The poses (in at least one degree of freedom) of the guided coordinate system

GF and the target coordinate system TF are used to compute the current state of the saw blade and the target state of the saw blade, respectively, or the current state of the tool and the target state of the tool respectively.

[0201] Each guide constraint has a constraint direction defined along or about the x, y, or z axis of the target coordinate system. The constraint direction is the direction along which the constraint can effectively apply force. For the case of rotational constraints, the constraint direction is the axis about which the constraint can effectively apply torque. The constraint directions could also be defined in the guided coordinate system (GF), or the constraint directions could be defined using any known relationships to either the target coordinate system (TF) or the guided coordinate system (GF). In one example, 3 translational guide constraints and 3 rotational constraints may be used to fully align the position and orientation of the guided frame with the target frame. However, fewer than 3 translational constraints may be used, and fewer than three rotational constraints may be used.

[0202] In one example, the guide constraints are computed in three degrees of freedom – 1 position and 2 orientations. The position guide constraint is defined in elevation, and the orientation constraints are defined in pitch and roll, which are used to align the saw blade to the target plane TP. The orientations are computed by comparing the orientation of the target pose (TF) and the guided frame on the saw blade. The roll (rotation about X-axis) and pitch (rotation about Y-axis) are used to define how much the saw blade needs to be rotated until the X-Y plane of the saw blade (the guided coordinate system) is parallel to the X-Y plane of the target pose (the target coordinate system). For this example, the three constraint directions would be along the z axis of TF (elevation), about the x axis of TF (roll), and about the y axis of TF (pitch). In another example for other virtual objects, 2 position guide constraints and 2 orientation guide constraints may be used.

[0203] Alternatively, any number of degrees of freedom could be used in the guided coordinate system to align the saw blade or other tool to the target pose. For example, a 1-DOF position–point on a plane, the 3-DOF position and orientation described above, the 4-DOF position and orientation, or a full 6-DOF pose, which would include guide constraints to align three positions and three orientations.

[0204] The guide constraints (and other virtual constraints, if used) are defined primarily by three runtime parameters: a constraint Jacobian J_p , which maps each one-dimensional, guide constraint to a coordinate system employed for the virtual simulation (e.g., between the target coordinate system TF and the virtual mass coordinate system VM); a desired velocity V_{des} (or V_{p2}) which is a scalar velocity (linear or angular) of the guide constraint along or about the applicable

constraint direction defined by the target coordinate system TF (e.g., the desired velocity may be zero when the patient is immobile and the associated target state defined relative to the patient is not moving, but may be other than zero when the patient moves since the target state may be tied to the patient); and a constraint distance Δd , which is how close the guided frame GF is to the target frame TF along or about the applicable constraint direction defined by TF and which dictates whether the constraint is being violated. In some cases, Δd refers to a distance/angle of the current state from the target state, and a guide constraint is violated any time the current state does not match the target state for the associated degree of freedom.

[0205] It should be appreciated that when other constraints are employed other than the guide constraint, the constraint solver is ultimately tasked with providing a solution for the constraint force F_c that satisfies, or attempts to satisfy, all the virtual constraints, and thus other constraints may influence the magnitude and/or direction of the constraint force.

JOINT CENTERING CONSTRAINTS

[0206] A joint centering constraint is another virtual constraint representing a virtual force and/or torque employed in the virtual simulation to influence the movement of the tool support 18 relative to a centering position for each actuator of the plurality of actuators. The joint centering constraint is used in implementing a particular restriction in the motion of tool support 18 relative to the hand-held portion that is considered by the control system 60 to maximize the amount of travel of the tool support 18 available relative to the hand-held portion 16. In one example, the particular restriction of motion to the tool 20 may be to have the joints return to their centered positions (or another joint position determined by the user, the control system 60, or both) when other constraints are not active. Alternatively, the joint centering constraint may facilitate positioning of the tool support 18 relative to the hand-held portion 16 for optimal balance for particular surgical procedures, such as for particular cuts in a total knee procedure or for particular trajectories in certain bone drilling procedures. The joint centering constraint, as described further below, may have configurable spring and damping properties so that the joint centering constraint is not infinitely stiff. More specifically, in some versions, the joint centering constraint is defined as a “soft constraint” such that the joint centering constraint does not completely prevent motion that violates it, such as motion resulting from forces and torques applied by other constraints in opposite directions.

[0207] The joint centering constraint may be used by the control system 60 to move the tool support 18. As described in more detail below, the control system 60 may operate to calculate the

constraint force F_c that satisfies, or attempts to satisfy, the joint centering constraint. The constraint force F_c incorporates the virtual forces and torques therein to move the tool support 18 towards the centering position. The joint centering constraint is considered as a one-dimensional, virtual constraint. In some versions, the joint centering constraint is a velocity impulse constraint in which forces and/or torques are calculated to apply a virtual impulse to an object in the virtual simulation to cause a change in the object's velocity in accordance with desired constraint parameters. It should be appreciated that when other constraints are employed other than the joint centering constraint, the constraint solver is ultimately tasked with providing a solution for the constraint force F_c that satisfies, or attempts to satisfy, all the virtual constraints, and thus other constraints may influence the magnitude and/or direction of the constraint force.

[0208] In Figure 21, the joint centering constraint is illustratively represented in the joint space of the respective actuators, (along the translation axis of the actuator 21, 22, 23). The constraint direction for a joint centering constraint is along the translation axis of that actuator 21, 22, 23, and therefore may only apply linear force along that direction. The constraint force that is calculated as a result of each jointing centering constraint is illustrated as comprising a linear force that incorporates spring and damping properties which acts along the translation axis of corresponding actuator that guides the actuator position to the centering position. It should be appreciated that the joint centering constraint may defined in other coordinate systems as well. It should be appreciated also that all or fewer than all of the actuators in the instrument may utilize joint centering constraints.

[0209] The joint centering constraint is defined primarily by three runtime parameters: a constraint Jacobian J_p , which maps the one-dimensional joint centering constraint to a coordinate system employed for the virtual simulation (e.g., between the motion of the joint and the virtual mass coordinate system VM); a previous commanded joint position, which is a position commanded used to control each actuator in a previous control iteration; and a joint centering position, which is a configured joint position to which it is desired for the actuator to return to when no other constraints are active. It should be appreciated that the current measured position of the actuators may also be used for the joint centering constraint. The previous commanded position may provide for less lag in control and improved stability. The joint centering constraint may be two-sided and always pulling the joint to the centering position when active.

[0210] The joint centering position may be the location at which each of the rotors 148 have a relatively high amount of travel along their respective leadscrews. In other words, the joint centering

position may be considered the ‘home’ or ‘idle’ position of each of the actuators as described above. By setting the joint centering position to the home position, a median position for the rotor along the leadscrew, for each actuator, the tool support may achieve maximum range of motion. Alternatively, the joint centering position may be set to a position other than the home position for one or more of the plurality of actuators. This may be considered a secondary joint centering position. The secondary joint centering position may be different for each of the actuators 21, 22, 23. It should be understood that when the actuator is located at the secondary joint centering position, the one or more actuators 21, 22, 23 may only be capable of a fraction of the travel in one direction that the same actuator may have had when the joint centering position was the home position. In one example, a first joint centering position is the ‘home position’ and a second joint centering position is a position other than the home position. Without being particularly limited, when the actuator is in the secondary joint centering position, the actuator may have less than 50 percent, less than 40 percent, or less than 30 percent of the range of motion in a particular direction than that same actuator would have had when set in the joint centering position equivalent to home. However, for certain surgical procedures or for certain users, it may be helpful to bias a joint centering position away from the actuator’s median position in order to provide more travel in a certain (potentially challenging) direction, to improve ergonomics or to account for how the instrument is held. It should be appreciated that each actuator may have a multitude of different joint centering positions, or presets for preferred balance arrangements. Groups of joint centering positions may be aggregated together (sets of joint centering positions for all of the actuators) which correspond to preferred grips/balance scenarios. These centering positions may be selectable by a user using one or more user input devices.

[0211] When each actuator 21, 22, 23 is at the first joint centering position (the home position), the amount of adjustability of the actuators 21, 22, 23 is typically symmetrically maximized to make it easier for the user to keep the tool 20 at a desired pose, i.e., the joint centering position is typically set to the median position or ‘home’ position of the actuator. Various levels of adjustment are possible depending on the particular geometry and configuration of the instrument 14. In some examples, when all the actuators 21, 22, 23 are in their first joint centering positions, the tool 20 may be adjusted in pitch orientation about $\pm 18^\circ$ relative to the joint center position, assuming zero changes in the roll orientation and no z-axis translation. In some examples, when all the actuators 21, 22, 23 are in their centering positions, the tool 20 may be adjusted in roll orientation about $\pm 33^\circ$ relative to the centering position, assuming zero changes in the pitch orientation and no z-axis translation. In some examples,

when all the actuators 21, 22, 23 are in their first joint centering positions, the tool 20 may be adjusted in z-axis translation about +/- 0.37 inches relative to the first joint centering position, assuming zero changes in the pitch orientation and roll orientation. The tool 20, of course, may be adjusted in pitch, roll, and z-axis translation simultaneously, sequentially, or combinations thereof during operation.

[0212] The joint centering constraint may be used to ‘freeze’ the one or more actuators into a free-hand/unguided mode at the position of the one or more actuators to prevent unnecessary actuation and movement, preventing the actuators from generating excessive heat from movement, such as when the instrument 14 is a substantial distance away from the target bone. The free-hand/unguided mode may be useful to perform some types of treatment, such as cutting the patella or other portions of the anatomy. When the actuators 21, 22, 23 are frozen from further movement in the free-hand/unguided mode, then the instrument 14 behaves much like a conventional cutting instrument, without any movement of the tool support 18 relative to the hand-held portion 16. The virtual boundaries 184 may also be deactivated in the unguided mode. The free-hand/unguided mode may be engaged by any suitable input device of any suitable user interface (e.g., push-button, foot switch, etc.). In some versions, the user may select this tool behavior (i.e., activate the joint centering constraint with a particular joint centering position and/or change the joint centering position) by actuating an input device, and selecting the free-hand/unguided mode where the instrument controller 28 commands a tool pose to be held or frozen in position. In some examples, to freeze the tool 20 at a particular pose, the instrument controller 28 may enable the joint centering constraints and set centering positions for each actuator 21, 22, 23 to the joint positions which correspond to the desired tool pose (e.g., by performing inverse kinematics on the desired tool pose to get the corresponding joint positions). Alternately, in another example, the joint centering positions may be left at or reset to zero (i.e., a home position). Further, the joint centering positions may be set to the current positions of the actuators, as determined using encoders or other actuator position feedback, at the time the mode is requested by the user. As described above, the joint centering position is adjustable. The secondary joint centering position may be set using a user input device, or may be set automatically.

[0213] The instrument controller 28 may automatically control a state of the joint centering constraint or behavior. For example, the state of the joint centering constraint may be controlled based on a state of the tool and the target state. Alternatively, the state of the joint centering constraint may be controlled based on the position of the tool 20 and the position of a reference location associated with bone in a known coordinate system. The state of the joint centering constraint could include a

value of the joint centering position for each of the plurality of actuators 21, 22, 23 and/or a tuning parameter of the joint centering constraint. For example, the instrument controller 28 may automatically enable the joint centering constraint with a particular joint centering position for each of the actuators when the tool 20 is removed from a cut based on a state of the tool 20 and the reference location associated with the bone as determined by the navigation system 32 so that the user may resume the procedure with the same grip about the hand-held portion 16 relative to the tool 20 for – maintaining a comfortable grip, control, convenience, familiarity with anatomy, unexpected anatomy, or a combination thereof. In such an example, the joint centering position is set to the positions of each actuator 21, 22, 23 that was measured at the time before removal of the saw blade 380 from the cut.

[0214] It should also be appreciated that while the joint centering positions were described in terms of the joint centering constraint, the joint centering position control described above may be utilized without the use of virtual constraints, such as with a position control system of the actuators. In such an implementation, the control system may simply control the position of each actuator to the set joint centering position. In instances where the joint centering behavior is utilized without implementing a constraint solver, the state of the joint centering behavior may be controlled in the same way as the joint centering constraint.

[0215] The instrument controller 28 may be configured to control the state of the joint centering constraint based a distance parameter (e.g. distance; magnitude) calculated between the position of the tool 20 and the position of the reference location associated with the bone. The distance parameter may be a direction, a magnitude, or both. In some cases, when the distance parameter has a direction away from bone and a magnitude greater than a first threshold value, such as 15 cm, the controller may switch to a different state.

[0216] As described above, the joint centering position is adjustable. The secondary joint centering position may be set using a user input device, or may be set automatically. In certain configurations, the secondary joint centering position and activation of joint centering constraint may be based on the state of a plane defined by the saw blade relative to a plurality of cutting planes in the known coordinate system, or may be based on the state of an axis defined by a tool relative to a plurality of planned trajectories.

[0217] More particularly, the secondary joint position of and activation of the joint centering constraint may be based on angles between a current orientation of the saw blade and a plurality of target orientations of the saw blade, a distance between a current position of the saw blade and a

plurality of target positions of the saw blade, or both the angles and the distances, and determining the one of the plurality of the plurality of cutting planes selected by the user based on the values of the angles, values of the distances, or both the values of the angles and the values of the distances. Thus, a particular secondary centering position for each of the actuators may be selected to optimize the pose of the tool support relative to the hand-held portion for purposes of improved usability. Similar implementations could be used for trajectories for other types of surgical tools.

[0218] With reference to Figures 22A-22C, one example of controlling the joint centering behavior is described below. In this example, virtual boundaries or distance parameters may be used to distinguish between regions IV and V, and a region immediately adjacent to the bone. In this example, referring first to Figure 22A and Figure 22B, the control system is configured to automatically save the current joint positions, which may be used later as joint centering positions when the tool moves from a first region (region IV) to a second region (region V). As can be seen in Figure 22A, the tool is on the cutting plane with the guide constraints actively aligning the tool 20 to the cutting plane. The control system 60 analyzes the current joint positions as the tool 20 moves from region IV to region V taking a “snapshot” of the joint positions, turning off the guide constraint, allowing the tool 20 to return to the centered position via its previously configured joint centering constraints (Figure 22B). When transitioning from region V back to region IV, the joint centering constraints are re-set to the value at the “snapshot”(e.g. restore alignment), causing the tool to align to an exit position (Figure 22C). The guide constraint may not be enabled until the tool 20 is within the zone defined by the region immediately adjacent to the entry of the bone. The restored joint positions may be implemented to re-align the user to an ergonomic start position for the handle, as captured when they previously exited the cut. The guide constraint may be reactivated when the pose of the blade (such as the VM of the blade) is close to the bone (consider a threshold distance from the VM of the blade to a reference coordinate system/reference position).

[0219] It should be appreciated that the joint centering constraint may be active at the same time as the guide constraint, the joint limit constraint, or the workspace constraint. In such a scenario, the constraint solver would seek to balance the forces exerted from each of the virtual constraints when computing how the actuators should be controlled, e.g., when computing the commanded pose. Thus, in certain instances, despite activation of the joint centering constraint with a particular joint centering position, the actuator may not actually be controlled to that joint centering position. This is because other constraints may have higher priority. The priority of the various constraints may be adjusted

through the use of the various tuning parameters, such as stiffness or damping. Of course, it is also contemplated that the different virtual constraints need not be active at the same time.

[0220] In one example, the virtual guide constraint may be activated as the TCP transitions from the region II to region I. A virtual joint centering constraint may be activated as it transitions from region III to region II. Similarly, the joint centering constraint may be deactivated as the TCP transitions from region II to region I. Of course, any number of regions may be defined, with any particular shape. It is contemplated that virtual joint limit constraints may be active in all three regions. As mentioned throughout, these regions may be defined as virtual objects of various shapes or as distance parameters relative to a reference location.

[0221] In some examples, the control system 60 modifies each of the virtual forces (the virtual constraints) with tuning parameters based on a pose of the instrument 14, a pose of the blade support or tool support, a pose of the hand-held portion, a commanded joint position of at least one of the actuators, a measured position of at least one actuator 21, 22, 23, a previous commanded position of at least one actuator 21, 22, 23, a previous measured position of at least one actuator 21, 22, 23, or combinations thereof. In some examples, the control system 60 generates a guide constraint based on the target pose of the saw blade 380 or tool and the measured pose of the hand-held portion 16. The control system 60 also generates a centering position for at least one actuator 21, 22, 23 and a joint centering constraint based on the position of at least one of the actuators 21, 22, 23. The control system 60 calculates a constraint force based on the guide constraint and the joint centering constraint by simulating dynamics of the virtual saw blade or tool in a virtual simulation based on the constraint force. In some examples, the control system 60 may also determine an external force applied to the instrument 14, such as the blade support or tool support, the hand-held portion, or between the blade/tool support and the hand-held portion and use the external force in the calculation to determine the constraint force and to apply it to the virtual rigid body in the virtual simulation. The external force could be measured in one or more degrees of freedom, and may be modeled as a force/torque vector. The result of the virtual simulation is a commanded pose which may ultimately be used to determine commanded joint positions for each of the plurality of actuators 21, 22, 23. The centering position may be between the median point of the actuator range, and the joint limit of that actuator.

[0222] In the virtual simulation, each of the virtual constraints may be modified with a tuning parameter. Each tuning parameter may cause the respective virtual constraints to have an increased effect on the constraint force in the virtual simulation. In one example, the joint centering constraint

may have a tuning parameter with a first value, and the guide constraint may have a tuning parameter with a second value, each of the tuning parameters causing the respective virtual constraints to have an increased effect on the ultimately calculated constraint force. In one example, the tuning parameter of the joint centering constraint is less than the tuning parameter of the guide constraint so that the constraint force biases the virtual simulation, and subsequently the commanded pose and commanded joint position, towards moving the tool 20 to the target pose while moving at least one of the actuators away from a joint centering position, e.g., a center point/home position. The control system 60 may further activate a joint limit constraint based on the position of at least one of the plurality of actuators and a position limit. The joint limit constraint may be solved along with other virtual constraints (e.g. guide constraint; joint centering constraint) to determine the constraint force. In one example, a joint centering constraint tuning parameter has a first value, a guide constraint tuning parameter has a second value, and a joint limit constraint tuning parameter has a third value greater than the value of guide constraint tuning parameter and the joint centering constraint parameter. The tuning parameter of the joint limit constraint being greater than the tuning parameter of the guide constraint and the tuning parameter of the joint centering constraint, the virtual simulation ensures that the constraint force applied to the virtual saw blade is more likely to satisfy the joint limit constraint. In this example, since the joint limit constraint has the highest value, the virtual force exerted on the virtual saw blade will be guided to a position within the joint limits, resulting in a commanded position which does not exceed the joint limit positions. One such tuning parameter that could be used in this example would be the stiffness of the constraint.

JOINT LIMIT CONSTRAINT

[0223] A joint limit constraint is another virtual constraint representing a virtual force and/or torque employed in the virtual simulation to influence the movement of the tool support 18 when controlling a plurality of actuators. The joint limit constraint is used by the control system 60 to implement a particular restriction in the motion of tool support 18 that is intended to prevent the actuators 21, 22, 23 from traveling outside their range of motion. The joint limit constraint may also enforce a threshold of travel which is considered too close to the actuator travel limit. The joint limit constraint, as described further below, has configurable spring and damping properties. However, joint limits, such as soft stops and hard stops are still operable to prevent the tool from overextending or retracting.

[0224] The joint limit constraint may be used by the control system 60 to guide the tool support 18. As described in more detail below, the control system 60 operates to calculate the constraint force F_c that satisfies, or attempts to satisfy, the virtual constraints (including the joint limit constraint). The constraint force F_c incorporates the virtual forces and torques therein to move the tool support 18 and tool 20 in a manner intended not to violate the actuator joint limits. The joint limit constraint is considered as a one-dimensional, virtual constraint. For example, a joint limit constraint may be one-sided, and thus may ‘push away’ from the joint limit but does not attract towards the joint limit. In some versions, the joint limit constraint is a velocity impulse constraint in which forces and/or torques are calculated to apply a virtual impulse to an object in the virtual simulation to cause a change in the object’s velocity in accordance with desired constraint parameters. It should be appreciated that when other constraints are employed in addition to the joint limit constraint, the constraint solver is ultimately tasked with providing a solution for the constraint force F_c that satisfies, or attempts to satisfy, all the virtual constraints, and thus other constraints may influence the magnitude and/or direction of the constraint force.

[0225] The joint limit constraint is defined primarily by three parameters: the previous commanded joint positions, the positions of the joint limits, and the same constraint Jacobian J_p , as used for the Joint Centering Constraint, relating the motion of the joint to the motion of the virtual mass. The joint limit constraint utilizes a computation of the difference in position between a joint limit position and the previous commanded position. In some implementations, the joint limit constraint may be computed based on current measured position instead of the previous commanded position.

[0226] The joint limit constraints are determined and calculated as a force to prevent the actuators 21, 22, 23 from extending and/or retracting past the physical and virtual limits of each of the actuators 21, 22, 23. The instrument controller 28 analyzes the previous commanded position along each active axis AA1, AA2, and AA3 to determine joint limit constraint. The joint limit constraint is balanced with the joint centering constraints, the guide constraints, a workspace constraint, and/or other virtual constraints when computing the commanded pose. The joint limit constraint may be based on the joint limits (soft stops) which may be software enabled stops set at count values just shy of the extreme ends of travel measured during the homing procedure. The soft stops may be values pre-programmed into the software. The soft stops may be a combination of count values and preprogrammed values.

WORKSPACE CONSTRAINT

[0227] A workspace limit constraint is another virtual constraint representing a virtual force and/or torque employed in the virtual simulation to influence the movement of the tool support 18 when controlling a plurality of actuators. The workspace limit constraint is used by the control system 60 to implement a particular restriction in the motion of tool support 18 that is intended to prevent the tool 20 from traveling outside its workspace. The workspace limit constraint exerts force along a direction defined in Cartesian space, rather than in joint space (which is the case for the joint limit constraint). The workspace limit constraint, as described further below, has configurable spring and damping properties so that the workspace constraint is not infinitely stiff. More specifically, in some versions, the workspace limit constraint is defined as a “soft constraint” such that the workspace constraint impedes but does not prevent motion that violates it, such as motion resulting from forces and torques applied by other constraints in opposite directions.

[0228] The workspace limit constraint may be used by the control system 60 to prevent the movement of the tool support 18 and the tool 20 into various locations outside a defined workspace. As described in more detail below, the control system 60 operates to calculate the constraint force F_c that satisfies, or attempts to satisfy, the virtual constraints (including the workspace constraint). The constraint force F_c incorporates the virtual forces and torques therein to move the tool support 18 and tool 20 in a manner intended not to violate the workspace limits. The workspace limit constraint is considered as a one-dimensional, virtual constraint, in that the workspace limit constraint may only apply forces in a single direction (i.e., ‘push away’ from the workspace limit but does not attract towards the workspace limit). In some versions, the workspace limit constraint is a velocity impulse constraint in which forces and/or torques are calculated to apply a virtual impulse to an object in the virtual simulation to cause a change in the object’s velocity in accordance with desired constraint parameters. As described above, the workspace limit constraint may include one or more tuning parameters that are adjustable either manually, or automatically (based on various positional/angular relationships described throughout).

[0229] The workspace limit constraint may be based on a pose of the tool and a predetermined Cartesian space, typically defined with respect to the BCS coordinate system. The pose of the tool 16 may be calculated as described above. As described in more detail below, the control system 60 operates to calculate the constraint force F_c that satisfies, or attempts to satisfy, the workspace limit constraints (and other virtual constraints, if used). The constraint force F_c incorporates the virtual

forces and torques therein to move the tool 20 in such a way that the workspace limit constraint is not violated. Each workspace limit constraint has a constraint direction that is along the normal to the workspace boundary at the point where the tool 20 contacts the workspace boundary, pointing inward towards the allowed workspace region. Typically, the constraint direction is defined in the BCS coordinate system; however other coordinate systems may be used. The constraint direction is the direction along which the workspace constraint can effectively apply force. The constraint Jacobian J_p may then be determined, relating the motion of the tool 20 along the constraint direction to the motion of the virtual mass VM. Additionally, the workspace limit constraint may also utilize the computation of a penetration depth (i.e. how much the workspace limit was violated along the constraint direction) by comparing the tool pose with the applicable workspace limit boundary being contacted by the tool.

[0230] It should be appreciated that when other constraints are employed other than the workspace limit constraint, the constraint solver is ultimately tasked with providing a solution for the constraint force F_c that satisfies, or attempts to satisfy, all the virtual constraints, and thus other constraints may influence the magnitude and/or direction of the constraint force.

[0231] As best shown in Figures 3A-5C and 23, the plurality of actuators 21, 22, 23 are capable of moving the tool support 18 and tool 20 relative to the hand-held portion 16 in at least three degrees of freedom including pitch, roll, and translation along the axis Z (vertical translation). These individual degrees of freedom are best shown in Figure 3A-3C (pitch), Figures 4A-4C (roll), and Figures 5A-5C (z-axis). Figure 23 shows one exemplary predetermined Cartesian space, illustrated as a volume in the shape of a cube. Other shapes of the predetermined Cartesian space may be implemented as a volume, such as an octahedron, an asymmetrical octahedron, a sphere, a cuboid, a cylinder, etc. Particularly, in some examples, the Cartesian space when defined as a volume, may be asymmetrical in shape, such as asymmetrical about a plane position between the tool support 18 and the hand-held portion when each of the actuators are in the home position, with the Cartesian volume being greater above the plane than below the plane. In this example, the volume may be defined by a plurality of Cartesian points. This volume may be less than the dexterous workspace (less than all reachable configurations). Alternatively, the predetermined Cartesian space may be defined in each degree of freedom separately. For example, the Cartesian space may be defined with a plurality of Cartesian points. The predetermined Cartesian space may also be defined by one or more orientations, based on any one, two or three of the axes along which or about which the saw blade 380 can be displaced (x, y, and z).

[0232] The instrument may be controlled in such a way that the range of motion of the blade support relative to the hand-held portion may be greater in pitch than in roll. Alternatively, or in addition, the instrument may be controlled in such a way that the range of motion of the blade support relative to the hand-held portion is greater in elevation than in roll. In one potential implementation, the instrument may be controlled using a combination of the joint limit constraint and a workspace constraint. In addition, one or more other virtual constraints may be used simultaneously with the joint limit constraint and the workspace constraint, such as the guide constraint and/or the joint centering constraint. The constraint solver may be configured to calculate a constraint force adapted to move a virtual saw blade based on the joint limit constraint and the workspace constraint (and any other virtual constraint being utilized). The dynamics of the virtual saw blade are simulated based on the constraint force and output a commanded pose. Based on that commanded pose, the system determines a commanded joint position of each of the plurality of actuators based on the commanded pose. Each of the plurality of actuators is then controlled using the commanded position.

[0233] The use of workspace limits (defined in Cartesian coordinates) in combination with joint limits (defined in joint space) may provide advantages with respect to control of the instrument. Implementation of both limits may provide additional options to avoid singularities in control, may provide additional robustness in design by avoiding vulnerable poses that could cause damage to the one more flex circuits, and/or may provide additional options to avoid mechanical interference. For example, the control system 60 may implement workspace limits in order to limit the amount of roll of the blade support 18 relative to the hand-held portion 16 by limiting the workspace constraint and the joint limit constraint more than the workspace constraint and joint limit constraints in pitch, z-axis elevation, or both. By setting the workspace limit on roll higher than in the other controlled degrees of freedom (pitch and elevation), the limited roll may be less roll than the mechanical capabilities. In some cases, the workspace constraint in the roll direction may have the same amount or less mechanical movement as the other controlled degrees of freedom in the pitch and z-axis directions.

[0234] Alternatively, the range of motion of the plurality of actuators may be controlled without constraints. In such an implementation, a joint limit behavior is determined based on a position of the actuators and a limit position and determining a workspace limit based on the pose of the tool and a predetermined Cartesian space. Then, the control system 60 is configured to limit each of the plurality of actuators 21, 22, 23 based on the pose of the saw blade 380, the joint limit position, and the predetermined cartesian space.

[0235] The workspace limits may also be used for reasons other than forming workspace constraints. For example, the defined workspace limits for the instrument may be used to control the drive motor. The control system may control the tool drive motor based on a workspace limit, a pose of one of the surgical tool, hand-held portion, and the tool support, and optionally, in consideration of the motor status. Furthermore, the control system may change workspace limits based on one the pose of the surgical tool, hand-held portion, and the tool support and a boundary and/or the motor status. This can be viewed as an alternative of setting actuator limits based on similar factors. Such an implementation is control in the cartesian space, versus control in the joint space. Thus, it is contemplated throughout that discussion of joint limits can be replaced within workspace limits, and such alternatives are expressly contemplated.

KINEMATIC MOTION CONSTRAINT

[0236] A kinematic motion constraint may be used by the control system to control the degrees of freedom that are not controlled by the plurality of actuators, i.e., the uncontrolled degrees of freedom. In one example, where the instrument includes three controlled degrees of freedom and three uncontrolled degrees of freedom, the kinematic motion constraint may be used with the three uncontrolled degrees of freedom (yaw, x-translation and y- translation). Because the virtual simulator models the virtual constraints using a virtual mass subjected to forces in six degrees of freedom, the kinematic motion constraints are utilized to ensure that the virtual mass model in the virtual simulator remains coincident with the physically-relevant kinematic pose of the tool 20, preventing the tool 20 from drifting away in the virtual simulation in the uncontrolled degrees of freedom. The kinematic motion constraints are used to measure the difference in yaw, X-translation and Y translation between the kinematic pose and the virtual mass. The constraint force computed based on these kinematic motion constraints is computed to counteract those differences, whether they are positive or negative; thus, this is a two-sided constraint. The kinematic motion constraints are computed in Cartesian space. While the joint limit constraints ensure that the plurality of actuators do not exceed their joint threshold, the kinematic motion constraints are always active, ensuring that the uncontrolled degrees of freedom are aligned in the coordinate system of the virtual mass.

BOUNDARY CONSTRAINT

[0237] The control system may also utilize one or more boundary constraints. The boundary constraint may be based on the one or more virtual boundaries described above, along with the pose of the tool. A boundary constraint may function for constraint generation and actuator control

(described here), drive motor control, be used together, separately, or a combination thereof. The boundary constraint may result in a force on the virtual mass that prevents the tool from crossing the virtual boundary. It should be understood that the boundary constraint may utilize any of the virtual boundaries described above with respect to control of the drive motor. In the case of the boundary constraint, it should be understood that the virtual boundaries are utilized to control the plurality of actuators rather than controlling the saw drive motor. In some examples, the boundary constraint or other boundary control methods may utilize collision detection.

[0238] In one example, the boundary may be defined as a triangle mesh and collision detection algorithms may be used to determine which part of the mesh may be contacted by the tool 20. First, the control system 60 performs a broad phase collision detection to generate a list of candidate triangles located in the region of the tool 20. Next, for each of the candidate triangles, a narrow phase collision detection is performed to confirm whether the tool 20 contacts the triangle and how much penetration depth (along the normal to the triangle) the tool 20 reaches through the boundary. Boundary constraints may only be generated for those triangles in contact with the tool, i.e., the output triangles from the narrow phase collision detection. In some cases, the tool 20 may be modeled using an array of primitive geometric shapes, such as discrete spheres (with diameters equal to the tool thickness) or discrete swept spheres (capsule shapes) located along the periphery of the tool 20. The collision detection process may be repeated for each for the primitive elements (e.g., discrete spheres) to look for collisions with the mesh triangles. Boundary constraints may be generated for each contact between a tool geometric primitive and a mesh triangle.

[0239] Typically, the boundary is defined relative to a patient tracker 54, 56, but other reference coordinate frames can be used. After the control system 60 determines the points of the boundary mesh which contact the geometric primitives or VM of the tool 20, the boundary constraints may be computed. A one-DOF, one-sided (force applied away from the boundary) boundary constraint may be computed for each resulting narrow phase triangle. The boundary constraint direction is along the normal to the triangle. The penetration depth of the boundary may also be measured along this boundary constraint direction. A constraint Jacobian J_p is computed mapping movement of the tool 20 along the triangle normal (boundary constraint direction) to resulting motion of the virtual mass. For any boundary constraints attached to an anatomy tracker (i.e., having a relative velocity with respect to the tool 20), V_{desired} may need to be computed. V_{desired} may be a projection of the relative velocity between bone and tool 20 onto the constraint direction. In another example, when

the tool is completely beyond the boundary, is handled by drive motor M control rather than via boundary constraint generation (and resulting actuator control).

[0240] It should be appreciated that when other constraints are employed other than the boundary constraint, the constraint solver is ultimately tasked with providing a solution for the constraint force F_c that satisfies, or attempts to satisfy, all the virtual constraints, and thus other constraints may influence the magnitude and/or direction of the constraint force.

EXTERNAL FORCE

[0241] In one version, the instrument 14 may be configured to calculate, estimate, or measure forces and torques placed on the instrument 14 by the user or by the bone in order to affect or influence the tool 20. For example, the instrument 14 may detect and measure the forces and torques applied by the user or by the bone onto the tool 20 and generates corresponding input used by the control system 60 (e.g., one or more corresponding input/output signals). The forces and torques applied by the user at least partially define an external force F_{ext} that is used to determine and facilitate control of the plurality of actuators. By including an external force/torque measurement into the virtual simulation, the forces applied by the user or bone may be brought into the virtual simulation. This may allow the virtual constraints to have compliance against physically applied forces. For example, the guide constraint has a particular stiffness and damping. When the external force (F_{ext}) is included in the virtual simulation, the tool may be positioned in a way such that the user would “feel” the compliance of the guide constraint. This may allow the control of the tool to be more responsive to the user applied force (i.e., an equilibrium may be found in the virtual simulation between the applied user/bone force and the guide constraint stiffness). If the user applies heavy force, then, if desired, the guide constraint may be partially overridden by the user based on its tuning parameters. This may be used to limit binding or fighting of the tool against the user in the case of small positional misalignments between the saw blade and cutting plane or the tool and the planned trajectory, the virtual compliance allowing that small error to be resolved (balanced out) without exerting high forces or positive feedback felt by the user through the handle when the blade or tool cannot perfectly reach its target pose. Without the F_{ext} measurement, the stiffness of the virtual constraints may find an equilibrium with forces applied by other virtual constraints, without taking into account any physical forces applied by the user or bone against the blade. Without including the external force into the virtual simulation, the force applied by the user is not considered in determining the commanded pose. For example, this external force may be used in computing the commanded pose by including the external force in the constraint

solver in combination with the other virtual constraints described above, and then applying the external force to the virtual rigid body in the virtual simulation. The external force F_{ext} may comprise other forces and torques, aside from those applied by the user or by the bone, such as gravity-compensating forces, backdrive forces, other virtual forces, and the like, as described in U.S. Patent No. 9,119,655, incorporated herein by reference. Thus, the forces and torques applied by the user at least partially define the external force F_{ext} , and in some cases may fully define the external force F_{ext} that influences overall movement of the tool 20. In some instances, the instrument may comprise a force/torque sensor S that is implemented as a 6-DOF force/torque transducer positioned on the hand-held portion, the tool platform, or between the two components. In other examples, a linear force sensors in each of the actuators 21, 22, 23, or torque sensors in each of the actuator motor outputs may also be used. Additionally, motor current may be used as a lower-fidelity approximation of motor torque, in place of a force/torque sensor. Each of these joint space force/torque measurements may be converted to an equivalent force/torque acting on the virtual mass VM using the appropriate Jacobian based on the manipulator kinematics. The instrument controller 28 and/or the navigation controller 36 may receive the input (e.g., signals) from the force/torque sensor. In some versions, the external force is transformed from a force/torque coordinate system F_T to another coordinate system, such as the VM coordinate system. In such a method, the method may include sensing an amount of current supplied to each of the plurality of actuators, estimating an amount of external force applied between the blade support and the hand-held portion based on the output of the one or more current sensors, and calculating a constraint force adapted to move a virtual saw blade towards the target pose based on the estimated amount of external force.

[0242] In an alternative implementation, the external force may be considered an amount of external effort applied to the tool support and the hand-held portion. The estimated amount of external effort may be a force or a torque. The estimated force or torque may be computed in one or more degrees of freedom. Referring to Figure 54, in such an implementation, the control system may control the display screen to display indicator 300 based on the estimated amount of external effort applied. This indicator 300 may be indicative that excessive ‘fighting’ of the instrument may be occurring, which may be indicative of a blade to tool registration error. Exemplary blade registration techniques are described in PCT application PCT/US2021/064328, which is hereby incorporated by reference in its entirety.

[0243] Alternatively, the control system 60 may be configured to control the drive motor M based on the estimated amount of external effort applied. For example, the control system 60 may slow or disable the drive motor M based on the estimated amount of external effort applied.

[0244] The control system 60 may control the indicator 300 or drive motor based M on the estimated amount of external effort applied and a force threshold. For example, the control system 60 may control the indicator 300 or drive motor M when the estimated amount of external effort applied exceeds the force/torque threshold in one or more degrees of freedom.

[0245] Furthermore, the control system 60 may control the indicator and/or the drive motor M based on the estimated amount of external force, a force threshold, and an error counter. The error counter is configured to trip for every instance of the estimated amount force exceeds the threshold for more than a de minimis time interval. Once the error counter exceeds a given number, such as an error counter threshold, such as three instances, the control system 60 may control the indicator 300 and/or the drive motor M so as to convey to the user than an excess amount of blade fighting is occurring.

[0246] Alternatively, the control system may control the indicator 300 and/or the drive motor M based on the estimated amount of force and a time threshold, such as 5 or 10 seconds. More particularly, the control system 60 may configured to control the indicator 300 and/or the drive motor M when the estimated amount of external force exceeds the force threshold in one or more degrees of freedom for longer than the time threshold, such as longer than 5 or 10 seconds.

[0247] The control system 60 may utilize different force thresholds, error counter thresholds, and/or time thresholds for each degree of freedom, such as different thresholds for the pitch degree of freedom, different thresholds for the elevation degree of freedom, and/or different thresholds for the roll degree of freedom.

[0248] The indicator 300 may be a visual indicator, tactile indicator, or audible indicator, and may be generated by a speaker, a display screen, a light, a vibration motor, or similar. The indicator may be mounted on the instrument 14 or located elsewhere, such as part of the navigation system 32 or console 33. The indicator 300 may take the form of a display screen or icon on an application associated with the user interface UI of the control system 60.

[0249] In instances where the indicator 300 is a display screen or icon, the control system 60 may be configured to control the user interface to prompt a user to check a tool to instrument registration based on the external effort applied. In other instances, the control system 60 may control

the user interface UI to initiate a tool to instrument registration workflow based on the estimated amount of external effort applied.

[0250] As described above, the amount of estimated external force may be estimated by using at least one of force sensors, torque sensors, and/or current sensors configured to detect the amount of current applied to each of the plurality of actuators.

OPERATION

[0251] Control of the instrument 14 takes into account the latest positions and/or orientations of the anatomy (e.g., the femur F or the tibia T) and the instrument 14, which are transmitted from the navigation controller 36 to the instrument controller 28 over the data connection. Using these data, the instrument controller 28 determines the pose (i.e., position and/or orientation) of the target plane or target trajectory and/or virtual boundaries 184 in a desired coordinate system. The relative pose of the tool 20 (e.g., the TCP) to the target plane and/or virtual boundaries 184 is also computed. The instrument controller 28 updates the navigation system 32 (including the displays 38) with the position and/or orientation of the tool 20 relative to the anatomy to which the tool 20 is to be applied. An indication of the location of the target plane and/or virtual boundaries 184 may also be presented.

[0252] The relative location of the tool 20 to the target plane and/or virtual boundaries 184 is evaluated by the instrument controller 28 to determine if action needs to be taken, i.e., moving the tool 20, changing a speed (such as an oscillation speed) of the tool 20, stopping operation of the tool 20, etc. Instructional data packets are sent, for example, to the motor controllers, such as from the instrument controller 28. These instructional data packets include the commanded positions for the rotors 148 of the motors 142 (or target position of the actuator). Here, each commanded position may be a positive or negative number representative of a targeted cumulative encoder count for the associated rotor 148, or other representation of the actuator's position. The instrument controller 28 generates and sends these instructional data packets to each motor controller at the rate of one packet every 0.05 to 4 milliseconds. In some examples, each motor controller receives an instructional data packet at least once every 0.125 milliseconds. Instrument controller 28 may also selectively regulate a cutting speed of the instrument 14 based on the relative location of the tool 20 to one or more of the virtual boundaries 184. For instance, the drive motor M that controls oscillation of the tool 20 and corresponding cutting, may be disabled by the instrument controller 28 any time the tool 20 is in an undesired relationship to the virtual boundaries 184, e.g., the tool 20 is off a target plane by more than a threshold value, the penetration of the tool 20 into the virtual boundary 184 is greater than a

threshold, etc. It is contemplated that the control system 60 may also control the drive motor M based on whether the optical tracking system retains line of sight for the tool tracker 52 and/or the patient tracker 54, 56. For example, the control system 60 may deactivate the drive motor M if line of sight has been compromised for a predetermined amount of time.

[0253] During use, in one potential implementation, the control system 60 determines a pose (a current pose) of the tool 20 with the navigation system 32 by virtue of the tool tracker 52 being located on the tool support 18. The instrument controller 28 may also determine a current position of each of the actuators 21, 22, 23 based on an output encoder signal from the one or more encoders located on each of the actuators 21, 22, 23. Once the current position of each of the actuators 21, 22, 23 is received, the instrument controller 28 may calculate a current pose of the tool (TCP) with respect to the hand-held portion 16 (BCS) using forward kinematics. The localizer data may be used to determine the relative pose between the patient tracker 54, 56 and the tool tracker 52. The aforementioned poses may be combined, along with additional calibration and registration data, to compute the pose of the hand-held portion 16 (e.g., a current pose of the base coordinate system BCS) with respect to a desired coordinate system, such as the patient tracker coordinate system.

[0254] In some examples, the current pose of the hand-held portion is determined with the navigation system 32 by virtue of tracker 53 located on the hand-held portion 16. The pose of BCS with respect to the desired coordinate system (e.g., patient tracker) may be determined directly using localization data in conjunction with additional calibration and registration data. In one instance, the instrument includes two trackers on the instrument 14, a hand-held portion tracker 53 on the hand-held portion 16 and a tool tracker 52 located on the tool support 18 as shown in Figure 24. The navigation system 32 determines the pose of BCS with respect to the desired coordinate system (e.g., patient tracker) from the location of the tracker 52 on the hand-held portion 16 and a tracker 54, 56 on the desired coordinate system (e.g., patient anatomy).

[0255] Once the instrument controller 28 has the pose of the hand-held portion 16 in the desired coordinate system, the instrument controller 28 may then control the plurality of actuators 21, 22, 23. In one implementation, the instrument controller 28 may determine a commanded pose of the tool 20 based on the current pose of the hand-held portion 16 and based on a position and/or orientation of a planned virtual object, subject as a target plane. The instrument computes a pose (a commanded pose) of TCP with respect to BCS that results in the TCP being on the desired plane or aligned with the planned virtual object. This commanded pose may optionally be computed using the virtual

constraints (guide constraints, joint centering constraints, joint limit constraints, workspace constraints). The instrument controller 28 may convert the commanded pose to a commanded position for each of the plurality of actuators 21, 22, 23 using inverse kinematics, then send command instructions to the actuators 21, 22, 23 to move to a commanded position, thereby changing the pose of the tool support 18 and tool 20 relative to the hand-held portion.

[0256] As can be seen in Figures 17A-17E, the control system determines the movements of the instrument and the energization of the drive motor M based on particular conditions and parameters. Starting at Figure 17D, one or more trackers 54, 56 are placed on a patient's anatomy (e.g. femur, tibia) and one or more trackers 52 are placed on the instrument 14. The localizer 44 captures the position of each the trackers 52, 54, 56, and processes the position information into a common coordinate system (Figure 17B). From the localizer 44, the data is then passed to the clinical application 190 and constraint generator 384.

[0257] The clinical application 190 is used to calculate registration and planning transforms used by the control system to command the tool. In Figure 17A, the clinical application receives the pose information of the device tracker 52 and the patient tracker(s) 54, 56 from the localizer 44. The clinical application 190 may also use the localizer data relating to the pointer tracker PT, device tracker 52 and patient tracker 54, 56 to calculate device command transforms based on the handpiece setup and registration, bone registration, implant planning, and bone preparation.

[0258] Within the clinical application 190, the tool tracker 52 and pointer tracker PT information is processed with hand piece setup and registration information to create tool tracker-to-TCP (tool tracker-to-TCP) transform. This may be computed by combining results of two registration steps: 1) registration of the tool support 18 to the tool tracker 52, and 2) registration of the tool support 18 to the tool (TCP). The resulting tool tracker-to-TCP transform (i.e., the instrument registration result) is then forwarded to the constraint generator 384. The position information from the localizer 44 is used with the bone registration data to calculate a bone-to-patient tracker transform and then inverts to yield a patient tracker-to-bone transform, associating the location of the patient tracker with the bone. Utilizing one or more of the user interfaces UI, the user may adjust the size and positioning of the desired implant with respect to an on-screen bone model to allow the Clinical Application to create a bone-to-implant transform based on the location of the bone relative to the planned position and/or orientation of the implant. Based on the known geometry and size of the selected implant, the Clinical Application looks up the transform of the planned pose of the implant to a desired one or more

target cutting planes TP, an implant-to-target-plane transform or a desired one or more target trajectories. A virtual boundary may also be calculated based on the selected implant. The patient tracker-to-bone transforms and the bone to implant transform (B-to-IM) are combined to yield a patient tracker 54, 56 to implant pose transformation (patient tracker-to-IM), which is a combined result of bone registration and implant planning, which is forwarded to the constraint generator 384. The IM to TP transform may be used to generate the guide constraint and the boundary may be used to generate a boundary constraint (if used) with the boundary generator. The boundary information may also be sent to the drive command handler 192.

[0259] Three transforms are utilized to ultimately determine the hand-held portion to localizer transform: a) a hand-held portion to TCP transform, the forward kinematic result received from the motion controller 188; b) a tool support to TCP transform, the tool registration result received from the clinical application 190; and c) a tool tracker to localizer transform received from the localizer 44. A localizer to patient tracker(s) transform(s) may also be received from the localizer 44. Then, a hand-held portion to patient tracker transform may be computed based on: a) a hand-held portion to localizer transform; and b) a localizer to patient tracker(s) transform. It should be appreciated that the tool tracker coordinate system and the tool support coordinate system may be used interchangeable with one another as the pose of the tool support may be fixed relative to the TCP with a known, calibrated, and/or registered transform.

[0260] As noted above, the constraint generator 384 receives the location data of the patient tracker(s) 54, 56, and device trackers from the localizer, the registration and planning transforms from the clinical application 190, and additional data inputs from the behavior controller 186 and the motion controller 188, including the motion constraint handler 390 (described further below) in order to compute the guide constraints and/or the optional boundary constraint(s). The constraint generator 384 processes the received data to create a set of constraints to be solved in order to compute a commanded pose for the tool 20. As noted above, the guide constraints are virtual constraints that are defined to yield the virtual forces and torques employed in the virtual simulation that move the tool 20 to the target state. Once the constraint generator 384 determines the set of active constraints to be solved, that information is transferred to the behavior controller 186.

[0261] The behavior controller 186 computes data that indicates the next commanded position and/or orientation (e.g., pose) for the tool 20. In some examples, the behavior controller 186 computes the next commanded pose based on solving the set of constraints and performing a virtual simulation.

Output from the motion constrain handler 390 of the motion controller 188 may feed as inputs into the behavior controller 186 to determine the next commanded position and/or orientation for the tool 20. As can be seen in Figure 17B, the behavior controller 186 processes various virtual constraints to determine the commanded pose. The constraint solver 189 takes in constraints generated by the motion constraint handler 390 of the motion controller 188 such as joint limit constraints and joint centering constraints, as well as workspace constraints and kinematic motion constraints. The constraint solver 189 also takes in constraints from the constraint generator 384 such as guide constraints and boundary constraints from the boundary handler 385. The constraint solver 189 further receives inertial and damping forces which are processed by the behavior controller 186 and added back into the constraint solver 189. Once these constraints are added into the constraint solver 189, the constraint solver 189 generates a constraint force, which is then summed with all virtual forces, such as the inertial and damping forces, and, optionally, an external force. The total virtual force is then processed with virtual forward dynamics. The pose and velocity output from the virtual forward dynamics is then sent to compute the inertial and damping forces within the behavior controller 186, and also forwarded as a commanded pose and a velocity command of the tool support (hand-held portion-to-TCP) into the motion controller 188. The commanded pose (hand-held portion-to-TCP) is also sent back to the constraint generator 384 for use in generating the constraints.

[0262] The motion controller 188 controls the motion of the tool support 18, and specifically the TCP coordinate system. The motion controller 188 receives data defining the next commanded pose from the behavior controller 186. Based on the data, the motion controller 188 determines the next position of each of the actuators (e.g., via inverse kinematics and Jacobian calculators) so that the tool support can assume the pose relative to the hand-held portion as commanded by the behavior controller 186, e.g., at the commanded pose. In other words, the motion controller 188 processes the commanded pose of the tool support relative to the hand-held portion, which may be defined in Cartesian coordinates, into commanded joint positions of the plurality of actuators 21, 22, 23 so that the instrument controller 28 can command the actuators accordingly. In one version, the motion controller 188 regulates the position of the tool support with respect to the hand-held portion and continually adjusts the torque that each actuator 21, 22, 23 outputs to, as closely as possible, ensure that the actuators 21, 22, 23 move the tool support 18 relative to the hand-held portion 16 such that the commanded pose can be reached.

[0263] Once the hand-held portion-to-TCP relationship enters the motion constraint handler 390 of the motion controller 188, the hand-held portion-to-TCP relationship is used to compute workspace constraints and kinematic motion constraints. These constraints are computed in the Cartesian coordinate system of the commanded pose – using the relationship between the hand-held portion and the TCP. Once the workspace constraints and kinematic motion constraints are calculated, the data from the motion constraint handler 390 is forwarded back to into the behavior controller 186 and into the constraint solver 384.

[0264] The hand-held portion-to-TCP data is also transformed with an inverse kinematics calculation. After the inverse kinematic modification is performed resulting in a set of commanded joint positions, the data is further processed to compute joint limit constraints and joint centering constraints. These constraints are computed in joint space. The joint limit constraint may be calculated based on the previous commanded joint position or measured joint position of each actuator, a constraint Jacobian J_p , which maps the one-dimensional joint limit constraint to a coordinate system employed for the virtual simulation (e.g., between the motion of the joint and the virtual mass coordinate system VM); and one or more limit positions. The joint centering constraint is calculated based on a constraint Jacobian J_p , which maps the one-dimensional joint centering constraint to a coordinate system employed for the virtual simulation (e.g., between the motion of the joint and the virtual mass coordinate system VM), a previous commanded joint position or measured joint position, and a joint centering position. Once the joint limit constraints and joint centering constraints are calculated, the data is sent back to the constraint solver 189 in the behavior controller 186.

[0265] Further, the inverse kinematic data transformation creates a commanded joint position (Joint Pos Cmd) and a joint velocity command (Joint Vel Cmd) for each of the actuators and sends the processed data to the joint position-velocity controllers (one for each actuator) and to the drive command handler 192 to be processed to determine a joint travel velocity override.

[0266] The motion controller 188 sends the commanded position of each actuator to the drive command handler 192, which may compare the one or more commanded or measured positions of each actuator and the respective joint thresholds to determine whether an override to the drive motor M is necessary (see box identified as joint position velocity override) in the drive command handler 192. In other words, as the control system 60 determines the commanded position for each actuator to move the TCP to the target pose, the control system 60 may control activation of the drive motor M based on one or more positions of the plurality of actuators. The one or more actuator positions may

be based on the commanded joint position of at least one actuator, a measured position of at least one actuator, a previous commanded position of at least one actuator, a previous measured position of at least one actuator, or combinations thereof. In one example, the drive motor M is controlled based on a commanded position of at least one of the actuators 21, 22, 23. The commanded joint position of the at least one actuator 21, 22, 23 is compared with an actuator motor override limit of the at least one actuator 21, 22, 23. The motor override limit may be a value, or a series of values defining the outer bounds of a range. Although this example demonstrates monitoring one actuator, the control system may monitor the commanded position and the actuator motor override limits of each actuator 21, 22, 23. The upper limit and the lower of the actuator motor override limit may be values corresponding to the position of the actuator relative to the operational range of each actuator. The upper limit may correspond to a maximum allowed traveled in a first direction, and the lower limit may correspond to a maximum allowed travel in a second, opposite direction before the drive motor parameter will be adjusted. More specifically, the control system 60 controls a motor parameter of the drive motor M at a first value and a second value based on whether the commanded joint position would keep the actuator position between the upper limit and lower limit of the motor override limits. The control system 60 may control one or more motor parameters of the drive motor M, the one or more motor parameters may be a speed, a torque, an operation time, a current, or a combination thereof. In one example, the motor parameter controlled by the control system 60 is the motor speed, the first value being zero (drive motor M is off) and the second value being greater than zero (drive motor M is on). The control system 60 switches the motor parameter between the first and second values based on the commanded position of the actuator 21, 22, 23. When the commanded position of the actuator 21, 22, 23 places the actuator within the upper limit and lower limit of the motor override limits, the control system 60 may command the second value of the drive motor parameter, allowing the drive motor M to be actuated and/or continue to be energized. When the commanded actuator position is between the lower and upper motor override limits, a joint velocity command override is not modified

[0267] In some examples, the drive motor override may be implemented as a lookup table or function that is evaluated based on the actuator position (P) data received. For the example of the joint position velocity override, this would allow the speed of the drive motor to get ramped down proportionally as the joint position approaches its motor override limit. In some examples, there may be no modification when the actuator position is within the lower and upper motor override limits. In other examples, proportional ramp down of drive motor M speed when one or more of the actuators

21, 22, 23 are at a position between 80% travel to 95% travel range, and may be fully disabled above 95% travel, which may provide a continual and gradual feedback to the user that the tool 20 is approaching the operational limits (the lower and upper motor override thresholds). In such an implementation, there may be a plurality of lower motor override thresholds and a plurality of upper motor override threshold, each threshold corresponding to a motor parameter (such as a motor speed). In some cases, the drive motor M speed may not be reduced to zero completely, but rather to a fixed lower speed, allowing the surgeon to be alerted but allowing a determination as to whether to proceed at the surgeon's discretion. When the commanded position of the actuator 21, 22, 23 places the actuator outside of the upper limit and lower limit of the motor override limit, the control system 60 may command the first value of the drive motor parameter, preventing the drive motor M from being actuated and/or continuing to be energized. The motor override limits for each actuator may be different than the joint thresholds for each actuator described above. For example, the motor override limits may define a narrower range than a range defined the joint thresholds, and the range of the motor override limits may be wholly within the joint threshold range.

[0268] The joint position velocity controllers 194 are used to process the data from the motion controller 188 and process the commanded joint position command (Joint Pos Cmd) and the joint velocity command (Joint Vel Cmd) to determine a joint torque command (Joint Torque Cmd) for each of the actuators. The calculation of the joint torque command may be done through a closed-loop control algorithm, such as PID control. The joint torque command is sent into the surgical instrument where each of the current controllers corresponding to each actuator interprets the joint torque command into a current. The current controller then selectively applies voltage as needed to drive the commanded current to each actuator motor causing each actuator to move the tool support towards a commanded position. The applied torque (or current) may cause each of the actuators to move and accelerate in the corresponding direction. The amount of travel and the speed the actuators move/accelerate may depend on the mechanical load, friction, other outside factors, or a combination thereof. By monitoring each of the actuators position feedback over time, the commanded torque (current) is adjusted by the position-velocity controller so that the commanded position of each actuator is tracked closely. As the actuator motors are adjusting the tool support, each motor encoder is collecting rotational and/or positional data for each rotor and sending the joint position data back to the current controller. The current controller then processes the joint position data of each actuator into a joint velocity measurement (Joint Vel Meas) and a joint position measurement (Joint Pos Meas)

and sends the joint velocity measurement data and the joint position measurement data through the joint position-velocity controller to the motion controller 188. The motion controller 188 then transforms the joint position and velocity measurement data of each actuator with forward kinematics to generate pose and velocity relationships between the TCP and the hand-held portion 16. The hand-held portion-to-TCP relationships are then sent into the constraint generators 384 so that they can utilize this data for generation of the various virtual constraints.

[0269] In addition, with reference to Figure 31 the joint velocity measurement and the joint position measurement may be used in the PID control loops. For example, PID loop may compute an error between the joint commanded position and the joint measured position, which may be used with a PID loop to control the joint commanded velocity. The commanded velocity of the joint may be compared versus the joint measured velocity to determine an error. That error may be used in a PID loop to control the commanded current. The commanded current may be compared versus the measured current to determine an error. That error may be used in a PID loop to output a commanded joint voltage.

[0270] The drive command handler 192 is a part of the control system which calculates and determines particular parameters for controlling the drive motor M (Figure 17C). The drive command handler 192 receives input command signals from one or more input devices to actuate the drive motor M. As can be seen in Figure 17E, one example of an input device is a trigger on the hand-held portion of the instrument. Another example, also displayed in Figure 17E is a foot switch. In another example, the drive command handler has a trigger source select, which may be used to multiplex between multiple user input devices (such as a button, a trigger, and a foot switch). In some examples, the trigger source select only evaluates a change in trigger source when both input devices are inactive, and then evaluates which input device becomes active first. The selected input device may then determines the active trigger percentage. In other examples, potentially one input device may have priority over the other. When one or more of the input devices are actuated, a command signal is sent to the drive command handler 192 which then analyzes the percentage which the input device was actuated (e.g. how far the trigger was squeezed by a user). The drive command handler 192 analyzes the command percentage with the maximum allowed velocity output from the bone preparation portion of the clinical application and modifies the command signal according to the data received.

[0271] The drive command handler 192 may also utilize results from the collision detection performed within constraint generator 384 or other component of the control system. In the illustrated

configuration, the constraint generator 384 compares the position and/or orientation of the tool to a boundary. Specifically, as described previously, collision detection determines whether the tool is violating the boundary by more than a threshold amount. Further, the collision detection step processes this location information to determine a boundary velocity override signal. As mentioned above, any number of suitable boundaries may be used for this collision detection step, such as the distal or lateral boundaries. The boundary may also be implemented as a distance between the tool and a reference location on bone. Based on this comparison, the instrument controller 28 may alter a motor parameter, which may be used to slow or stop the drive motor M.

[0272] In this example, a separate global inside/outside check, using techniques such as ray casting or a voxel lookup to determine whether the tool 20 is completely beyond the boundary. It should be appreciated that the drive motor control relative to the boundary may use the penetration depth computed above, for the case that the tool is in contact with the boundary, to determine if any part of the blade is penetrating by more than a threshold amount.) In examples in which the tool 20 is modeled with discrete geometric primitives (e.g., spheres), the in/out check will evaluate whether any of these spheres are located beyond the boundary. Once the control system 60 evaluates whether the tool 20 is beyond the boundary, the constraints may be generated and the tool support pose may be updated in a manner to prevent the tool from violating the boundary. However, if the user continues to move the tool beyond the boundary after the joint limits are reached, moves the hand-held portion 16 too quickly, or the bone moves too quickly, or proceeds beyond the boundary in an uncontrolled DOF of the tool 20, then the boundary may be violated. In this instance, the global in/out check may fail, and the drive motor M may be turned off or altered as described previously.

[0273] In addition to the boundary velocity override and the joint position velocity override functions, the command signal is then sent through to determine whether the error handling override conditions are met (whether the commands are within expected ranges for normal processing). If the error handling conditions are also met, a drive velocity command is sent from the drive command handler 192 to the drive velocity controller.

[0274] It should be appreciated that the boundary velocity override (controlling the speed of the driver motor based on the boundary), the joint position velocity override (controlling the speed of the driver motor based on the actuator position, and the error handling override may all be active simultaneously, and each provide a partial override. For example, the boundary velocity override might reduce the speed by 10%, i.e., multiple the input by 0.9 and then the next block might reduce

the speed further by 20%, i.e., multiple its (already reduced) input by 0.8 in that case the resulting output speed is $0.9 \times 0.8 = 0.72$ times the original requested speed command. In other words, the override multiplier (gain from input to output) applied by each block is not dependent on what the other override blocks determined. There may be other ways to combine the multiple override sources in addition to this (cascaded multiplication) approach, such as using only the most restrictive override, etc.

[0275] The drive velocity controller processes the drive velocity command signal and determines a drive torque command which is sent to the current controller in the handpiece. The current controller converts this drive torque command to a commanded current and selectively applies voltage as needed to drive the commanded current to the drive motor M, causing the tool to operate (e.g., cut). The drive motor encoder monitors the actuation of the drive motor sending an encoder signal relating to the operation of the drive motor back through the current controller in the instrument. The current controller transforms the encoder data into a drive velocity measurement and sends the transformed feedback data into the drive velocity controller.

[0276] As shown in Figures 17A-17C, two inputs into the constraint generator 384 comprise the current state (localizer data, kinematic data) and the target state (cutting planes relative to a localized tracker). The constraint generator 384 obtains the target state for the tool 20 and generates one or more guide constraints based on the target state and the current state of the hand-held portion. The current state may be defined based upon the previous commanded pose CP, since the previous commanded pose CP correlates to the current pose of the tool 20. The target state may be defined in the anatomical coordinate system, anatomy tracker coordinate system, or the like, and transformed to a common coordinate system with the current state. Other inputs into the constraint generator 384 comprise the configuration and tuning parameters for the guide constraints. The constraint generator 384 defines the one or more guide constraints based on the relationship between the current state and the target state and the configuration and tuning parameters. The guide constraints are output from the constraint generator 384 into the constraint solver 189.

[0277] Various virtual constraints may be fed into the constraint solver 189, including, but not limited to, the guide constraints, joint limit constraints, joint centering constraints, kinematic motion constraints, boundary constraints, and other inputs such as external sensed forces. These constraints may be turned on/off by the control system 60. For example, in some cases, there may be neither joint centering constraints nor boundary constraints being generated. Similarly, there may be no guide

constraints being generated in some instances, and in certain modes of operation. All of the virtual constraints employed in the behavior control 186 may affect movement of the tool 20.

[0278] The constraint solver 189 calculates the constraint force F_c to be virtually applied to the tool 20 in the virtual simulator 388 based on the virtual constraints fed into the constraint solver 189. When the guide constraint is active, the constraint force F_c comprises components of force and/or torque adapted to move the tool 20 toward the target state from the current state based on the one or more virtual constraints. In cases where only the guide constraints are input into the constraint solver 189, the constraint force F_c can be considered to be the virtual force computed to satisfy the guide constraints. However, when other constraints are employed, such as the boundary constraint, the joint centering constraint, an/or the joint limit constraint, the constraint solver 189 is ultimately tasked with providing, as closely as possible, a solution for the constraint force F_c that satisfies all of the constraints based on their respective tuning parameters, and thus other constraints may also influence the magnitude/direction of the constraint force F_c .

[0279] 189 In order to solve for F_p , as described below, the equation shown in Figure 26 is converted into a matrix equation where each row represents a single, one-dimensional constraint. The constraint data is placed in the constraint equation, along with other information known by the constraint solver 189, such as the external force $F_{c_{ext}}$, (if applied) a damping force $F_{damping}$, an inertial force $F_{inertial}$, the virtual mass matrix M , a virtual mass velocity V_{cg1} , and the time step Δt (e.g., 125 microseconds). The resulting F_p is a force vector expressed in a constraint space, in which each component of F_p is a scalar constraint force or torque acting along or about the constraint direction corresponding to that row of the constraint equation.

[0280] The virtual mass matrix M combines 3 x 3 mass and inertia matrices. The damping and inertial forces $F_{damping}$ and $F_{inertial}$ are calculated by the virtual simulator 388 based on the virtual mass velocity V_{cg1} (e.g., the velocity of the virtual mass coordinate system VM) output by the virtual simulator 388 in a prior time step. The virtual mass velocity V_{cg1} is a 6-DOF velocity vector comprising linear and angular velocity components. The damping force $F_{damping}$ is a 6-DOF force/torque vector computed as a function of the virtual mass velocity V_{cg1} and a damping coefficient matrix (linear and rotational coefficients may not be equal). Damping is applied to the virtual mass to improve its stability. The inertial force $F_{inertial}$ is also a 6-DOF force/torque vector computed as a function of the virtual mass velocity V_{cg1} and the virtual mass matrix M . The damping and inertial

forces, F_{damping} and F_{inertial} , can be determined in the manner described in U.S. Patent No. 9,566,122 to Bowling et al., hereby incorporated herein by reference.

[0281] The constraint solver 189 may be configured with any suitable algorithmic instructions (e.g., an iterative constraint solver, Projected Gauss-Seidel solver, etc.) to solve this system of constraint equations in order to provide a solution satisfying the system of equations (e.g., satisfying the various constraints). In some cases, all constraints may not simultaneously be met. For example, in the case where motion is over-constrained by the various constraints, the constraint solver 189 will essentially find a ‘best fit’ solution given the relative stiffness/damping of the various constraints. The constraint solver 189 solves the system of equations and ultimately outputs the constraint force F_c .

[0282] When a Projected Gauss-Seidel solver is employed, the constraint solver 189 constructs A and b matrices based on the constraints, uses Projected Gauss-Seidel to solve the system of equations to determine the resulting force vector F_p , takes the output of Projected Gauss-Seidel and transforms it from constraint space to the virtual mass coordinate system VM using the aggregate constraint Jacobian J_p for the full set of constraints. For example, using the equation $F_c = J_p^T F_p$, wherein F_c is the constraint force, in which the aggregate action of the components of F_p is converted to a force/torque vector F_c applied to the virtual mass coordinate system VM .

[0283] Methods of using Project Gauss-Seidel to solve a system of equations for multiple constraints is shown, for example, in “Constraint based physics solver” by Marijn Tamis and Giuseppe Maggiore, dated June 15, 2015 (v1.02), which can be found at http://www.mft-spirit.nl/files/MTamis_ConstraintBasedPhysicsSolver.pdf, or in “Comparison between Projected Gauss-Seidel and Sequential Impulse Solvers for Real-Time Physics Simulations,” by Marijn Tamis, dated July 1, 2015 (v1.01), which can be found at http://www.mft-spirit.nl/files/MTamis_PGS_SI_Comparison.pdf, both of which are hereby incorporated herein by reference in their entirety.

[0284] The Projected Gauss-Seidel method addresses Linear Complementarity Problems (LCP). Inequality associated with LCP arises since some constraint types (e.g., one-sided constraints, such as the boundary constraints, joint limit constraints, and workspace limit constraints) can only push (apply force) in one direction, e.g., positive constraint force. If the calculated force for such a constraint is negative (or, more broadly, outside its allowed range) for a given iteration of the constraint solver 189, which is invalid, the given constraint must be pruned (or alternately limited/capped at its upper or lower allowed value) and the remaining constraints solved, until a suitable result (i.e.,

convergence) is found. In this manner, the constraint solver 189 determines the active set of constraints for a given time step, and then solves for their values. Other constraint types can apply forces in both positive and negative directions, e.g., two-sided constraints. Such constraints include the guide constraints, joint centering constraints, and kinematic motion constraints. Such two-sided constraints, when enabled, are usually active and not pruned/limited during the constraint solver 189 iterations.

[0285] The constraint force F_c calculated by the constraint solver 189 comprises three components of force along x, y, z axes of the VM coordinate system and three components of torque about the x, y, z axes of the VM coordinate system. The virtual simulator 388 utilizes the constraint force F_c , along with the external force $F_{c\text{ext}}$ (if used), the damping force F_{damping} , and the inertial force F_{inertial} (all of which may comprise six components of force/torque), in its virtual simulation. In some cases, these components of force/torque are first transformed into a common coordinate system (e.g., the virtual mass coordinate system VM) and then summed to define a total force F_T . The resulting 6-DOF force (i.e., force and torque) is applied to the virtual rigid body and the resulting motion is calculated by the virtual simulator 388. The virtual simulator 388 thus acts to effectively simulate how the various constraints, among other things (e.g. external forces), affects motion of the virtual rigid body. The virtual simulator 388 performs forward dynamics to calculate the resulting 6-DOF pose and velocity of the virtual rigid body based on the given total force F_T being applied to the virtual rigid body. In one example, the virtual simulator 388 comprises a physics engine, which is executable software stored in a non-transitory memory of any one or more of the aforementioned controllers 28, 36 and implemented by the control system 60.

[0286] For the virtual simulation, the virtual simulator 388 models the tool 20 as the virtual rigid body in the virtual mass coordinate system VM with the origin of the virtual mass coordinate system VM being located at the center of mass of the virtual rigid body, and with the coordinate axes being aligned with the principal axes of the virtual rigid body. The virtual rigid body is a dynamic object and a rigid body representation of the tool 20 for purposes of the virtual simulation. The virtual rigid body is free to move according to six degrees of freedom (6-DOF) in Cartesian space according to the virtual simulation. The virtual simulation may be processed computationally without visual or graphical representations. Thus, it is not required that the virtual simulation display dynamics of the virtual rigid body. In other words, the virtual rigid body need not be modeled within a graphics

application executed on a processing unit. The virtual rigid body may exist only for the virtual simulation.

[0287] The virtual rigid body and its properties (mass, inertia matrix, center of mass, principal axes, etc.) define how the tool 20 will move in response to applied forces and torques (e.g., from the total force F_T , which optionally incorporates forces and torques applied by the user with virtual forces and torques). It governs how the tool 20 will move (e.g., accelerate in translation and rotation) in response to present conditions. By adjusting the properties of the virtual rigid body, the control system 60 can adjust how the tool 20 reacts. It may be desirable to have the properties of the virtual rigid body modeled to be reasonably close to the actual properties of the tool 20, for as realistic motion as possible, but that is not required. For control stability reasons (given the finite acceleration of the actuator assembly, control latencies, etc.), the virtual mass and inertia may be modeled to be somewhat higher than that of the instrument.

[0288] The virtual rigid body may correspond to components, which may be on or within the tool 20. Additionally, or alternatively, the virtual rigid body may extend, in part, beyond the physical tool 20. The virtual rigid body may take into account the tool 20 with the tool support 18 or may take into account the tool 20 without the tool support 18. Furthermore, the virtual rigid body may be based on the TCP. In one example, the center of mass of the virtual rigid body is understood to be the point around which the virtual rigid body would rotate if a virtual force is applied to another point of the virtual rigid body and the virtual rigid body were otherwise unconstrained. The center of mass of the virtual rigid body may be close to, but need not be the same as, the actual center of mass of the tool 20. The center of mass of the virtual rigid body can be determined empirically. Once the tool 20 is attached to the tool support 18, the position of the center of mass can be reset to accommodate the preferences of the individual practitioners. In some examples in which no external force is used in the virtual simulation, the precise numerical properties and units of the virtual mass (e.g., center of mass location, mass, inertia matrix) are somewhat arbitrary, because for such a case the virtual simulation does not interact with physical forces measured from the real-world. In such cases, for computational simplicity, it may be desired to simply place the virtual mass at the TCP, setting the mass to 1 and setting the inertia matrix to identity. Other options are possible as well, however, to allow for tuning of the constraints in physically sensible units, more realistic properties for the virtual rigid body may be set if desired. In either case, the constraint tuning parameters should take into account the properties chosen for the virtual mass.

[0289] The virtual simulator 388 effectively simulates rigid body dynamics of the tool 20 by virtually applying forces and/or torques on the virtual rigid body in the virtual simulation, i.e., by virtually applying the components of force and torque from the total force F_T on the center of mass of the virtual rigid body in the virtual mass coordinate system VM. Thus, the forces/torques virtually applied to the virtual rigid body may comprise forces/torques associated with the external force F_{cgext} (e.g., which may be based on input from the one or more sensors), the damping force $F_{damping}$, the inertial force $F_{inertial}$, and/or the forces/torques from the constraint force F_c associated with the various constraints (by virtue of being embodied in the constraint force F_c).

[0290] Rigid body Jacobians can be used to transform velocities and forces from one coordinate system (reference frame) to another on the same virtual rigid body and may be employed here to transform the forces and torques of F_{ext} to the virtual mass coordinate system VM as well (e.g., to yield F_{cgext} used in the constraint equation). The virtual simulator 388 then internally calculates the damping force $F_{damping}$ and the inertial force $F_{inertial}$, and also to output the damping force $F_{damping}$ and the inertial force $F_{inertial}$ for use by the constraint solver 189 in its system of equations in the next time step. If used, the F_{ext} may also be fed to the constraint solver. These forces may be summed together, and then input with the constraint force, to get a total calculation.

[0291] A virtual forward dynamics algorithm, as shown in Figures 26 and 27, may be employed in the virtual simulation to simulate the motion of the virtual rigid body as it would move upon application of the total force F_T . Effectively, the virtual forward dynamics algorithm solves the equation $F=ma$ (or $a=F/m$) in 6-DOF and integrates the acceleration to yield velocity, which is then integrated again to determine a new pose, with details shown in Figure 27. The control system 60 inputs the virtual forces and/or torques (e.g., the total force F_T) into the virtual simulator 388 and these virtual forces and/or torques are applied to the virtual rigid body at the center of mass (e.g., the CG) in the virtual simulation 388 when the virtual rigid body is in the initial pose with the initial velocity. The virtual rigid body is moved to a final pose having a different state (i.e., position and/or orientation) and with a final velocity within Cartesian space in response to the control system 60 satisfying the inputted virtual forces and/or torques. The next commanded pose CP to be sent to the instrument controller 28 is based on the final pose calculated by the virtual simulator 388. Thus, the virtual simulator 388 operates to determine the next commanded pose CP by simulating the effects of applying the total force F_T on the virtual rigid body using virtual forward dynamics as shown in Figure 27.

[0292] While the virtual simulation is conducted in six degrees of freedom, it should be noted that the actuator assembly may be controllable in fewer than six degrees of freedom, such as three degrees of freedom. In such a situation, the kinematic motion constraint may be used to constrain the uncontrolled degrees of freedom such that the simulation may be meaningfully conducted (i.e., to keep the VM coordinate system aligned to the physical tool).

[0293] Velocity limits may be imposed on the virtual rigid body in the simulation. In some cases, the velocity limits may be set high so that they generally don't affect the simulation, or they may be set at any desired value. In some cases, velocity limits may be implemented by computing the damping force to be applied to the virtual rigid body in a non-linear way, in which the amount of damping increases significantly above a threshold velocity. The virtual rigid body is in an initial pose (initial state) and has an initial velocity at commencement of each iteration of the virtual simulation (e.g., at each time step/interval dt). The initial pose and initial velocity may be defined as the final pose and the final velocity output by the virtual simulator 388 in the previous time step.

[0294] Thereafter, the virtual simulator 388 calculates and outputs the next commanded pose CP based on its virtual simulation. In this implementation, the control system 60 is configured to command the tool support 18 to move the tool 20 based on the commanded pose CP, which ideally causes movement of the tool 20 in a manner that guides the tool 20 to the target state and in accordance with other virtual constraints.

[0295] Figure 28 summarizes various steps carried out by the behavior control 186. These include steps performed by the constraint solver 189 and the virtual simulator 388 as described above. In step 350, the external force F_{ext} is (optionally) calculated based on readings taken from the force/torque sensor S or alternate sensing method. In step 352, the constraints data associated with the various virtual constraints are fed into the constraint solver 189.

[0296] In steps 354-358, rigid body calculations are carried out by the virtual simulator 388 to determine the inverse mass matrix M^{-1} , the inertial force $F_{inertial}$, and the damping force $F_{damping}$ of the virtual rigid body. In steps 360-364, the constraint solver 189 utilizes the output from the rigid body calculations performed in steps 354-358 and the constraints data provided in step 352 to perform the constraint force calculations previously described to ultimately yield the constraint force F_c . In step 366, the constraint force F_c is summed with the external force F_{ext} transformed to the virtual mass coordinate system VM ($F_{c_{gext}}$), the damping force $F_{damping}$, and the inertial force $F_{inertial}$ to yield the total force F_T . In step 368, the total force F_T is applied to the virtual rigid body in the virtual simulation

conducted by the virtual simulator 388 to determine a new pose and velocity of the virtual rigid body in step 370, and ultimately to transform the new pose and velocity to the TCP in step 372. The new commanded pose and velocity (V_{TCP}) are output by the virtual simulator 388 in step 374.

KNEE APPLICATION

[0297] Figures 29A-29D illustrate an application of the guide. In this example, the control system 60 has activated the guide constraint and the virtual constraints to in place the TCP of the tool 20 at a target pose. The localizer LCLZ detects a tool tracker 52 and the patient tracker 54. The localizer LCLZ monitors the position of the instrument 14 relative to the target anatomy. The clinical application uses the implant plan to determine the target cutting plane TP relative to the patient tracker 54 and provides this to the control system. Once the particular cut is selected, receives location information from the localizer LCLZ relating to the position of the instrument 14 and the patient anatomy. The control system 60 further uses the device tracker and patient tracker locations and the encoder data of the joint position of each actuator 21, 22, 23 to determine the pose of the base coordinate system BCS of the hand-held portion 16 with respect to the patient tracker 54. The control system 60 determines a set of virtual constraints which will move the tool support 18 and the saw blade 20, 380 towards the target pose. In this instance, the control system will attempt to place the saw blade 20, 380 onto the target pose TP while balancing a plurality of virtual forces to keep the actuators 21, 22, 23 within their operating limits. The control system 60 generates several guide constraints based on the location data. The guide constraints are employed in three degrees of freedom to guide the tool support 18 toward the target state, i.e. a position constraints along the z axes of the target coordinate system TF to guide the origin of the guided coordinate system GF to the origin of the target coordinate system TF and two orientation constraints about the x, and y axes of the target coordinate system TF to guide the z axis of the guided coordinate system GF to align with the z axis of the target coordinate system TF. Additionally, joint limit constraints are computed, typically having a much larger stiffness than the guide constraints, to ensure that the actuators 21, 22, 23 are not commanded to a position outside the limits of travel.

[0298] In some cases, only one, two, three, four, or more guide constraints may be used. More than six guide constraints could also be used, such as when more than one guide constraint is defined for any degree of freedom. The progression from Figure 29A through 29D shows the guided coordinate system GF aligning with the target coordinate system TF in three degrees of freedom for

illustration purposes. In the progression from Figure 29A through Figure 29D, the TCP of the tool 20 is shown moving toward the target state (in this case, toward the origin of the target coordinate system TF). At each time step, the constraint force F_c is calculated and takes into account the guide constraints, the joint limit constraints, the workspace constraints, the joint centering constraints the kinematic motion constraints, or a combination thereof to effectively guide the tool support 18 into applying forces and torques that ideally move the saw blade 380 toward the target state. In one example, only the guide constraint and joint limit constraint are active when the TCP is at this position. The virtual constraints may be dynamic by virtue of their tuning parameters being adjusted at each time step. For example, some of the virtual constraints may have stronger spring and/or damping properties and other virtual constraints may have weaker spring and/or damping properties the closer the current state gets to the target state (e.g., the closer the guided coordinate system GF gets to the target coordinate system TF). In one instance, the guide constraint has stronger spring and/or damping properties the closer the current state gets to the target state. Thus, the constraint force F_c (which may comprise components of force and/or torque that correlate to the stronger spring and/or damping properties) may increase in magnitude as the guided coordinate system GF approaches the target coordinate system TF.

[0299] In one example, the control system determines a target pose of the saw blade 380 in at least one degree of freedom with respect to a known coordinate system, such as the patient anatomy. The control system 60 also determines the pose of the hand-held portion 16 within the same coordinate system, i.e., relative to the patient anatomy. The control system 60 then processes the location information of the saw blade 380 and the hand-held portion 16 to calculate one or more guide constraints based on the target pose of the saw blade 380 and the pose of the hand-held portion 16. Once the one or more guide constraints are generated, a constraint force is calculated by the control system 60 and adapted to move a virtual saw blade within a virtual simulation. The virtual simulation simulates dynamics of the virtual saw blade based on the constraint force and calculates a commanded pose based on the virtual simulation. The commanded pose is output from the virtual simulation and used to determine a commanded joint position of each of the actuators 21, 22, 23. The control system 60 forwarding the commanded joint position signal to each actuator 21, 22, 23, energizing the actuator 21, 22, 23 to move the tool support 18 and the saw blade 380 to the target pose.

[0300] Figures 18-20 illustrate another example of the guide being used in placing the tool 20 (e.g., with the saw blade 380) at the target state. In this example, the control system 60 has activated

the guide and the associated guide constraints to assist the user in placing the TCP of the tool 20 at a target pose in at least one degree of freedom located relative to a desired cutting plane 73c for a total knee replacement, which includes placing the TCP at a target orientation and elevation that aligns the tool 20 with the desired cutting plane 73c. In this case, the origin of the target coordinate system TF is offset from the desired cutting plane 73c by at least half the blade thickness to account for blade thickness. At least one guide constraint is calculated and employed in at least one degree of freedom to move the tool support 18 towards the target pose. In one example, three guide constraints are employed in three degrees of freedom to move the saw blade to the target state, i.e., one position constraint along the z axis of the target coordinate system TF and two orientation constraints about the x, y axes of the target coordinate system TF.

[0301] At each time step, the constraint force F_c is calculated and takes into account the active virtual constraints (e.g. guide constraints, joint limit constraints, joint centering constraints, kinematic motion constraints, and/or workspace constraints), to effectively guide the tool support 18 into applying forces and torques that ideally move the saw blade 380 toward the target state. The virtual constraints may be dynamic by virtue of their tuning parameters being adjusted at each time step. Referring to Figure 20, for example, the guide constraints may have greater stiffness the closer the current state gets to the target state (e.g., the closer the guided coordinate system GF gets to the target coordinate system TF in the x-axis direction – see the x distance). Thus, referring to Figure 20, the stiffness associated with the tuning parameters for the guide constraints may increase in magnitude as the x distance decreases.

[0302] Alignment of the tool 20 to the desired cutting plane assists the user in making precise cuts along the femur and/or tibia to make room for a total knee implant, for example. Referring back to Figure 13, guide constraints could be used to align the tool 20 to each of the five target cutting planes TP, 73a-73e that may be required for the femur. The guide constraints can similarly remain active during the cutting process so that the blade is maintained at the target state.

[0303] The guide constraint computation may also be used to control the tool drive motor M. Because the control system 60 has already computed the guide constraints for purposes of determining a commanded joint position for each of the plurality of actuators 21, 22, 23, such an implementation may ease computational load of the control system 60. As described above, the guide constraint includes at least one guide constraint error and at least one guide constraint error measured along each

guide constraint direction. The control system 60 may control the tool drive motor M based on the guide constraint direction and the guide constraint error.

[0304] As described above, each guide constraint has a direction defined along or about the x, y, or z-axis of the target coordinate system. The control system 60 may utilize fewer than six guide constraints to control the tool drive motor M. For example, the control system 60 may use exactly two, or only three guide constraints to control the tool drive motor M. This may include one guide constraint about a translation degree of freedom, such as elevation, and two guide constraints about orientation degrees of freedom, such as pitch and roll.

[0305] The control system 60 may utilize the guide constraint error in the chosen degrees of freedom to control the tool drive motor M, referred to above as the constraint distance Δd , which is how close the guided frame GF is to the target frame TF along or about the applicable constraint direction defined by TF and which dictates whether the constraint is being violated.

[0306] The control system 60 may control the drive motor M based on a guide constraint error threshold in addition to the guide constraint error. The control system 60 may utilize a different guide constraint error threshold for each degree of freedom, such as a different guide constraint error threshold for the elevation degree of freedom from the guide constraint error threshold for the pitch and/or roll degrees of freedom. This may express a greater tolerance for deviations from the target plane TP and/or axis in various degrees of freedom.

[0307] The guide constraint error threshold may be expressed as a permissive error range of values. In some examples, the permissive error range may be from -0.5 to 0.5 (translation guide constraint error threshold) or from -5 to 5 (orientation guide constraint error threshold). In some implementations, the error range is asymmetrical, such as asymmetrical about a median value of 0. For example, the translation guide constraint error threshold may be -0.3 to 0.5. This may express more tolerance in one of the directions of the selected degree of freedom than the other. For example, for the elevation degree of freedom, the range of -0.3 to 0.5 may express a greater tolerance for errors above the target cut plane than below the cut plane (into bone). However, other asymmetrical ranges are also contemplated.

[0308] The control system 60 may change the motor parameter of the drive motor M when the guide constraint error or other error value exceeds the threshold or range for any of the selected degrees of freedom, such as slow the drive motor M or stop the drive motor M. This situation can occur when

the saw blade 20 deviates from the target plane TP in one or more degrees of freedom by more than a tolerated amount (angle and/or distance) beyond the set threshold, such as the set error ranges.

[0309] The control system 60 may further consider the status of the drive motor M when considering the appropriate guide constraint error threshold, such as guide constraint error range. For example, the control system 60 may select a first guide constraint error range when the drive motor M has a permissive state and the second guide constraint error range when the drive motor M is in a restricted state, with the first guide constraint error range differing from the second guide constraint error range. The control system 60 may ultimately control the tool drive motor M based on the selected guide constraint error threshold and the guide constraint error. This can prevent the drive motor from turning on and off repeatedly when the error value is close to the outer bounds of the error range.

[0310] While it is described above that the guide constraint error may be used to control the drive motor, alternative error computations may also be used. In such cases, the control system would be configured to determine an error value between the state of the surgical tool and the target pose of the surgical tool in at least one degree of freedom and control the tool drive motor based on an error threshold and the error value in a manner similar as described for the guide constraint based drive motor control. Such an implementation may be useful when the robotic system does not utilize guide constraints for controlling the hand-held robotic system. As described above with respect to the guide constraint control of the drive motor, the control system may be configured to determine error values in multiple degrees of freedom based on the target pose of the surgical tool and the pose of the surgical tool, such as the previously commanded pose of the surgical tool and error thresholds for each of those degrees of freedom. The control system may slow or stop the motor when the error value exceeds the threshold in a first degree of freedom or the control system may slow or stop the motor when the error value exceeds a different threshold in a second degree of freedom. Similar to the error computation for the guide constraint, the control may utilize the motor status in selecting the appropriate error range for controlling the drive motor based on the error between the state of the surgical tool and the target pose of the surgical tool

[0311] This approach to controlling the drive motor can have several advantages. Principally, this control approach provides greater flexibility to the user as long as the blade remains close to the plane, i.e., within an error threshold in one or more degrees of freedom, the user is able to position the hand-held portion in more orientations/positions relative to the blade/tool platform without causing the drive motor to shut off. This tolerated flexibility provides the user with the ability to position the

hand-held portion in numerous ways to continue cutting despite obstructions that the user's hand might encounter, such as patient tracker(s), retractors, or portions of patient anatomy that may be in the way. Furthermore, because the control system continues to control the plurality of actuators while in saw blade is in the cut, the system provides for accurate cutting of the target plane. Because portions of the bone to be cut may be relatively softer and because the tool, such as the saw blade, may flex during the cutting process, the control system's continued control of the plurality of actuators while the blade is in the cut can prevent error from accumulating as the blade proceeds through the cut due to numerous minor corrections of the blade position and/or orientation during this flexing and/or soft bone resection. Furthermore, by continuing to control the plurality of actuators to align to the target plane while the blade is in the cut, the control system prevents errors when the bone section is ultimately removed, as the blade would no longer be constrained by presence of the section of the bone that was previously constraining the blade in place.

[0312] By controlling the drive motor based on the error between the target pose and the pose of the tool, as opposed to controlling the drive motor based on the actuator positions, the control system will continue to allow resection when one or more of the actuators have reached the range of motion limits, i.e., joint limits. More particular, in this implementation of the control system, the control system permits the saw drive motor to run when the position of one or more of the plurality of actuators is coincident with a joint limit for that actuator. This results in the ability to continue running of the drive motor even if the actuators are no longer able to reposition the saw blade in one or more degrees of freedom thus allowing the instrument to continue to resect bone regardless of the position of the hand-held portion. The control system will shut off, however, if the blade veers too far from the plane in one or more degrees of freedom as described above. This implementation results in permitting the saw drive motor to run when a position of one or more of the plurality of actuators is coincident with a joint limit for that actuator. The step of permitting may be further defined as permitting the saw drive motor to run without consideration of the position of one or more of the plurality of actuators. The position of the actuator may be a measured position, a commanded position, a previous measured position, or a previous commanded position. Other control logic may apply in combination with this control approach to control the tool drive motor, such as control the tool drive motor when the saw blade violates a distal boundary, controlling the tool drive motor when the tool is away from the bone, and/or controlling the tool drive motor based on the error and error thresholds in one or more degrees of freedom.

[0313] Further, the virtual boundary 184 may be optionally employed to control the operation of the drive motor M. As the drive motor M is actuated, oscillating the saw blade 380 during the cut, the actuation signal to the drive motor M may be stopped and/or changed based on the state of the saw blade 380 relative to the virtual boundary 184. The virtual boundary 184 may prevent the user from cutting the patient anatomy incorrectly, particularly preventing the saw blade 380 from cutting a portion of the patient anatomy that is not intended to be affected (e.g. ligaments). Looking at Figure 18, as the saw blade 380 is advanced along target cut plane, one or more motor parameters of the drive motor are controlled. In one example, the motor parameter is a speed of the drive motor (and thus the cutting speed of the saw blade 380) based on the location of the saw blade 380 relative to a virtual boundary 184. However, other motor parameters are contemplated, such as torque, operation time, current, acceleration, or a combination thereof. The virtual boundary, such as that shown in Figure 13, corresponds with an end point of a particular cut, depending on which cut the user is making to fit the implant to the patient anatomy. In other examples, the virtual boundary 184 may be a mesh, a point, a plane, or a combination thereof as described above. The virtual boundary may be based on the anatomy, the planned implant, image data, etc. As the saw blade 380 progresses through the patient anatomy, the location data of the instrument 14 relative to the patient tracker, and subsequently the target plane is updated in real time. When the saw blade 380 reaches the virtual boundary 184, the motor parameter (speed of the motor) may be set to 0 or reduced. When the motor parameter has a value of 0, the drive motor M is shut off so the user does not cut past the virtual boundary 184.

[0314] In another example, the drive motor M is controlled based on the pose of the tool relative to the boundary 184 in at least one uncontrolled degree of freedom which the actuators 21, 22, 23 are incapable of adjusting the tool support 18. A controlled degree of freedom is a movement direction which is controlled by the actuator assembly 400 and is based on the arrangement of the actuators 21, 22, 23. In some configurations, the arrangement of the actuator assembly 400 may provide for six controlled degrees of freedom, five controlled degrees of freedom, four controlled degrees of freedom, three controlled degrees of freedom, or at least one controlled degree of freedom. For example, the actuator assembly 400 is arranged to control pitch (Figures 3A-3C), roll (Figures 4A-4C), and z-axis translation (elevation relative to the hand-held portion 16 – Figures 5A-5C). The instrument 14 is able to adjust the tool support 18 and the tool 20 relative to the hand-held portion in these movement directions. When a degree of freedom is uncontrolled, the actuators, 21, 22, 23 are incapable of adjusting in that particular direction. For example, in some configurations, the yaw of the

tool support 18 cannot be adjusted since the actuators 21, 22, 23 are arranged to control pitch, roll, and z-axis translation (elevation relative to the hand-held portion 16). As another example, when the actuators 21, 22, 23 are arranged to control pitch, roll, and z-axis translation (elevation relative to the hand-held portion 16), the linear translation along a longitudinal axis (x translation) is an uncontrolled degree of freedom since the actuator assembly 400 does not control translational movement along the longitudinal axis. In this way, the virtual boundaries may be established to control the boundary in those degrees of freedom that are uncontrollable by the actuator assembly, such as x-axis translation. This may be configured as the boundary for controlling depth of the tool described above. As mentioned, the boundary for controlling depth may be generally perpendicular to the target plane. As such, while this boundary may not be used for controlling the plurality of actuators, the boundary may be used for controlling the drive motor. In some examples, both the uncontrolled degrees of freedom and the controlled degrees of freedom may be used as an in/out check to control the drive motor M. The control system 60 may use the controlled degrees of freedom as a secondary error mitigation, such as when the saw blade does not stay on plane due to an error or malfunction. In this example, both the controlled degrees of freedom and uncontrolled degrees of freedom, along with the boundary, control the energization of the drive motor M. Thus, while the actuator assembly would not function to prevent the tool from being positioned by a user beyond this boundary, the control system 60 would prevent the user from actuating the drive motor M when the TCP was indicative of the distal end of the tool being beyond the boundary. It should be appreciated that the virtual boundaries may also be used to control the drive motor in the controlled degrees of freedom.

[0315] The control system may compute the appropriate motion parameter to move the tool support relative to the hand-held portion. The motion parameter may be computed based on the commanded pose. Based on this determined motion parameter, the control system may compute the appropriate signal to send to each of the plurality of actuators. In one example, the control system may output a joint velocity command based on the determined motion parameter and the commanded position for that actuator. It should be appreciated that in some examples, the tool support moves relative to the hand-held portion at a variable velocity. The motion of each actuator may be based on the force applied to the tool support by each of the plurality of actuators.

[0316] Referring to Figures 30A and 30B, once a kerf is established, the control system 60 may automatically adjust values of one or more motion parameters of the tool 20 relative to the hand-held portion 16 with the one or more virtual constraints as the user cuts the target cut plane which is

associated with anatomy of a patient (e.g. bone to be cut). In one example, while approaching the cut, the guide constraints enabled and the tool is automatically aligning to the target plane. The control system 60 maintains the active state of the guide constraints as the tool contacts bone and enters beyond a specified depth boundary, distance parameter relative to a reference location/reference coordinate system. At the moment the tool passes the specified depth, the control system 60 senses the current positions of the actuators, and sets the current position of the actuators as the new joint centering positions, enabling the joint centering constraints and disabling the guide constraints. This causes the system to enter a free hand mode with the 'saw blade to handle' alignment frozen as it was when it first entered and proceeded into the bone. The user may continue cutting, but the control system 60 does not automatically correct for alignment while the blade remains within the bone beyond the specified depth because the guide constraints are inactive. Even though the instrument is frozen in a fixed pose, the blade still stays approximately on the cutting plane, since the slots in the bone formed by the initial cut is mechanically constraining the motion of the blade to stay in that cut plane. As the user starts to move the blade towards the bone exit, the system returns to a mode where the guide constraints are active once the depth is less than the earlier configured value (e.g., the pose of the blade relative to a reference location/reference coordinate system is at a threshold value). At this point, joint centering constraints are disabled and the guide constraint is reenabled to resume aligning the blade to the plane. By disabling the guide constraints and enabling joint centering constraints, the tool is prevented or less likely to bind the blade within bone. Once a certain depth of cut is reached in hard bone, the blade is effectively constrained on the top and bottom by bone slot formed during the initial cut entry. If the accuracy of the blade alignment has any small errors (due to calibration inaccuracy, blade skiving or diving due to compliance, etc.), the robotic system may be prevented from restoring the blade to the cutting plane since the top and bottom of the blade do not remove bone, and the already machined surface of the bone may block the blade from returning to the cut plane. As a result, the control system is limited in restoring the alignment of the blade when deep into the bone, and, if binding occurs, cause the user to have to apply increased force to complete the cut. Such an approach may ensure that the guide constraints are enabled upon bone approach (within a threshold value of a reference location/reference coordinate system) and first cut entry, to ensure that the initial cut entry performed in the bone is as accurate as possible, and to continue this alignment until a certain depth is reached sufficient to mechanically constrain further (deeper) motion of the blade.

[0317] In this example, the guide constraints may have a virtual force approaching 0, meaning that the guide constraints may be shut off and/or their tuning parameters adjusted since the saw blade is established within the kerf (Figure 30B). The joint centering constraints, which direct the rotors 148 towards a center point on the leadscrew of each actuator 21, 22, 23, may also be shut off and/or have the centering positions re-set to the current position of the actuators 21, 22, 23 when a specified cutting depth is reached, while the saw blade 380 cuts into the patient anatomy (Figure 30B). The control system 60 may change the rate of adjustment of the actuators 21, 22, 23 automatically based on a distance parameter (e.g. direction, magnitude) determined from the pose of the tool 20 (e.g., from the TCP) relative to the reference location associated with the bone. The pose of the tool 20 may be maintained while the guidance array 200 directs the user to move the hand-held portion 16 to maintain or correct to the desired plane. It is contemplated that the joint limit constraints and/or the workspace constraints may remain active even after the kerf is established.

[0318] With reference to Figure 30A, one exemplary way of controlling the plurality of actuators is described. When the position of the saw blade (TCP) is spaced from the reference location associated with bone (RL) with a first distance parameter (DP1), the instrument is controlled such that the tool support is moved relative to the handheld portion, e.g., a motion parameter with a magnitude greater than zero is used. This is because the kerf has not yet been sufficiently established. In this instance, the guide constraints have a value greater than zero and have a high stiffness value, actively adjusting and commanding the tool support 18 to stay on the desired cutting plane.

[0319] With reference to Figure 30B, when the position of the saw blade (TCP) is spaced from the reference location associated with bone (RL) with a second distance parameter (DP2), the instrument is controlled such that a motion parameter has a lower magnitude, such as a magnitude of zero is utilized or the movement of the tool support relative to the hand-held portion is otherwise stopped. This is because the kerf has been sufficiently established. In this instance, the guide constraint force value is reduced or inactive and the joint centering constraint force value is also reduced and/or disabled. Alternately, the joint centering constraint may be re-set to hold this fixed relative pose between the tool support 18 and hand-held portion 16.

[0320] Once the tool 20 establishes the kerf, the instrument controller 28 may set the value of the motion parameter to a lower magnitude or zero and/or control the state of the virtual constraints, to stop or reduce the actuators 21, 22, 23 from adjusting the tool support 18 relative to the hand-held portion 16. Once the tool 20 has established a cut path within the bone, the tool 20 may flex and move

off course a small amount (e.g. skive), pushing back onto the hand-held portion 16 as the control system attempts to adjust for the error. The user may perceive this force as a push-back, since a saw blade is not typically designed to remove hard bone in the direction necessary to adjust pitch and/or roll, for example, once embedded into bone. The sense of “push-back” or “fighting” the hand-held portion is created by the instrument controller 28 controlling the actuators 21, 22, 23 while the tool 20 is in the cutting slot 290. Thus, the only movement that is caused by controlling the actuators to move towards the desired plane is movement of the hand-held portion 16. This means that the instrument controller 28 may cause forces to be applied to the hand-held portion 16, which are then transferred to a user’s hand. These forces may result in fatigue and/or discomfort during the cutting process. By changing the motion parameter, the tool 20 may provide less resistance further in the cut. A user may find that by setting the motion parameter value to 0 or by otherwise stopping the movement of the hand-held portion relative to the tool support allows the cut to be finished without struggling against the hand-held portion 16 when the tool 20 is within the cutting slot 290, the cutting slot 290 serving as a natural cut guide (See Figures 30A-30B). More particularly, the instrument controller 28 may actively change values of the motion parameter relating to force, velocity, acceleration, or other states of each of the virtual constraints, so that the further the tool 20 enters into the target anatomy, the actuators 21, 22, 23 adjust towards the target plane with a relatively lower force, velocity and/or acceleration than when the cut was first initiated, eventually stopping actuator movement when the tool 20 is mid cut, utilizing the path cut into the bone as the guide. In some examples, an external force/torque sensor may allow the user’s applied force to be considered in the virtual simulation. In such cases, the stiffness of the guide constraint may be reduced once the saw blade is sufficiently into the bone and the kerf is established. With reduced guide stiffness and sensing of the user applied force, the constraint solver may find an equilibrium in which the user is able to balance out the guide forces with a small magnitude of applied force. This may give the user haptic feedback indicating to the user that the tool 20 is not perfectly aligned on plane, but at a magnitude such that it does not create fatigue or cause the hand-held portion 16 to push back excessively to the point that the joint limits of the actuators 21, 22, 23 are exhausted.

[0321] One exemplary way to control the motion parameter of the tool support is by changing the state of the of the virtual constraints as mentioned above. For example, changing the state of the one or more virtual constraints may include activating the one or more of the virtual constraints, deactivating one or more of the virtual constraints, or changing the tuning parameter of one or more

of the virtual constraints (i.e., increasing or decreasing the tuning parameters of the virtual constraint). The joint limit constraints may remain active when the guide constraints or the joint centering constraints are inactive. In other words, by changing the states of the virtual constraints, the tool support 18 may move with a greater force, velocity and/or acceleration when the cut is first begun (high stiffness for the guide constraints), then the force, velocity and/or acceleration after the tool 20 has progressed a threshold distance into bone relative to the reference location (low stiffness for the guide constraint constraints). While stopping the actuators 21, 22, 23 from adjusting the tool support 18 was described in terms of setting the motion parameter to zero, it should be appreciated that the actuators 21, 22, 23 may be stopped with other suitable control logic, such as by stopping the motion control aspect of the algorithm or otherwise freezing the position of the plurality of actuators 21, 22, 23. As described above, the states of the virtual constraints may be controlled based on monitoring any suitable variable, such as the state of the tool, such as the saw blade, relative to a reference location on the patient, such as bone. Alternatively, the states of the virtual constraints may be controlled based on the state of the tool relative to a virtual object, such as the target plane. Figure 11 illustrates processes carried out to execute the guide, such as when the tool 20 comprises the saw blade 380. In this version, the behavior controller 186 comprises the guide handler which may be synonymous with the constraint generator 384, the constraint solver 189, and the virtual simulator 388. The behavior control 186 further comprises the boundary handler 389 to optionally generate virtual boundary constraints based on the one or more virtual boundaries 184 generated by the boundary generator 182. The guide handler/constraint generator 384, constraint solver 189, virtual simulator 388, and boundary handler 389 each comprise executable software stored in a non-transitory memory of any one or more of the aforementioned controllers and implemented by the control system 60.

[0322] In addition, in another exemplary configuration, based on the magnitude of sensed external force, either from a force/torque sensor or derived via actuator motor currents, the control system may trigger the joint centering mode. This allows the control system to detect ‘fighting’ and go into ‘fixed handle’/free-hand/unguided mode when detected. Such a method would also typically be utilized in conjunction with drive motor boundary control, to ensure that the saw blade stays sufficiently on plane when the handle is fixed (and hopefully being guided by the kerf) to allow the cut to continue. If the boundary gets violated (due to the saw blade drifting too far off plane), either feedback could be given to the user through a suitable indicator or the drive motor parameter may be adjusted (e.g., the drive motor may be turned off).

[0323] The guide constraint may be used to align a drill bit or bur and/or tap for a screw, anchor, or other fastener when other types of tools are coupled to the tool platform. The guide constraint may be used to align an impactor with a desired trajectory for impacting an acetabular cup implant to seat the acetabular cup implant into a prepared acetabulum. The guide constraint may be used to align tools used to seat other types of implants. The guide constraint may be used for aligning/guiding tools for placing k-wires, cannula, trocars, retractors, and the like.

[0324] Input devices, such as on the various user interfaces UI may be employed to switch/activate the various modes or states of operation of the instrument 14. For example, the UI of the tool 20 may have an input device (button, touch sensor, gesture input, foot pedal, trigger, etc.) that can be actuated to activate the one or more virtual constraints so that the constraint force F_c comprises components of force and torque associated with moving the tool. The control system 60 may be configured to automatically change states of the virtual constraints in certain situations. The control system 60 may also first prompt the user before automatically continuing in another mode or state, such as by providing selectable prompts on one or more of the displays 38 to continue in the selected mode.

[0325] Further, it is contemplated that the instrument controller 28, the user, or both may switch the instrument 14 between modes and behaviors and states manually through an input device, automatically based on navigation data, actuator data, drive motor data, or a combination thereof. In some cases, the user may determine that the instrument should be held in a particular pose (the tool support relative to the hand-held portion) and override the instrument controller with an input device.

[0326] In some configurations, the surface of an anatomical feature to be cut (e.g. surface of a bone) may serve as a reference point, a virtual boundary, or both causing the instrument controller 28 to change operation modes or behavior of: (i) the instrument 14; (ii) one or more actuators 21, 22, 23; (iii) guidance array 200; (iv) one or more visual indicators 201, 202, 203; (v) or a combination thereof.

[0327] In some examples, the instrument controller 28 may utilize one or more inputs to determine one or more outputs. The one or more inputs may include a pose of the bone determined by a patient tracker 54, 56, such as the reference location, the tool center point TCP of the tool 20 or pose of the TCP coordinate system by a tool tracker 52 on the tool support 18, the pose of the hand-held portion 16, a commanded pose of the tool 20, a distance parameter, actuator information (such as a commanded or measured position and/or pose, a current position and/or pose, a past position and/or pose, etc.), an input signal from a footswitch, trigger, or touch-screen, or a combination thereof. The

one or more outputs of the instrument controller 28 may include changing a motor parameter of the drive motor M, adjusting a motion parameter (e.g. changing the state or tuning parameter of a constraint) of the tool support 18, including changing force, acceleration or velocity, may turn off the boundary control, hold or freeze the tool 20 and tool support 18 relative to the hand-held portion 16, activate a homing mode, or a combination thereof. Any suitable combination of inputs may be utilized with any suitable output.

[0328] The current state of the tool 20 and/or current state of one or more actuators relative to the target state and/or relative to the surgical site or relative to the commanded position may be output by the navigation system 32 and represented on the displays 38 via graphical representations of the tool 20, tool support 18, hand-held portion 16, actuators 21, 22, 23, target state, virtual boundaries 184, and/or the surgical site, e.g., the femur F, tibia T, pelvis, vertebral body, or other anatomy. These graphical representations may update in real-time so that the user is able to visualize their movement relative to the target state, virtual boundaries 184, anatomy, etc. For example, the graphical representations of the tool 20 and anatomy may move on the displays 38 in real-time with actual movement of the tool 20 by the tool support 18 and actual movement of the anatomy.

[0329] It should be understood that the combination of position and orientation of an object is referred to as the pose of the object. Throughout this disclosure, it is contemplated that the term pose may be replaced by position and/or orientation in one or more degrees of freedom and vice-versa to achieve suitable alternatives of the concepts described herein. In other words, any use of the term pose can be replaced with position and any use of the term position may be replaced with pose.

[0330] The methods in accordance with the present teachings is for example a computer implemented method. For example, all the steps or merely some of the steps (i.e. less than the total number of steps) of the method in accordance with the present teachings can be executed by a computer (for example, at least one computer). A configuration of the computer implemented method is a use of the computer for performing a data processing method. Further, in the present teachings, the methods disclosed herein comprise executing, on at least one processor of at least one computer (for example at least one computer being part of the navigation system), the following exemplary steps which are executed by the at least one processor.

[0331] The computer for example comprises at least one processor and for example at least one memory in order to (technically) process the data, for example electronically and/or optically. The processor being for example made of a substance or composition which is a semiconductor, for

example at least partly n- and/or p-doped semiconductor, for example at least one of II-, III-, IV-, V-, VI-semiconductor material, for example (doped) silicon and/or gallium arsenide. The calculating or determining steps described are for example performed by a computer. Determining steps or calculating steps are for example steps of determining data within the framework of the technical method, for example within the framework of a program. A computer is for example any kind of data processing device, for example electronic data processing device. A computer can be a device which is generally thought of as such, for example desktop PCs, notebooks, netbooks, etc., but can also be any programmable apparatus, such as for example a mobile phone or an embedded processor. A computer can for example comprise a system (network) of "sub-computers", wherein each sub-computer represents a computer in its own right. The term "computer" includes a cloud computer, for example a cloud server. The term computer includes a server resource. The term "cloud computer" includes a cloud computer system which for example comprises a system of at least one cloud computer and for example a plurality of operatively interconnected cloud computers such as a server farm. Such a cloud computer is preferably connected to a wide area network such as the world wide web (WWW) and located in a so-called cloud of computers which are all connected to the world wide web. Such an infrastructure is used for "cloud computing", which describes computation, software, data access and storage services which do not require the end user to know the physical location and/or configuration of the computer delivering a specific service. For example, the term "cloud" is used in this respect as a metaphor for the Internet (world wide web). For example, the cloud provides computing infrastructure as a service (IaaS). The cloud computer can function as a virtual host for an operating system and/or data processing application which is used to execute the method of the present teachings. The cloud computer is for example an elastic compute cloud (EC2) as provided by Amazon Web Services™. A computer for example comprises interfaces in order to receive or output data and/or perform an analogue-to-digital conversion. For example, the present teachings may not involve or in particular comprise or encompass an invasive step which would represent a substantial physical interference with the body requiring professional medical expertise to be carried out and entailing a substantial health risk even when carried out with the required professional care and expertise. The data are for example data which represent physical properties and/or which are generated from technical signals. The technical signals are for example generated by means of (technical) detection devices (such as for example devices for detecting marker devices) and/or (technical) analytical devices (such as for example devices for performing (medical) imaging methods), wherein the

technical signals are for example electrical or optical signals. The technical signals for example represent the data received or outputted by the computer. The computer is preferably operatively coupled to a display device which allows information outputted by the computer to be displayed, for example to a user. One example of a display device is a virtual reality device or an augmented reality device (also referred to as virtual reality glasses or augmented reality glasses) Another example of a display device would be a standard computer monitor comprising for example a liquid crystal display operatively coupled to the computer for receiving display control data from the computer for generating signals used to display image information content on the display device.

[0332] The present teachings also relate to a computer program comprising instructions which, when on the program is executed by a computer, cause the computer to carry out the method or methods, for example, the steps of the method or methods, described herein and/or to a computer-readable storage medium (for example, a non-transitory computer-readable storage medium) on which the program is stored and/or to a computer comprising said program storage medium and/or to a (physical, for example electrical, for example technically generated) signal wave, for example a digital signal wave, such as an electromagnetic carrier wave carrying information which represents the program, for example the aforementioned program, which for example comprises code means which are adapted to perform any or all of the method steps described herein. The signal wave is in one example a data carrier signal carrying the aforementioned computer program. The present teachings also relate to a computer comprising at least one processor and/or the aforementioned computer-readable storage medium and for example a memory, wherein the program is executed by the processor.

[0333] Within the framework of the present teachings, computer program elements can be embodied by hardware and/or software (this includes firmware, resident software, micro-code, etc.). Within the framework of the present teachings, computer program elements can take the form of a computer program product which can be embodied by a computer-usable, for example computer-readable data storage medium comprising computer-usable, for example computer-readable program instructions, "code" or a "computer program" embodied in said data storage medium for use on or in connection with the instruction executing system. Such a system can be a computer; a computer can be a data processing device comprising means for executing the computer program elements and/or the program in accordance with the present teachings, for example a data processing device comprising a digital processor (central processing unit or CPU) which executes the computer program elements,

and optionally a volatile memory (for example a random access memory or RAM) for storing data used for and/or produced by executing the computer program elements. Within the framework of the present teachings, a computer-usable, for example computer-readable data storage medium can be any data storage medium which can include, store, communicate, propagate or transport the program for use on or in connection with the instruction-executing system, apparatus or device. The computer-usable, for example computer-readable data storage medium can for example be, but is not limited to, an electronic, magnetic, optical, electromagnetic, infrared or semiconductor system, apparatus or device or a medium of propagation such as for example the Internet.

[0334] In this application, including the definitions below, the term “controller” may be replaced with the term “circuit.” The term “controller” may refer to, be part of, or include: an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor circuit (shared, dedicated, or group) that executes code; a memory circuit (shared, dedicated, or group) that stores code executed by the processor circuit; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

[0335] The controller(s) may include one or more interface circuits. In some examples, the interface circuit(s) may implement wired or wireless interfaces that connect to a local area network (LAN) or a wireless personal area network (WPAN). Examples of a LAN are Institute of Electrical and Electronics Engineers (IEEE) Standard 802.11-2016 (also known as the WIFI wireless networking standard) and IEEE Standard 802.3-2015 (also known as the ETHERNET wired networking standard). Examples of a WPAN are the BLUETOOTH wireless networking standard from the Bluetooth Special Interest Group and IEEE Standard 802.15.4.

[0336] The controller may communicate with other controllers using the interface circuit(s). Although the controller may be depicted in the present disclosure as logically communicating directly with other controllers, in various configurations the controller may actually communicate via a communications system. The communications system includes physical and/or virtual networking equipment such as hubs, switches, routers, and gateways. In some configurations, the communications system connects to or traverses a wide area network (WAN) such as the Internet. For example, the communications system may include multiple LANs connected to each other over the Internet or

point-to-point leased lines using technologies including Multiprotocol Label Switching (MPLS) and virtual private networks (VPNs).

[0337] In various configurations, the functionality of the controller may be distributed among multiple controllers that are connected via the communications system. For example, multiple controllers may implement the same functionality distributed by a load balancing system. In a further example, the functionality of the controller may be split between a server (also known as remote, or cloud) controller and a client (or, user) controller.

[0338] Some or all hardware features of a controller may be defined using a language for hardware description, such as IEEE Standard 1364-2005 (commonly called “Verilog”) and IEEE Standard 10182-2008 (commonly called “VHDL”). The hardware description language may be used to manufacture and/or program a hardware circuit. In some configurations, some or all features of a controller may be defined by a language, such as IEEE 1666-2005 (commonly called “SystemC”), that encompasses both code, as described below, and hardware description.

[0339] The various controller programs may be stored on a memory circuit. The term memory circuit is a subset of the term computer-readable medium. The term computer-readable medium, as used herein, does not encompass transitory electrical or electromagnetic signals propagating through a medium (such as on a carrier wave); the term computer-readable medium may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory computer-readable medium are nonvolatile memory circuits (such as a flash memory circuit, an erasable programmable read-only memory circuit, or a mask read-only memory circuit), volatile memory circuits (such as a static random access memory circuit or a dynamic random access memory circuit), magnetic storage media (such as an analog or digital magnetic tape or a hard disk drive), and optical storage media (such as a CD, a DVD, or a Blu-ray Disc).

[0340] The apparatuses and methods described in this application may be partially or fully implemented by a special purpose computer created by configuring a general purpose computer to execute one or more particular functions embodied in computer programs. The functional blocks and flowchart elements described above serve as software specifications, which can be translated into the computer programs by the routine work of a skilled technician or programmer.

[0341] The computer programs include processor-executable instructions that are stored on at least one non-transitory computer-readable medium. The computer programs may also include or rely on stored data. The computer programs may encompass a basic input/output system (BIOS) that

interacts with hardware of the special purpose computer, device drivers that interact with particular devices of the special purpose computer, one or more operating systems, user applications, background services, background applications, etc.

[0342] The computer programs may include: (i) descriptive text to be parsed, such as HTML (hypertext markup language), XML (extensible markup language), or JSON (JavaScript Object Notation), (ii) assembly code, (iii) object code generated from source code by a compiler, (iv) source code for execution by an interpreter, (v) source code for compilation and execution by a just-in-time compiler, etc. As examples only, source code may be written using syntax from languages including C, C++, C#, Objective C, Swift, Haskell, Go, SQL, R, Lisp, Java®, Fortran, Perl, Pascal, Curl, OCaml, JavaScript®, HTML5 (Hypertext Markup Language 5th revision), Ada, ASP (Active Server Pages), PHP (PHP: Hypertext Preprocessor), Scala, Eiffel, Smalltalk, Erlang, Ruby, Flash®, Visual Basic®, Lua, MATLAB, SENSORLINK, and Python®.

[0343] Several embodiments have been described in the foregoing description. However, the embodiments discussed herein are not intended to be exhaustive or limit the present teachings to any particular form. The terminology, which has been used, is intended to be in the nature of words of description rather than of limitation. Many modifications and variations are possible in light of the above teachings and the presentation teachings may be practiced otherwise than as specifically described.

[0344] Referring now to Figures 32-33C, the system may define different spatial regions to specify where guided mode of instrument 14 should be enabled. These spatial regions may be defined in a number of different ways, such as using or more different virtual objects (Figures 33A-33C) or using various distance parameters (Figure 32). In one example, the spatial regions may be specified in a reference coordinate system, where the control system is configured to determine the position and/or orientation of the reference coordinate system relative to the known coordinate system.

[0345] In general, wherein the instrument 14 is far from the patient anatomy, such as far from the knee, guided mode of the instrument should be disabled. In other words, the guide constraint should be deactivated. In instances where the instrument 14 is near the knee (within a given spatial region), the guided mode should be enabled. In other words, the guide constraint should be active.

[0346] Referring now to Figures 33A-33C, one way for the system 10 to determine which region the instrument 14 is in is by monitoring the position of the TCP of the blade 20 relative to the patient anatomy, such as relative to a virtual object 500, 502 defined relative to the patient or relative

to a reference location that is known relative to the patient anatomy. As such, the control system 60 may determine a state of the surgical tool 20 in the known coordinate system. As described above, the state of the TCP of the blade 20 or other surgical tool may be determined based on tracking one of the tool support 18 and/or the hand-held portion, along with CAD data or a blade registration process. In certain instances, the user may position the instrument 14 such that the TCP of the blade 20 or other tool is on the edge of the different spatial regions. There is frequently some deviation in the TCP position, either based on the steadiness of the user's hand and/or the noise in the measurements of the localizer. In this case, the TCP may move inadvertently back and forth between the two different spatial regions, which could cause the instrument to transition between the mode where the instrument 14 is guided and the mode where the instrument 14 is unguided. This would likely be unpleasant to the user since they would feel the motors of the plurality of actuators rapidly engage and disengage, and flutter/chatter on/off as they move between the different spatial regions.

[0347] To rectify one or more of the issues, the control system may be configured to activate the guided mode based on a first relationship criteria between the state of the surgical tool 20 and the reference system and the control system may be configured to deactivate the guided mode based on a second relationship criteria between the state of the surgical tool 20 and the reference coordinate system, where the first and second relationship criteria are different. Alternatively, the control system need not utilize a reference coordinate system, but rather activate and deactivate the guided mode based on relationships between the state of the surgical tool and the patient coordinate system, i.e., one defined relative to a tracker coupled to a portion of the patient's anatomy. The reference coordinate system may also be based on the target pose of the surgical tool.

[0348] In this instance, guided mode may be defined as a mode operable to control the plurality of actuators to align the surgical tool with a virtual object, such as the cutting plane. Guided mode is not limited to use of the guide constraint to align the surgical tool to the virtual object, but guided mode may include activation of the guide constraint in some instances. In some instances, the state of the tool may be characterized as the pose of the surgical tool

[0349] Virtual objects 500, 502, such as a small sphere 500 could be used as a basis to enable the guided mode when the system 60 is in the unguided mode and a somewhat larger sphere 502 may be used as a basis to disable the guided mode when the system 60 is in the guided mode. Thus, the first relationship criteria may be based on the first virtual object 500, and the second relationship may be based on a second virtual object 502. The pose and/or shape of the first virtual object 500 and

second virtual object 502 may be defined with respect to the reference coordinate system. The pose and/or shape of the first virtual object 500 and second virtual object 502 may be different. In other words, referring to Figure 33A, if the user initially has the instrument 14 positioned such that the TCP is outside of the smaller sphere 500, the system will remain in the unguided mode until the TCP enters the smaller sphere 500. Referring to Figure 33B, once the user moves the instrument 14 such that the TCP enters the small sphere 500 or first virtual object, the control system 60 controls the instrument 14 to operate in the guided mode, and automatically changes the spatial definition to the larger sphere 502, or second virtual object. Referring to Figure 33C, where the TCP has not yet exited the larger sphere 502, the system 60 remains in the guided mode until the user positions the instrument 14 such that the TCP exits the larger sphere 502. Often, the user would then perform the cut of the bone (staying generally within the smaller sphere 500), and after completing the cut, move the instrument such that the TCP exits the larger sphere 502, and the control system 60 transitions the instrument 14 to the unguided mode, and then the control system 14 transitions the spatial definition back to the smaller sphere 500 or first virtual object (back to Figure 33A). Then, the system 60 remains in the unguided mode until the TCP once again re-enters the smaller sphere 502. To summarize, the first relationship criteria may be based on the pose of the surgical tool and the first virtual object and the second relationship criteria may be based on the pose of the surgical tool at a second time and based on the second virtual object. These virtual objects may be configured in any number of ways, such as one, two, or three dimensional objects, such as meshes.

[0350] The spatial difference between the regions/virtual objects may be predefined or selectable, based on user preference or for different surgical applications or different cuts within a given procedure. In some exemplary embodiments, the size difference between the spatial regions, such as the outer boundaries of the two virtual objects, may be at least 3, 5, or 10 cm. The spatial difference should be chosen to be large enough to exceed the user caused and noise caused jitter in the TCP position, but small enough not to be overly noticeable by the user. While different size spheres 500, 502 were contemplated in the example, other shapes could be used, such as any suitable polygon.

[0351] Referring now to Figure 32, the different spatial regions may be defined using distance parameters DP3, DP4 as well instead of virtual objects. In such a configuration, the first relationship criteria may be based on determining a first distance parameter DP3 based on the state of the surgical tool 20 and the reference coordinate system or reference location RL and the second relationship criteria is based on a second distance parameter DP4 based on the state of the surgical tool 20 and the

reference coordinate system or reference location, with the first distance parameter DP3 is different from the second distance parameter DP4. The distance parameters DP3, DP4 are often different with distance parameter DP3 being smaller than distance parameter DP4.

[0352] In such an implementation, when the surgical tool 20 has a state that is relatively close to the bone to be cut (the state of the tool results in a distance less than distance parameter DP3), the control system will operate in the guided mode. Once the control system 60 is operating in the guided mode, the control system 60 assess the state of the surgical tool 20 relative to the larger distance parameter, DP4. So long as the distance between the surgical tool 20 and the reference location RL is less than the second distance parameter DP4, the control system will remain in the guided mode. However, once the distance between the surgical tool 20 exceeds the second distance parameter DP4, the control system will enter into the unguided mode, and compare the distance between the tool 20 and the reference location RL against the first distance parameter DP3.

[0353] In another aspect of the control system, the control system may define a range of joint angles/actuator positions in which the drive motor is allowed to run. Once any of the joints/actuators exceed these ranges, the control system will no longer be able to ensure that the tool support and saw blade/cutting tool are aligned with the cutting plane/target pose. Once the joint/actuator travel is used up for at least one of the joints/actuators, the control system loses its ability to robotically align the tool support in one or more degrees of freedom. Thus, the control system may be configured to disable the tool drive motor and the ability of the saw blade or other surgical tool to cut bone. This helps prevent cutting in the wrong location for improved accuracy of the cut/surgical operation. The drive motor turning off also gives the user feedback that they need to just the position of the hand-held portion of the instrument to get the instrument back into its allowed range of motion.

[0354] In one exemplary configuration, the control system may determine an actuator position/joint angle value, whether commanded or measured, past or current. In the case of an actuator basis of computation, an exemplary actuator may move -10 to +10 mm over its full travel range, with 0 mm as its home position. One can think of actuator position as a fraction of its full travel, such that the actuator travel goes from -100% to 0% to +100%. The control system may further define a motor status of the tool drive motor, and control the tool drive motor based on the actuator position/joint angle value and the motor status.

[0355] With reference to Figure 7, the software program 378 may be configured to determine a first actuator/joint threshold based on the motor status, and the control system 60 may control the

tool drive motor M based on the actuator position/joint angle value, the first actuator/joint threshold and the motor status. Furthermore, the control system 60 may be configured to determine a second actuator/joint threshold based on the motor status, and control the tool drive motor M based on the second actuator/joint threshold and the actuator position/joint angle value, wherein the second actuator joint threshold is different than the first actuator joint threshold. For such a system, the first joint/actuator threshold may be set at a range between -80% and +80. In this example, the joint/actuator thresholds encompass only a subset of the full operating range of each actuator so that the tool drive motor M is disabled when the system 60 still has full control to keep the saw blade 20 or other tool on the target plane TP or aligned with a virtual object. In this example, if the measured or commanded joint position/angle exceeds the first joint/actuator threshold range, the control system 60 may control the drive motor M by setting the drive motor M to a restricted state, where the drive motor M is no longer permitted to run. If the joint/actuator thresholds remain static, or the same regardless of drive motor status, a user may have a tendency to hold the hand-held portion 16 such that the joints/actuators are frequently hitting the actuator/joint thresholds, resulting in the tool drive motor M frequently turning on and off. For an optimal user experience, it is desirable that the tool drive motor M turns off as little as possible, letting the user perform the cut without interruption.

[0356] The first actuator/joint threshold may be used when the motor status of the tool drive motor M is in the permissive state, where the drive motor M is permitted to run. The second actuator/joint threshold may be used when the motor status of the tool drive motor M is in the restricted state, where the tool drive motor M is not permitted to run. If the first joint/actuator threshold is a range from -80% to +80% when the drive motor M is in the permissive state, the second joint/actuator threshold may be a range -50% to +50% when the tool drive motor M is in the restricted state.

[0357] When in the permissive state, the tool drive motor M is permitted to run (if the user is depressing the trigger/footswitch/user input (Figure 17C – see R/S) and so long as the measured/commanded actuator positions/joint angles remain within the first threshold. As in the previous example, if any of the joints/actuators have angles/positions that that exceed the first threshold range, the control system 60 sets the drive motor M to the restricted state. As part of the transition to the restricted state based on the motor status changing, the joint/actuator threshold may be updated to the second actuator/joint threshold, which is typically smaller and encompassed within the first actuator/joint threshold/range. The control system 60 continues determining the angles/positions of the joints/actuators relative to the second actuator/joint threshold. The drive motor

M is not set back to the permissive state until all of the measurements of the joints/angles are within the second actuator/joint threshold. Once that happens, the control system 60 again sets the motor status to the permissive state and the tool drive motor becomes re-enabled (i.e., allowed to run again), and the joint/actuator threshold is again changed to the first actuator/joint threshold, which is wider and more useable).

[0358] As described above, the actuator position/joint angle value may be a current measured position, a previous measured position, a commanded position, a current measured joint angle, a previous measured joint angle, a commanded joint angle, or combinations thereof. Similarly, the actuator/joint thresholds may be defined in terms of current measured position, a previous measured position, a commanded position, a current measured joint angle, a previous measured joint angle, a commanded joint angle, or combinations thereof.

[0359] The benefit of using the two different actuator/joint thresholds is that it may prevent the rapid on/off switching of the tool drive motor M, since it is no longer possible to hover right near the edges of the first actuator/joint threshold. Once the status of the drive motor M is set to the restricted state, the user is forced to evaluate their positioning of the hand-held portion 16 more consciously, and align the hand-held portion 16 accurately (within the second, smaller range) in order for the control system 60 to transition the tool drive motor M back to the permissive state. This methodology may result in a slightly longer recovery time after the control system 60 initially places the drive motor M in the restricted state, however, it makes up for that by reducing chances of an immediate and subsequent transition back to the restricted state. This control system 60 implementation may train the user of the proper positioning of the hand-held portion to make inadvertent shut off the drive motor M less likely due to the monitored joint/actuator positions/actuators exceeding the actuator/joint thresholds. This results in less interruptions during the surgical procedure, quicker procedure time, and enhanced user experience.

[0360] Referring now to Figure 34A, an additional example may involve the control system 60 configured to control the drive motor M based on pose of the hand-held portion 16 or the tool support 18, a boundary 601 and a motor status. Boundary 601 can define a volumetric slot/box (having a thickness at least as large as the saw blade, but possibly at least 0.2 to 0.5 more mm more). When the saw blade is sufficiently on plane, the saw blade would be within the slot and the drive motor would be permitted to run. Once the penetration depth of the blade exceeded the boundary 601 by a certain threshold, the control system would stop the drive motor M, i.e., set the drive motor to a

restricted state. Such a method may involve determining a motor status of the drive motor, and selecting an actuator/joint threshold based on the pose of the hand-held portion 16 or the tool support 18, the boundary 601, and the motor status. The control system 60 may also determine a value of the actuators/joints of the actuator assembly, and control the tool drive motor M based on the actuator/joint threshold and the actuator position/joint angle value. In such an example, the control system 60 may determine when to disable the tool drive motor M (i.e., set the drive motor to the restricted state) based on the position and/or orientation of one or more components of the instrument 14, such as the state/pose of the tool 20, the tool support 18, and/or the hand-held portion 20 and use the determined joint/actuator angle/position values to determine when to re-enable the tool drive motor M (i.e., set the tool drive motor to the permissive state). When the control system 60 determines that the drive motor status is in the permissive state, the control system 60 will assess whether the saw blade 20 or tool (or representation thereof) exceeds the boundary 601 by more than a specified amount. In this configuration, the control system 60 uses information from the localizer, such as a pose of tracker 52, 54, to determine the position/orientation, also known as state, of the saw blade 20 with respect to the bone. The control system 60 will change the motor status from the permissive state to the restricted state based on whether the control system 60 determines that any aspect of the blade 20 or tool penetrates the boundary 601 by more than a specified amount (such as 0.25 mm). If the blade penetrates the boundary 601, the control system 60 transitions the drive motor M to the restricted state, which causes the tool drive motor M to turn off.

[0361] At this point, the control system 60 now controls the tool drive motor M based on the determined joint angles/actuator positions and an actuator/joint threshold or range as described above with the previous example. In other words, the control system 60 is configured such that the drive motor M is disabled until all joint angles/actuator positions are within the actuator/joint threshold or range. Once the control system 60 determines that the joint angles/actuator positions are within the actuator/joint threshold range, the control system 60 sets the drive motor status back to the permissive state. Once the drive motor status is set back to permissive state, the control system 60 again controls the drive motor M based on the position of the blade 20 (or other component of the instrument) and the boundary 601. While the actuator/joint thresholds/ranges may vary depending on user preference, in one example, the actuator/joint threshold may be exemplified as a range from -50% to +50%. In this example, the control system 60 may continue to operate in the guided mode, and attempt to perform alignment to the target plane TP to the best of its capabilities (given restrictions in

joint/actuator movement), but the drive motor M is only permitted to run while the saw blade 20 does not exceed the boundary 601 beyond the set amount.

[0362] This exemplary implementation may be more forgiving to a user during bone resection since it is less likely to disable the drive motor M. In this case, only the final position of the blade 20 or other component of the instrument 14 (as measured via localization) is used to disable the drive motor M (transition the drive motor from the permissive state to the restricted state).

[0363] As long as the blade 20 is positioned near the target plane 20 and is not penetrating the boundary 601 by more than the specified threshold, the user is allowed to run the drive motor M. This applies even if the monitored joint angle/actuator position is beyond the actuator/joint threshold(s) described above. This is because it is possible that the blade 20 may remain on the target plane TP even if one or more actuators/joints have reached their thresholds, as it is possible that the user is holding the hand-held portion 16 such that the blade 20 is still on/near the target plane TP even though full robotic alignment is no longer possible. One situation in which this may occur is when the user has cut deep enough, such as greater than 2.5 cm, into the bone such that the unresected bone/kerf is nearly constraining the movement of the blade (such that the blade is forced to stay on the target plane). Once the initial cut has been made and the kerf has been accurately established, the saw blade 20 will tend to stay on that same plane (even with limited robotic alignment). As long as the localization data shows that the blade is cutting on the target plane and is proximal/outside the boundary 601, it is not strictly necessary to disable the tool drive motor M. The result is that the user may be interrupted less frequently with stopping the drive motor M.

[0364] In this configuration, the control system 60 sets the motor status to a restricted state when the saw blade 20 is penetrates the boundary 601. When this motor status is set, the control system 60 then determines the joint angle/actuator position value and controls the drive motor M based on the joint angle/actuator position values and the joint/actuator thresholds. Regardless of the motor status, in this configuration, the control system 60 continues to operate in the guided mode and attempts to align the blade 20 with the target plane TP. When the drive motor status has been set to the restricted state, the user has already been disrupted somewhat, so while this disruption is present, it is also advantageous to ensure that the hand-held portion 16 is aligned with the tool support 18 reasonably well before setting the drive motor M to permissive state again. By ensuring that the hand-held portion 16 is reasonably aligned with the tool support 18 before permitting operation of the drive motor M (by

setting actuator/joint thresholds), the control system 60 reduces the likelihood of any subsequent drive motor M shut offs (or sets to the restricted state).

[0365] It should be appreciated that the posterior protection boundary 600 and the slot boundary 601 may be combined as a single virtual object. In such an implementation, the saw would penetrate the slot-shaped boundary 601 or posterior boundary 600 when the saw blade was no longer sufficiently on plane or if the saw blade went too deep in the posterior aspect of the cut.

[0366] In Figure 34B, in addition to controlling to boundaries 600, 601 as described above, the control system 60 may be further configured to select a first actuator/joint threshold when the surgical tool 20 is outside boundary 602 and select a second actuator joint threshold when the surgical tool is within the boundary 602, with the first actuator/joint threshold being different from the second actuator/joint threshold. The control system 60 may be configured to select the second actuator/joint threshold when the surgical tool 20 is within the boundary 602 and wherein the tool drive motor is in a restricted state. It should be understood that the control system 60 may determine the pose of the boundary in some configurations and control the actuator/joint threshold based on the pose of the boundary 602 or shape of the boundary 602.

[0367] With continued reference to Figure 34A, the control system 60 may be configured, based on the motor status, to select one of a drive motor control criterion and a second drive motor control criterion. The first drive motor control criterion may include the actuator position/joint angle value of at least one actuator or joint of the actuator assembly. The second drive motor control criterion may be based on a boundary 600. The control system 600 may also be configured to drive the tool drive motor 60 based on the selected drive motor control criterion. The control system 60 may select the first drive motor control criterion when the motor status is in the restricted state. The control system 60 may select the second drive motor control criterion when the motor status is in the permissive state. In certain implementations, the first drive motor control criterion includes the actuator position/joint angle value and the actuator/joint threshold. The control system 60 may perform the selection of the first or second drive motor control criterion when the control system 60 determines that the motor status has changed or transitioned. Other control criterion are also contemplated for use for the first or second drive motor control criterion, such as status of guided mode, and/or state of the tool relative to other virtual objects.

[0368] As described above, the control system may control the plurality of actuators such that the blade is aligned with the target pose while the control system is operating in the guided mode. In

certain instances, the instrument 14 may include a plurality of actuators that operate to control the pose of the saw blade 20 in three degrees of freedom, referred to as the controlled degrees of freedom. The additional degrees of freedom that affect the gross positioning of the handpiece are provided by the user. As described above, when performing certain surgical procedures, such as a total knee procedure, it may be desirable for the control system 60 to prevent over resection even while on the cutting plane, e.g., to control the depth of the cut or prevent excessive cutting in the medial or lateral direction (see posterior boundary 600 above shown in Figure 34A). The control system can achieve this control by monitoring the position of the blade (using localization data) and controlling the tool drive motor based on the position of the blade and a boundary, such as disabling the drive motor if the saw blade surpasses or exceeds or is outside/within a defined boundary. This feature can, if desired by the user, help protect soft tissue such as ligaments or tendons. As mentioned above, the boundary may be defined through a variety of techniques, such as geometric primitive, as a plane or a mesh. The boundary could be positioned in a reference coordinate system or projected along an axis. The boundary could also be predefined based on the implant type and size, computed based on pre-operative imaging or specified manually by the surgeon, such as by selecting landmarks or a location on the anatomy with a navigated pointer device.

[0369] Referring now to Figure 35, in a contemplated alternative implementation, two different boundaries 700, 702 may be used instead of one. The control system 60 may determine a motor status of the tool drive motor M; and select the boundary 700, 702 based on the motor status. In this example, at the start of a cut, the saw blade 20 is proximal the boundary or ‘outside’ of the first boundary 700. The first boundary 700 may be a mesh that is implemented as a closed boundary that is designed to provided posterior protection of the anatomy. At the cut progresses, the drive motor M is in the permissive state. As the cut progresses and the user proceeds in removing bone using the saw 20 (with the saw blade 20 being controlled to align with the target plane TP via robotic alignment in the guided mode), the user may ultimately reach the first boundary 700. When the control system 60 determines that the saw blade 20 is penetrating/has reached the first boundary 700, the control system 60 stops the drive motor M by setting the drive motor M to a restricted state. Upon this transition in the motor status, i.e., while the motor status is in the restricted state, the first boundary 700 is replaced with a second boundary 702. In other words, the control system 60 may determine that the motor status is now in the restricted state, and based on this restricted state, select the second boundary 702.

[0370] While the drive motor M is in the restricted state, the drive motor M is disabled, thus preventing the user from cutting any deeper into the bone or soft tissue. The second boundary 702 may encompass a larger volume and/or be more anterior relative to the first boundary 700. The second boundary 702 may encompass the first boundary 700 in instances where the first and second boundaries are volumetric. When the control system 60 determines that the saw blade 20 has exited the second boundary 702 or moved anteriorly of the second boundary 702, the control system 60 again sets the drive motor status to a permissive state. This results in the user needing to move the saw blade 20 away from the bone (in the anterior direction) to reduce the cutting depth, until the saw blade 20 is outside this second boundary 702.

[0371] The second boundary 702 may be located such that the saw blade 20 is still within the outline of the bone, but at smaller depth than the first boundary 700, such as correlated with a position that is 5-10 mm less cutting depth than the first boundary 700. When the drive motor status is set back to the permissive state, the control system 60 again controls the drive motor M based on the first boundary 700. While the control system 60 is described in terms of determining the state or pose of the blade 20 and determining the state or pose of the blade 20/tool relative to the boundaries 700, 702, the control system 60 may control the drive motor M based on other components of the instrument 14, such as the pose of the tool support 16 or hand-held portion 18. It should be appreciated that this implementation may be used with our surgical tools, such as drills, taps, bits, screwdrivers or burs.

[0372] Referring to Figures 36A and 36B, in an alternative configuration, the control system 60 may configure the first and second boundaries in a single dimension, such as considering the position of the saw blade 20/surgical tool along a single axis, e.g., in the depth of cut direction. This one-dimensional depth position value, also referred to as a distance parameter, can then be compared to values/thresholds for the first and second boundaries. The first boundary would be present at a greater depth than the second boundary. For example, the control system may compare a measured distance against a value associated with the first boundary, referred to here as the first distance parameter 800, and set the motor status of the tool drive motor M to a restricted state when the measured distance exceeds the value associated with the first distance parameter 800 (See Figure 36A). An exemplary value for the first boundary might be 15 mm behind a reference location defined at the knee center. Once the drive motor status is in the restricted state, the control system may control the drive motor M based on the second boundary or value associated with the second boundary, referred to here as the second distance parameter 802, which is different from the value associated with the

first distance parameter 800. An exemplary second value might be 10 mm. Once the saw blade 20 is determined to be outside of this second boundary, i.e., once the measured distance associated with the saw blade 20 is lesser than the value associated with the second distance parameter 802, the control system 60 may again set the motor status to the permissive state. When the motor status is changed to the permissive state, the control system 60 may again monitor the position/pose or state of the saw blade 20 with respect to the first distance parameter 800.

[0373] This can be more generally understood as the control system 60 being configured to select a distance parameter 800, 802 based on the motor status, and control the tool drive motor M based on the state of the surgical tool, such as the pose of the surgical tool, in the at least one degree of freedom and the selected distance parameter. The distance parameter may be characterized as a first distance parameter 800, and the control system is configured to select the first distance parameter 800 when the tool drive motor M is in a permissive state, and wherein the control system 60 is configured to select a second distance parameter when the tool drive motor M is in a restricted state, with the first distance parameter 800 and second distance parameter 802 being different values.

[0374] The control system 60 may provide functionality to allow the user to disable the boundaries, such as the boundary to prevent cutting too deep. The boundary may not be necessary for certain surgical techniques. In other cases, a user may want to have the boundary enabled while performing the initial ‘bulk removal’ cutting, but then disable the boundary to allow careful, powered completion of the cut. The user may set the boundary at various poses/positions, such as 1-5 mm before the posterior edge of the bone. So, with the boundary enabled, the control system 60 will protect against over resection, but the boundary may prevent the user from fully completing the cut. One option is to break off the remaining piece of bone and complete the last portion of the cut using a manual instrument. Alternatively, the user may choose to disable the boundary and then very slowly remove the small amount of bone remaining with the instrument 14. For the final removal step with the robotic instrument 14, the control system may continue to control the instrument 14 to align the blade support 18 with the target plane TP (operate in the guided mode), or the instrument 14 may assume the unguided mode, where the user is in full control of the saw blade positioning.

[0375] During the workflow for a navigated procedure using the robotic instrument described above, it is desirable to give the user as much flexibility as possible regarding what order to perform the cutting operations, such as saw blade cuts during a total knee procedure. Different users, depending on their training or past experience, and potentially based on clinical parameters of the

patient, may prefer to perform cuts in a particular order. Other surgeons have preferences in terms of whether to resect tibia first or femur first. For this reason, the control system does not necessarily mandate a strict cutting sequence and allows this to be chosen by the user. The default order for bone preparation may be pre-configured through a user preferences screen, and when reaching the bone preparation step of the workflow, the surgeon can use the UI of Figure 1 or other user input to select a particular cut and/or move forward/backwards between cuts. Referring to Figure 37, an exemplary user input device is provided in the form of a UI. The UI provides icons that are associated with each of the five target cutting planes TP, 73a-73e that may be required for the femur.

[0376] However, the control system 60 needs to be able to manage contingencies that arise during a surgical procedure. One such potential contingency is what do if the instrument 14, the localizer, or other components of the robotic system 10 were to fail or get damaged during a surgical procedure. In one possible contingency scenario, the control system 60 may facilitate execution of a bail-out plan.

[0377] For a non-robotic procedure, the first cut that gets performed on the femur is the distal cut – see icon associated with 73C in Figure 37. Typically, an intramedullary rod is placed into the IM canal for alignment. The IM rod is then used in conjunction with other instrumentation to place and pin a distal femur resection guide, which is then used to perform the distal femur cut. Next, a femoral sizer may be placed on the distal cut surface and against the posterior condyles to determine the size and alignment of the implant to and provide a guide for drilling fixation pin holes for the 4:1 cutting block. The 4:1 cutting block is placed on the distal femur cut surface, inserted into the fixation peg holes previously drilled. Finally, the slots in the 4:1 cutting block are used to manually constrain the saw blade for the 4 remaining cuts of the femur: anterior cortex, posterior condyles, posterior chamfer, and anterior chamfer. U.S. Patent No. 8,382,765, U.S. Patent Pub. No. 20200275943, or the Triathlon Knee System Surgical Protocol, which are each hereby incorporated herein by reference, describes aspects of a total knee procedure.

[0378] If a robotic system is being used exclusively to perform the cuts, technically the user could perform the femur cuts in any order desired. However, for contingency purposes, it is important that the robotic instrument 14 does not perform any steps that would prevent execution of a bail-out plan (i.e., the manual procedure described above) in case the robotic system 10 fails at any point in the procedure. As described above, the distal femur cut surface plays a key role in allowing the surgeon to manually perform the 4 remaining femur cuts. In one implementation, once the 4:1 cutting block is

installed onto the distal femur cut surface, the remaining femur cuts can be performed in any order. As long as the robotic system 10, cuts the distal femur cut surface before the remaining cuts, it remains possible for the surgeon to install the 4:1 cutting block onto the already cut distal femur surface and complete the procedure manually.

[0379] In an alternative configuration, the control system may further require that the posterior femur cut be performed last of the femur cuts. Thus, in this implementation, the control system would require that the user performs the distal femur cut first, the other three femur cuts in the user chosen order, and then the posterior cut last. It should be appreciated that the tibia cut may be may at any time without restriction such as before the femur cut, interleaved between one of the various femur cuts, or after completion of the femur cuts.

[0380] To fulfill the above workflow, ensuring that the distal femur cut is performed before the remaining cuts, the control system 60 may have a method to determine whether a cut (in the above case, the distal femur cut) has been completed. There are multiple ways that the control system 60 could determine whether a cut has been completed. One simple method would be to monitor whether the distal femur cut has been selected via the user interface UI – icon associated with cut 73C. The downside to this approach is that merely selecting a cut on the UI does not necessarily mean that the cut was fully completed.

[0381] The control system 60 may monitor, in addition to the cut being selected, whether the drive motor M was run and/or whether the control system 60 was controlling the instrument 14 to align to the target plane TP associated with the selected cut 73C. Furthermore, the control system 60 could utilize a timer module to monitor the length of time that the drive motor M was run while the cut icon was selected, and optionally compare that length of time to a ‘minimum resection time’ threshold, to mark the icon associated with the distal femur cut as completed.

[0382] Referring now to Figure 38, in addition to the implementations described above, it is further possible for the control system 60 to monitor the locations in which the saw blade 20 was moved while the drive motor M was running. In other words, it is possible for the control system 60 to monitor the regions (1st region, 2nd region), in which the saw blade 20 was located while the drive motor M was running (i.e., nonzero drive motor speed, or current was being drawn by the drive motor M). This could be done in a low fidelity manner (e.g., keeping track of coarse regions of bone removed, perhaps 1-8 regions for a particular cut) or in a high-fidelity manner, e.g., keeping track of bone removal on a voxel-by-voxel basis, such as with a 1-5 mm³ manner. The representation of the bone

used for bone removal could either be a 2-D or 3-D model MOD generated (approximately) from pointer registration (for an imageless workflow) or could alternately be constructed from a CT scan. For the imageless workflow, the coarse region method may be more appropriate. The patient model MOD may be spatially mapped to the plurality of regions, including the first region to be cut and the second region to be cut. The control system may determine a status of the first region and the status of the second region separately based on the pose of the tool, tool support, or hand-held portion and optionally the motor status at each pose, such as whether the drive motor is running (nonzero speed) at a given current threshold.

[0383] Alternatively, it may be possible to simply monitor the locations in which the saw blade 20 was located without regard to the status of the drive motor. With this approach, if the blade presents itself in a location inside the bone, it can reasonably be inferred that the blade was running and the software may not need to keep track of the motor status.

[0384] The control system 60 may further compute a ‘percentage completion’ of bone removal based on the # of regions completed, which could be based on the number of voxels touched, or some other metric while the drive motor was running. The regions completed may be compared to the total number of regions for that cut. For the example shown in Figure 38, there are two regions. The 2nd region was marked as completed on the UI, indicated with the diagonal fill lines. The 1st region is not yet marked as completed, indicated with the absence of the diagonal fill lines. The control system 60 may show the cut completion status and/or percentage removed on the user input device UI or display. When the control system determines that a particular cut is complete, based on the strategies described above and below, the user input device UI may show a check mark or provide graphical updates to a cut selection icon, such as by shading, coloring, beyond what is shown in Figure 38.

[0385] The control system 60 may designate the region as complete when the percentage completion exceeds a threshold set by the system for a given region, such as 80% or more for the high-fidelity system or 50% for the imageless system. In the example, the 1st region has not yet been indicated as completed. Furthermore, the control system would not indicate the cut as completed as a region of the cut has not been completed (the 1st region).

[0386] The control system 60 may also allow the user to override the completion status for a particular cut manually based on a user input device UI and mark the cut as complete, such as by selecting an override icon on the UI. The control system 60 may implement this feature in way that requires intentional user action or confirmation so that the user does not inadvertently prevent

execution of the bail-out plan. This may be desirable, since in many cases in robotic surgery, the surgeon will additionally use manual instruments not tracked by the system remove bone and/or tissue.

[0387] In another exemplary implementation, with reference to Figure 10, the control system 60 may track the state of the saw blade 20 or other surgical tool while the instrument 14 is in the unguided mode, i.e., the actuators are not aligning the saw blade 20 to a target plane TP or target axis. It may also be desirable to keep track of bone removal while in this unguided mode and use this as part of the criteria to determine whether a cut has been completed. Even though the plurality of actuators are not robotically aligning the saw blade 20 to the target plane TP, the localizer 44 is still active and the control system 60 may continue to monitor the state or pose of the saw blade 20 relative to the bone F, T, and whether the drive motor M is running, and use this information to determine the procedure status. More particularly, the control system 60 may utilize the status of the drive motor M and pose of the blade 20 to mark regions as completed while the instrument 14 is in the unguided mode. Alternatively, the control system may utilize the pose of the blade without the status of the drive motor to mark regions as completed while the instrument is in the unguided mode. In the unguided mode, the control system 60 may ignore bone removal that is not located on or near the target plane TP. The control system 60 could be configured to ignore bone removal if the saw blade 20 was more than a certain distance, such as 2-5 mm from the desired cutting plane TP (instances where the drive motor M is running and the state of saw blade 20 is spaced apart from the target plane TP by a threshold distance and/or threshold angle). Because the alignment of the saw blade 20 to the cutting plane may have some inaccuracy in the unguided mode, the control system 60 may want to project the geometry of the saw blade 20 (or cutting portion of the saw blade) onto the desired cutting plane, e.g., determine the 'shadow cast' by the blade geometry on the cutting plane, for bone removal assessment, for cases in which the TCP is near to the target plane.

[0388] One case in which it might be valuable to track unguided bone removal would be when the user is cutting with the instrument 14 to finish or clean up at back of the cut. In this situation, a particular cut is selected using the user input or automatically, and the user is removing bone at or near the desired cutting plane (since the saw blade alignment is somewhat mechanically constrained by the kerf of bone removed). If the control system 60 determines that the bone is being removed while the control system 60 determines that the drive motor M is running (and the instrument 14 is in the unguided mode), it may make sense for the control system 60 to utilize this information to supplement

the procedure status determination, such as whether the cut is completed or whether one or more regions have been completed.

[0389] In addition, when the control system has determined that the distal femur cut has been completed using the methodologies described above, the control system may ‘open up’ or enable other paths in the workflow, such as allowing selection of the remaining three or four femur cuts, such as when the control system determines that the distal cut has been completed. As mentioned above, in some implementations, the control system may further restrict the workflow by requiring that the posterior femur cut be performed last. In this implementation, the control system may allow open up or enable three of the remaining femur cuts, but not allow the posterior femur cut until the three other cuts are performed after the distal femur cut.

[0390] The control system may also allow the tibial implant alignment workflow step, the femoral implant alignment, or the knee alignment workflow step based on the procedure status of one or more cuts. Because the control system is able to determine which cuts are complete, the control system can anticipate/react to the user’s expected workflow preferences. For example, the control system may guide the workflow, bring up appropriate workflow steps based on the cuts which have been completed, and/or prevent access to certain workflow steps until certain cuts have been complete. In other words, the control system may limit an ability to select a second target pose of the saw blade based on the procedure status, with the second target pose associated with a second planned cut. The first target pose of the saw blade may be associated with the distal femur cut and the second target pose is associated with one of the following cuts: anterior cortex cut, a posterior condyle cut, a posterior chamfer cut, or an anterior chamfer cut.

[0391] The first target cut includes a first region to be cut, and a second region to be cut, the first region being spatially separate from the second region. The control system is configured to determine the procedure status based on a status of the first region and a status of the second region. The control system is configured to determine a status of the first region and the second regions separately based on the pose of tool, the hand-held portion or the blade support and the motor status at each pose. The control system may further configured to determine a pose of the tool, blade support or the hand-held portion at a second time, and to determine the status of the first region based on the pose of the blade support or hand-held portion and the motor status at the first time and determine the status of the second region based on the pose of the blade support and the hand-held portion and the motor status of the second time.

[0392] The selection of the particular cut may be accomplished in different ways, such as through manual selection of the cut using the user input device, such as mouse or touchscreen, through automatic selection (via movement of the instrument/pose of the instrument), or a predetermined order, in which the procedure status information, i.e., whether a particular cut has been completed, could be used to automatically advance to the next cut in the workflow.

[0393] With reference to Figure 1, when the robotic system 10 utilizes optical trackers for tracking one or more aspects in the procedure, it is common that gaps in visibility of the optical trackers may occur. This may result from momentary obstructions from manual instruments, surgical debris, irrigation fluid splatter, soft tissue, or arms/hands of users/assistants. In most instances, the loss of visibility is of a short duration and resolves quickly. In other cases, the visibility blockage may be longer, requiring the system to take appropriate mitigations to preserve accuracy, such as having the control system 60 disable the drive motor M to prevent cutting with the surgical tool 20 in the wrong location. The control system 60 is implemented in such a way that the control system 60 is tolerant of short occlusion events without unnecessarily disrupting the surgical procedure.

[0394] For example, there may be instances during the procedure where one of the trackers 52, 54, 56 may be right on the edge of visibility, in which case the localizer rapidly toggles between a tracking status of occluded and unoccluded. The control system 60 should implement a methodology that does not frustrate a user by rapid toggling the drive motor M on and off. The control system may be configured to control the tool drive motor based on the occlusion event.

[0395] In one potential implementation, the control system 60 may determine that the tracking status of the trackers 52, 54, 56 in the system, such as the tool tracker 52 or patient tracker 54, 56, is unoccluded. During this time, the control system 60 may control the actuator assembly to align the saw blade to the target plane while the user is depressing a trigger or other user input device FS and removing bone. At this point in the procedure, it is possible that the tracking status for one or more of the trackers 52, 54, 56 changes from the unoccluded status to the occluded status. To resolve this period of visibility loss, the control system 60 may be configured to assume the one or more tracker poses have not changed from their prior values of a prior time step. The system may also be configured to continue to perform the downstream control calculations, so it not necessarily true that the commanded pose will stay perfectly constant when the tracking status is occluded. In other words, the pose of the saw blade relative to the hand-held portion may continue to move even when one or more of the trackers 52, 54, 56 having a tracking status of occluded. The stiffness of the various constraints

described above are not infinite, and the control system 60 may take multiple time steps to move the platform in line with a given target plane.

[0396] Based on the motor status and the tracking status, the control system may select one of a first drive motor control criterion and a second drive motor control criterion, wherein the first drive motor control criterion includes a first time period and the second drive motor control criterion includes a second time period, where the first time period is different from the second time period. The control system may control the tool drive motor based on the selected drive motor criterion.

[0397] For a first time period, the control system 60 permits the drive motor M to remain in the permissive state, i.e., allow the drive motor M to continue running despite this initial occlusion. However, at some point, after a first period of time, if the localizer 44 continues to determine that the one or more trackers 52, 54, 56 have a tracking status of occluded, the control system 60 does not have enough localizing information to continue to control the plurality of actuators to align the saw blade to the target plane.

[0398] The first time period, the amount of time that the control system 60 continues operating with the tracking status of one or more trackers 52, 54, 56 being occluded, can vary, such as 10 ms, 20 ms, or more. The control system 60 may also require a certain number of consecutive samples of a new value from the localizer for a particular tracker before the tracking status changes from unoccluded to occluded. In this case, if the control system 60 does not receive localization data for all the trackers 52, 54, 56 for 10 consecutive milliseconds, then the control system 60 may operate to change the drive motor status to the restricted state, i.e., prevent the drive motor M from running. However, if before the 10 ms is elapsed, a timer for tracking the first time period may be reset anytime that a valid set of tracker updates is received, and the control system continues to control the drive motor such that the motor status remains in the permissive state. In addition to changing the motor status in response to the tracking status of one or more trackers 52, 54, 56, the control system 60 may control the UI or other indicator to alert the user as to why the drive motor M stopped, i.e., due to the tracking status of the one or more trackers.

[0399] Once the control system 60 sets the motor status to a restricted state, the control system 60 may be configured in different ways in managing the transition of the motor status back to the permissive state. One method is for the control system 60 to set the motor status back to the permissive state as soon as the localizer 44 receives tracking data from one or more trackers, such as when the

tracking status for all the trackers is unoccluded. This implementation has the advantage of a quick recovery for the user, but may result in a moderate amount of on/off cycling of the drive motor M.

[0400] In another implementation, the control system 60 may require that the tracking status of one or more trackers 52, 54, 56 to remain unoccluded for a second time period before transitioning the motor status back to the permissive state. The second time period may optionally be the same as the first time period. The benefit in this approach is that it reduces the amount of drive motor on/off cycling, if the tracking status for either tracker 52, 54, 56 is occluded during the second time period, the timer restarts and control system 60 continues to maintain the motor status in the restricted state.

[0401] In one additional approach, the second time period may be greater than the first time period, such as having the second time period to have a duration of 100 ms or even 1 second. This increases the recovery time, but helps ensure that the tracker visibility is reliable before resuming operation of the drive motor M. The idea with this approach is that once the control system 60 sets the motor status to the restricted state, really make sure the visibility is good before resetting the motor status back to the permissive state. This may be a reminder for the user to reset and help reduce the changes of subsequent disable events.

[0402] In yet another exemplary implementation, as described above and with reference to Figures 39A-C, the control system 60 may control the plurality of actuators to assume different centering positions. While in guided mode, the control system 60 controls the plurality of actuators such that the saw blade is aligned with a desired cutting plane. While in unguided mode, the plurality of actuators are controlled such that the plurality of each actuators are controlled to maintain their positions at a set of predefined centering position. In this unguided mode, the instrument 14 may be positioned in its home state (See Figure 39C), a pose resultant when each of the plurality of actuators are in their predefined centering position. The control system 60 may be responsive to input signals in order to enter the guided mode or the unguided mode, respectively. Because the control system may be responsive to certain input signals that evolve from user selection at different points during the workflow of performing a total knee procedure or during a particular cut, such as to reach certain regions not allowed by the system, clean up soft tissue, etc. When the instrument 14 is in the home state, the instrument 14 may feel similar to a conventional power tool. Therefore, in some situations, to move from a pose that is being assumed by tool support in guided mode – the initial state of the instrument (see Figures 39A and 39B) - at the time of receiving the input signal indicating a desire to transition to the unguided mode, the control system may need to control the plurality of actuators such

that one or more actuators of the actuator assembly return to their home (or predefined) positions to ultimately move the instrument 14 back to its home state (Figure 39C).

[0403] However, there are certain times when it is not desirable to allow the user to switch from the guided mode to the unguided mode, or vice-versa, and the control system 60 can potentially monitor and control the instrument 14 to influence user behavior accordingly.

[0404] In one exemplary scenario, the saw blade 20 may be located deep within a particular cut. While robotic alignment is happening during operative in the guided mode, the user may have the hand-held portion 16 offset from the tool support 18 by a fair amount, such as 15-30 degrees from the position of the tool support 16 when the instrument 14 is in its home state, and depending on the range of motion of the instrument 14, the actuators may still be able to align the saw blade 20 to the target plane. In this condition, if the control system 60 allows for the instrument 14 to transition to the home state, it may result in significant and potentially sudden or unexpected movement of the hand-held portion 16.

[0405] In such an implementation, the control system may determine an initial state of the instrument based on an input signal received that is indicative of a desire to move the plurality of actuators to positions associated with the home state of the instrument. The control system may be further configured to control the system based on the initial state of the instrument. For example, the control system may be configured to control the system by being configured to provide an indication to the user based on the initial state with an indicator, such as the UI. The indication may be a tactile alert, a visual alert, or an audio alert. Another way that the control system may control the system based on the initial state of the instrument is by controlling the drive motor based on the initial state of the instrument, such as by stopping the drive motor if the initial state is outside a given range of poses or actuator positions/angles.

[0406] The initial state, like the home state, may be calculated in joint space, such as the angle of for each of the joints; in actuator space, such as the position of the actuators; or in cartesian space, based on a pose of the tool support with respect to the hand-held portion. The initial state may be determined at the time of the controller receiving the input signal indicative of the desire to move the plurality of actuators to positions associated with the home state of the instrument, or any suitable time after, such as a fixed time period after the input signal is received. The initial state could be computed based on current measured, previous measured, commanded or previous commanded, angles, poses, or positions, depending on how the initial state is computed.

[0407] In one exemplary control implementation, with reference to Figures 40 and 41, the control system 60 may control the plurality of actuators of the instrument 14 based on a virtual object (see Figure 40) or distance parameter (Figure 41) and based on an input signal indicating desire to transition the instrument 14 to the home state. It should be appreciated that the transition to the unguided mode may include a transition to the home state, but need not necessarily do so. In other words, in some implementations, by selecting the UI to enter the unguided mode, the control system may naturally also control the instrument to assume the home state (subject to the conditions described above and below, but need not do so).

[0408] For example, with reference to Figure 40, the control system 60 may reject the request to transition from the guided mode to the unguided mode if the state of saw blade 20 is within a defined boundary or cutting region, such as if the saw blade is within a virtual object 1000, optionally centered around the knee or patient tracker, such as a sphere centered around the knee or other reference location. If the user indicates through the user input UI that he or she wishes to transition to the unguided mode within the virtual object 1000, the system would alert the user through the UI, that the change is rejected, and the control system 60 would continue to control the plurality of actuators to align the saw blade with the selected target plane. Alternatively, the control system 60 could control the drive motor M based on the user input signal and the virtual object 1000, such as by stopping the drive motor and requiring the user to release and repress the trigger or foot pedal to resume operation, perhaps cueing the user to look at the display for more information about the status of the system. In this implementation, the user would be required to move the hand-held portion 16 such that the saw blade 20 was outside the virtual object 1000 before the control system 60 would control the plurality of actuators to move the tool support 18 back to its pose associated with the home state of the instrument. The size and position of the virtual object 1000 would be chosen so that the pose of the saw blade 20 that is outside of the virtual object 1000 was far enough way from the anatomy so that subsequent movement of the hand-held portion 16 or saw blade 20 would have plenty of clearance so as to not interfere with the patient anatomy.

[0409] With reference to Figure 41, the distance parameter DP5 could be set so as to mimic the virtual object 1000. In other words, the control system 60 may reject the request to transition from the guided mode to the unguided mode if the state of saw blade 20 is within a distance parameter DP5 of a reference location RL. Alternatively, the system could reject the transition based on the pose of the surgical tool, the hand-held portion or the tool support is within the distance parameter DP 5 of a

reference location. If the user indicates through the user input device that he or she wishes to transition to the unguided mode while the measured distance between the blade and the reference location is less than the distance parameter DP5, the system would alert the user through the UI, that the change is rejected, and the control system 60 would continue to control the plurality of actuators to align the saw blade/surgical tool 20 with the selected target plane. Alternatively, the control system 60 could control the drive motor M based on the user input signal and the measured distance, such as by stopping the drive motor and requiring the user to release and repress the trigger or foot pedal to resume operation, perhaps cueing the user to look at the display for more information. In this implementation, the user would be required to move the hand-held portion 16 such that the measured distance of the saw blade 20 to the reference location was greater than the distance parameter DP5 before the control system 60 would control the plurality of actuators to move the tool support 18 back to its pose associated with the home state of the instrument 14. The magnitude of the distance parameter DP5 would be chosen so that the pose of the saw blade 20 that is at a greater distance than the distance parameter DP5 was far enough away from the anatomy so that subsequent movement of the hand-held portion 16 or saw blade 20 would have plenty of clearance so as to not interfere with the patient anatomy.

[0410] In another exemplary implementation, the control system 60 may be configured to control the plurality of actuators based on the input signal indicating a desire to move the instrument to a home state based on a degree of alignment of an initial state of the instrument with the home state. The control system could compare the degree of alignment with a threshold, and control the plurality of actuators based on such a comparison in response to receiving the input signal.

[0411] The degree of alignment could be calculated in joint space, such as the angle of movement required for each of the joints to move the tool support from the initial pose to the pose associated with the home state of the instrument; in actuator space, such as the distance required for each of the actuators to move from their initial position at the initial pose and the position at the home state of the instrument. This may include calculating the degree of alignment by determining a position of at least one actuator of the plurality of actuators at the initial state of the instrument and a position of the at least one actuator when the instrument is in the home state.

[0412] Alternatively, the degree of alignment could be calculated in cartesian space, such as amount of adjustment in roll, pitch, or elevation degrees of freedom versus thresholds for roll, pitch, and elevation. This could be determined based on the pose of the tool support and/or hand-held portion while the instrument is in the initial state and the pose of the tool support or hand-held portion while

the instrument is in the home state. If the degree of alignment exceeds the threshold, the control system 60 may continue controlling the plurality of actuators such that the saw blade 20 maintains alignment with the target plane. The control system 60 may also notify the user of the reason why the control system 60 rejected the request to transition the instrument to the home state, such as by providing an indicator to the user based on the degree of alignment between the tool support and the hand-held portion. The indicator may provide a tactile, visual or audio alert based on the degree of alignment. The user could then reposition the hand-held portion 16 with respect to the tool platform such that it was more closely aligned with a pose of the hand-held portion with respect to the tool platform commensurate with the home state of instrument 14.

[0413] Referring again to Figure 40, it would also be possible for the control system 60 to be configured to combine both implementations, such as controlling the transition to the home state based on both the pose/shape of the virtual object 1000 and the degree of alignment in response to receiving the input signal indicative of the user's desire to transition the instrument 14 to the home state. In some cases, the control system 60 could be configured to delay the transition to the home state once the conditions have been satisfied. In other words, the control system 60 may wait a predefined time period before reinitiating the signal indicative of the user's desire to transition the instrument 14 to the home state.

[0414] In another implementation, the control system 60 may control the plurality of actuators to behave differently when the control system 60 receives the input signal indicative of a user's desire to transition the instrument from the guided mode to the unguided mode where the instrument assumes the home state. For example, the control system may change the motion or tuning parameters such that the joints/actuators move very slowly/smoothly/gradually to align the instrument 14 to its home state from its initial pose. In such a case, the control system 60 need not necessarily monitor the pose of the saw blade or the degree of alignment since the joints/actuators will move very gradually. While it is important that the joints/actuators move quickly in the guided mode for optimal cutting accuracy, it is okay that the joints/actuators move slowly when they are transitioning from the guided mode to the unguided mode. When the control system 60 receives a further input signal indicative of a user's desire to transition the instrument from the unguided mode to the guided mode, the control system may adjust the motion or tuning parameters back to their more aggressive settings for responsive, fast, and accurate joint/actuator movement.

[0415] In such an instance, the control system may determine a pose of one of the surgical tool, hand-held portion, or tool support, and generate a guide constraint tuning parameter, where the guide constraint tuning parameter has a first value. The control system may be further configured to generate a joint centering constraint based on the position of at least one of the plurality of actuators, a centering position for at least one actuator of the plurality of actuators, and a joint centering tuning parameter. The joint centering parameter may have a second value, different the value of the tuning parameter for the guide constraint tuning parameter. The control system may determine the commanded joint position of each of the plurality of actuators based on the guide constraint while the system is operating in the guided mode. The control system may also determine a joint commanded position based on the joint centering constraint when in the unguided mode, such as when the control system receives the input signal indicative of the user's desire to transition to the unguided mode.

[0416] If the control system is in the guided mode when it receives the input signal, the control system may activate the joint centering constraint when receiving the input signal, and deactivate the guide constraint. On the other hand, if the control system receives an input signal indicating a desire to enter the guided mode, the control system may deactivate the joint centering constraint and activate the guide constraint. It should be appreciated that, in some configurations, only one of the joint centering constraint and the guide constraint may be active at one time.

[0417] Furthermore, with reference to Figure 42, the control system 60 may be configured to adjust the tuning parameters over time for one or more constraints based on receipt of an input signal, such as the input signal indicative of the user's desire to transition from the guided mode to the unguided mode or vice-versa. T_i in Figure 42 is associated with a time that the control system receives the input signal indicative of the user's desire to transition from the unguided mode to the guided mode. For example, one or more tuning parameters of the guide constraint may be defined by a function of time. The magnitude of the tuning parameters (see stiffness values associated with times T_1 and T_2 in Figure 42) may grow larger or smaller as the amount of time since receipt of the input signal is received. This results in a less aggressive/slower movement of the tool support 18 relative to the hand-held portion 16 at a first time (T_1) and a more aggressive/faster movement of the tool support at a second time (T_2). In other words, the different values of tuning parameters are blended in over time.

[0418] It should be appreciated that the tuning parameters of the joint centering constraint may also be defined as a function of time. In such an implementation, the stiffness of the joint centering

constraint may increase over time after receipt of an input signal indicative of a user's desire to transition from the guided mode to the unguided mode, which would lead to a less aggressive movement as a first time and a more aggressive/faster movement of the tool support at a later time.

[0419] With reference to Figure 43, the control system 60 may be configured to limit the velocity of the tool support 18 relative to the hand-held portion 16. In one particular configuration, the velocity of the tool support 18 relative to the hand-held portion 16 may be limited in one or more degrees of freedom, such as three degrees of freedom. The control system 60 may be configured to further limit the velocity of the tool support 18 relative to the hand-held portion 16 in response to receiving an input signal that is indicative of a user's desire to transition the instrument to the home state from the guided mode. In other words, the control system 60 may limit the velocity of the tool support relative to the hand-held portion when the control system is operating the instrument in the guided mode in accordance with a first velocity threshold VT1. This first velocity threshold VT1 may be associated with normal operation. The velocity may be a commanded velocity, a measured velocity, past commanded velocity, or past measured velocity.

[0420] The value of the first velocity threshold may be set that it does not impede the function of the instrument during normal operation, which requires fast and responsive movement of the actuators to maintain the tool at the target pose. This value of the first velocity threshold would ordinarily capture error scenarios where the control system had malfunctioned and inadvertently caused the tool support to move relative to the hand-held portion at an unintended speed. The control system may reduce the calculated commanded velocity to the first velocity threshold during the ordinary operation of the instrument while the control system operates in guided mode.

[0421] The control system may be further configured to further limit the velocity of the tool support relative to the hand-held portion in accordance with a second velocity threshold VT2 based on the input signal that indicates a desire to transition the instrument back to its home state or other mode transition. The control system may reduce the calculated commanded velocity to the second velocity threshold while the control system operates in the unguided mode and/or transitions to the home state of the instrument. This second velocity threshold VT2 may be lower than the first velocity threshold VT1 such that the second velocity threshold VT2 being sufficient to result in the tool support moving relative to the hand-held portion at a velocity that is acceptable by the user such that user is not surprised at the behavior of the instrument when the instrument begins moving towards its home state. In Figure 43, the T_i is indicative of the time that the control system 60 received the input signal

indicating a desire to transition the instrument back to its home state. While a step function is illustrated, any suitable function type is contemplated. Furthermore, the first velocity threshold may be 150%, 200%, or 300% greater than the second velocity threshold. In addition, different velocity thresholds may be used during other state or mode transitions, such as when the control system switches from the unguided mode to the guided mode, in which case similar first and second velocity limit thresholds may be utilized to achieve a similar effect.

[0422] Note that some or all the various conditions described in this document concerning disabling and re-enabling of the drive motor could be combined in a real system. One typical method would be to transition to state B (i.e., disable the drive motor) if **any** of the adverse conditions are present, and to only transition back to state A (i.e., allow the drive motor to run again) if **all** of the adverse conditions are resolved.

STERILIZATION

[0423] In some configurations, the hand-held robotic surgical instrument 14 is configured to be sterilized after use for subsequent re-use. Particularly, the instrument 14 may be subject to any suitable sterilization process. For example, the instrument 14 may be subject to a low-temperature sterilization process, such as, but not limited to, Hydrogen Peroxide Sterilization.

[0424] Referring to Figures 45 through 48B, the robotic system 10 includes a sterilization container 1200. The sterilization container 1200 is formed to allow sterilant, such as Hydrogen Peroxide, to enter the sterilization container 1200 and residual sterilant to exit the sterilization container 1200 to sterilize the contents of the sterilization container 1200. The sterilization container 1200 may include a base 1202 and a lid 1203 (shown in Figures 48A and 48B) that couple to one another. Accordingly, the sterilization container 1200 defines a void 1204. In other configurations, the sterilization container 1200 may include a removable tray 1205 that is sized to be removably received in the sterilization container 1200. Similarly, the removable tray 1205 may include features that define aspects of the void 1204. The void 1204 may be configured to receive the instrument 14 to support the instrument 14 during a sterilization process. In some configurations, it is desirable to minimize the size of the sterilization container 1200 such that the sterilization container 1200 does not occupy excessive space within a sterilization apparatus. However, reducing the size of the sterilization container 1200 presents a challenge. Particularly, the instrument 14 must fit within the void 1204 to facilitate the sterilization process. Particularly, there are a variety of poses of the tool support 18 relative to the hand-held portion 16 that can be achieved by the instrument 14 during execution of a

surgical procedure that would result in the dimensions of the instrument 14 being such that they do not fit within the void 1204 of the sterilization container 1200 or tray 1205. For example, when the actuators 21, 22, and 23 are fully extended, the instrument 14 may not fit within the void 1204. Accordingly, the instrument 14 may be required to move to a sterilization pose 1206 (one example shown in Figure 46B) where the instrument 14 fits within the void 1204 so that the instrument 14 is capable of being subjected to the sterilization process.

[0425] In one example, the control system, such as the instrument controller 28 and/or the navigation controller 36 may be configured to operate the instrument 14 in at least a working mode and a sterilization mode. In the working mode, the control system may control the instrument 14 such that the actuator assembly 400 moves the tool support 18 relative to the hand-held portion such that the tool 20 is aligned with a target virtual object 184, such as a desired cutting plane. Accordingly, when operating in the working mode, the instrument 14 is capable of moving the tool support 18 relative to the hand-held portion 16 into a pose where the instrument 14 is sized (in one or more dimensions) such that the hand-held robotic surgical instrument cannot be received in the void 1204. In the sterilization mode, however, control system may control the instrument 14 such that the actuator assembly 400 moves the tool support 18 relative to the hand-held portion 16 into a sterilization pose (such as indicated by reference numeral 1206) that is suitable for the instrument 14 to fit within the void 1204 of the sterilization container 1200 to facilitate the sterilization process or to fit within the removable tray 1205 disposed within the sterilization container 1200.

[0426] In one configuration, referring to Figures 46A through 47B, when the control system sends a command to the instrument 14 to enter the sterilization mode – the sterilization command, one or more actuators of the actuator assembly 400 retracts the tool support 18 relative to the hand-held portion 16 such that at least one of the dimensions (such as the height, length and/or width) of the instrument 14 are reduced (shown in Figure 46B) to allow the instrument 14 to fit within the void 1204 of the sterilization container 1200 (shown in Figures 47A and 47B). For example, in one configuration of the sterilization mode, the control system controls the actuators such that at least one of the actuators 21, 22, 23 of the actuator assembly 400 do not extend greater than within 25% of the second position. Accordingly, upon acting upon the sterilization command, one or more dimensions (such as the height, length and/or width) of the instrument 14 are reduced such that the instrument 14 is sized to be received in the void 1204 of the sterilization container 1200 (shown in Figures 47A and 47B) or the removable tray 1205. Beyond moving at least one actuator, it should be appreciated that at least two or at least

three of the actuators 21, 22, 23 of the actuator assembly 400 may be moved such that one or more of the dimensions of the instrument 14 are reduced such that the instrument 14 is sized to be received in the void 1204.

[0427] Additionally, it should be appreciated that a variety of positions of the at least one actuator relative to the second position may be sufficient to reduce the at least one dimension of the instrument 14 such that the instrument 14 is sized to be received in the void 1204. For example, in some configurations, the at least one actuator may not extend greater than within 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, or even 50% of the second position. Ultimately, it should be appreciated that when in the sterilization mode, the control system is configured to move the tool support 18 relative to the hand-held portion 16 into a sterilization pose that is suitable to facilitate sterilization of the instrument 14, such as poses of the instrument 14 that fit within the void 1204.

[0428] In other configurations, however, the size of the sterilization container 1200 is not a concern regarding space within a sterilization apparatus. Accordingly, in the sterilization mode, the control system may control the actuator assembly 400 to extend the tool support 18 relative to the hand-held portion 16 such that one or more dimensions (such as the height, length and/or width) of the instrument 14 are increased to allow more effective sterilization of the actuator assembly 400. Particularly, increasing the dimensions of the actuator assembly 400 may facilitate an easier flow path of sterilant through the actuator assembly 400 and/or increase the surface area of the actuator assembly 400 to facilitate sterilization of the actuator assembly 400. For example, the control system may control the actuators such that at least one of the actuators 21, 22, 23 of the actuator assembly 400 do not extend greater than within 25% of the first position (i.e., at least 75% extension of the actuators 21, 22, 23 from their lower limit defined by the second position). Accordingly, upon acting upon the sterilization command, one or more dimensions (such as the height, length and/or width) of the instrument 14 are increased such that the instrument 14 is sized to facilitate sterilization of the actuator assembly 400.

[0429] Similarly, it should be appreciated that a variety of positions of the at least one actuator relative to the first position may be sufficient to increase the at least one dimension of the instrument 14 such that the instrument 14 is sized to facilitate more effective sterilization of the actuator assembly 400. For example, in some configurations, the at least one actuator may not extend greater than within 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, or even 50% of the first position (i.e., the upper limit of the actuator). For example, in the configuration shown in Figures 49A and 49B, the actuator

assembly 400 may be arranged into another suitable sterilization pose where the tool support 18 is tilted relative to the hand-held portion 16. For example, in some configurations, when the instrument 14 is operating in the sterilization mode, the actuator assembly 400 may actuate at least one of the actuators 21, 22, 23 to within 25% of its upper limit of actuation and actuate another one or more of the actuators 21, 22, 23 to within 25% of its lower limit, thereby improving the flow of sterilant through the instrument 14 to facilitate sterilization of the instrument 14.

[0430] The control system may be configured to transition the instrument 14 into the sterilization mode in response to an input signal – the sterilization command. The input signal may be generated in response to a variety of conditions/inputs. In one example, the input signal may be generated from an input device configured to be actuated by a user. The input device may be any suitable device configured to be actuated by a user such as, but not limited to, a physical interface (such as a button or switch) arranged on the instrument 14, such as on the tool tracker, the navigation system 32 or the console 33, or a graphic interface element arranged on a user interface UI of the instrument 14, the navigation system 32, or the console 33. In one configuration, the input device may be a dedicated input device for commanding the instrument 14 to transition to the sterilization mode. However, it is contemplated that the input device may be configured to toggle the instrument 14 between a variety of operational modes, including, but not limited to, the working mode and the sterilization mode. In another configuration, the input device may be a power input device configured to generate the input signal.

[0431] In response to the input signal generated by the power input device, the control system may be configured to transition the instrument 14 into the sterilization mode and subsequently initiate a shut down procedure of the hand-held robotic surgical instrument. Similarly, the power input device may be any suitable device configured to be actuated by a user such as, but not limited to, a physical interface (such as a button or switch) arranged on the instrument 14, the navigation system 32 or the console 33, or a graphic interface element arranged on a user interface UI of the instrument 14, the navigation system 32 or the console 33.

[0432] As mentioned above, the robotic system 10 may further include a tool tracker 52 attached to the instrument 14, at least one patient tracker 54, 56 fixed to the anatomy of the patient, and a localizer 44 configured to monitor the tool tracker 52 and the patient tracker(s) 54, 56 to determine a position and/or orientation of the instrument 14 and the patient anatomy in a known coordinate system (shown in Figure 10). In some configurations, the control system is configured to

select the operating mode of the instrument 14 and generate the input signal based on the position and/or orientation of the instrument 14 relative to a reference location in the known coordinate system. For example, the control system may be configured to select the operating mode of the instrument 14 and generate the input signal based on the position and/or orientation of the instrument 14 relative to the patient anatomy as tracked by the tool tracker 52 and/or the patient tracker(s) 54, 56 or as determined by the localizer in another manner, such as using machine vision.

[0433] For example, referring back to Figure 10, in one configuration, the control system may be configured to calculate an angular parameter A of the instrument 14 based on the orientation of the instrument 14 relative to the reference location in the known coordinate system. For example, the control system may be configured to calculate the angular parameter A of the instrument 14 based on the orientation of the instrument 14 relative to a suitable reference location such as, but not limited to, a target virtual object 184, such as a desired cutting plane. Additionally, control system may be configured to compare the angular parameter A to at least one threshold angle and generate the input signal based on the comparison. For example, if the angular parameter A regarding the pose of the instrument 14 relative to the known coordinate system exceeds a specified threshold angle, the control system may be configured to generate the input signal to cause the instrument 14 to transition to the sterilization mode.

[0434] Similarly, with continued reference to Figure 10, in one configuration the control system may be configured to calculate a distance parameter D of the instrument 14 based on the position of the instrument 14 and a position of the reference location in the known coordinate system. For example, the control system may be configured to calculate the distance parameter D of the instrument 14 based on the distance between a suitable reference position of the instrument 14 (such as, but not limited to, the tool center point TCP) relative to a suitable reference location of the patient anatomy (such as, but not limited to, a location defined relative to the patient tracker(s) 54, 56). Additionally, the control system may be configured to compare the distance parameter D to at least one threshold distance and generate the input signal based on the comparison. The distance parameter may have a magnitude and direction.

[0435] Still referring to Figure 10, the at least one threshold distance may include a plurality of threshold distances I, II, III defining different zones pertaining to different operating modes of the instrument 14. For example, the plurality of threshold distances may include a sterilization mode threshold distance III (shown in Figure 10). For example, when the distance parameter D exceeds the

sterilization mode threshold distance III, the control system may be configured to generate the input signal to transition the instrument 14 to the sterilization mode. Additionally, the plurality of threshold distances may include a home mode threshold distance II (shown in Figure 10).

[0436] Similarly, the control system may be configured to compare the distance parameter D to the home mode threshold distance II and/or the sterilization mode threshold distance III. For example, if the distance parameter D exceeds the home mode threshold distance II and/or is below the sterilization mode threshold distance III, the control system may be configured to generate a second input signal commanding the instrument 14 to operate in a home mode where the control system is configured to operate the actuator assembly 400 of the instrument 14 to transition each of the actuators 21, 22, 23 to their respective home positions. In this implementation, it should be understood that a home pose of the instrument 14 in home mode is different than the sterilization pose of the instrument 14 the sterilization mode. For example, the home pose of the instrument 14 may be cumulatively defined by home positions of each of the actuators 21, 22, 23 of the actuator assembly 400. Meanwhile, the sterilization pose of the instrument 14 may be defined by moving at least one of the actuators 21, 22, 23 from their home position to move the tool support 18 relative to the hand-held portion 16 into a pose that is suitable for sterilization.

[0437] Further, the plurality of threshold distances may include a working mode threshold distance I (shown in Figure 10). Also, similarly, the control system may be configured to compare the distance parameter D to the working mode threshold distance I. Based on this comparison, the control system may be configured to transition the instrument 14 to the working mode in response to the distance parameter D being within the working mode threshold distance I to actively align the tool 20 with a target virtual object 184. In one example, such as shown in Figure 10, the threshold distances I, II, III may be defined by one or more virtual objects 184 arranged at various radii from a target anatomy of a patient.

[0438] In another configuration, the control system may be configured to generate the input signal to transition the instrument 14 to the sterilization mode after performing a homing procedure (described above) to establish the home position of each of the actuators 21, 22, 23 to cumulatively define a home pose of the instrument 14. For example, the home pose of the instrument may be a nominal reference position or may be a position where each of the actuators 21, 22, 23 have maximum adjustability to align the tool support 18 with a target virtual object 184, such as a target cutting plane.

[0439] In other configurations, the sterilization mode may facilitate the homing procedure. As mentioned above, in one configuration of the sterilization mode, the actuators 21, 22, 23 of the actuator assembly 400 do not extend greater than within a certain range (such as 25% of actuator travel) from the second position (i.e., the lower limit of the actuators). For example, the instrument 14 may be in this configuration when it is removed from the sterilization container 1200, and requires the homing procedure to be performed before use. Accordingly, the instrument 14 may execute the homing procedure by, for example, moving the actuators 21, 22, 23 between the lower and upper limits of the actuators 21, 22, 23 to establish the home position of each of the actuators 21, 22, 23. Notably, however, since the actuators 21, 22, 23 are within a certain range of the second position at the start of the homing procedure, the instrument 14 can perform the homing procedure faster. Particularly, since the actuators 21, 22, 23 will already be within a certain range of the second position, the instrument 14 can move to the lower limit of the actuators 21, 22, 23 in less time, reducing the overall time required to complete the homing procedure and thus saving expensive operating room time. Further, the time required to complete the homing procedure may be further reduced because since the location of the actuators 21, 22, 23 is approximately known in the sterilization mode, the instrument 14 can move the actuators 21, 22, 23 at a higher velocity with less risk of violently colliding with the upper or lower actuator limit, saving further time in conducting the homing procedure.

[0440] Additionally, in yet another configuration, the control system may be in communication with the surgical console 33 (as described above). Accordingly, the control system may be configured to generate the input signal to transition the instrument 14 to the sterilization mode when the control system detects an error with the instrument 14 and/or the surgical console 33. For example, the error may be a communication error between the instrument 14 and the surgical console 33, such as a loss of connection between the instrument 14 and the surgical console 33. As another example, the error may be a “line-of-sight” error between various devices of the surgical system 10, such as between localizer 44 and the instrument 14, the instrument tracker 42, or the patient tracker(s) 54, 56. In yet another example, the error may be a failure of an application running on the surgical console 33, such as an application running on the surgical console 33 crashing or the surgical console 33 losing power. As a further example, the error may be an error within the instrument 14 itself, such as an over-current condition of the drive motor M, a jammed condition of the drive motor M, or an invalid sensor reading of a sensor of the instrument 14. As another further example, the error may be a timeout error due to

a user not interacting with the instrument 14 or the surgical console 33 for at least a prescribed time period.

[0441] In another configuration, the control system may also be configured to operate the instrument 14 in a freeze mode (also referred to as “a free-hand mode” above) where the pose of the hand-held portion 16 relative to the pose of the tool support 18 is fixed in a freeze pose as a user operates on a patient, as opposed to the tool support 18 moving relative to the hand-held portion 16 in the working mode to align the tool 20 with a target virtual object 184. For example, in response to the input signal the control system may be configured to transition the instrument 14 between at least the working mode and the freeze mode. For example, the instrument 14 may be operating in the operating in the working mode and receive the input signal to transition the instrument 14 to the freeze mode. Accordingly, the control system may control the actuator assembly 400 such that the instrument 14 may be positioned solely by the user.

[0442] As contemplated above, when the instrument 14 transitions to the freeze mode, the instrument 14 may remain in its current pose of the tool support 18 relative to the hand-held portion 16. However, in other configurations, the instrument 14 may move to a prescribed freeze pose, which may be the home position defined for each of the actuators or may be a preferred pose defined by a user.

[0443] In other configurations, the freeze pose may be the same as the sterilization pose. For example, the control system may control the actuator assembly 400 such that instrument 14 moves to the sterilization pose in response to the input signal commanding the instrument 14 to operate in the freeze mode. Using the sterilization pose as the prescribed freeze pose may reduce the size of the instrument 14, making the instrument 14 easier to hold/position for a user, and prevent the need for adjusting the actuator assembly such that the instrument 14 is in the sterilization pose after a user finishes an operation in the freeze mode. Accordingly, when the freeze pose is configured to be the same as the sterilization pose, in response to receiving the input signal, the control system may be configured to transition the instrument 14 to the freeze mode, and the control system may be configured to control the actuator assembly 400 to move the tool support 18 relative to the hand-held portion 16 into the sterilization pose before controlling the actuator assembly 400 to maintain the pose of the tool support 18 relative to the hand-held portion 16 in the freeze pose as a user operates on a patient.

[0444] In some configurations the actuators 21, 22, 23 are back-drivable. Accordingly, when in the freeze mode, the control system may control the actuator assembly 400 to actively apply current to the actuator 21, 22, 23 to maintain the pose of the tool support 18 relative to the hand-held portion 16. In other configurations, the actuators 21, 22, 23 are non-back-drivable. Accordingly, when in the freeze mode, the actuator assembly 400 is controlled to remain stationary. For example, the control system may apply current to one or more of the actuators 21, 22, 23 of the actuator assembly 400 such that the forces generated by the one or more actuators 21, 22, 23 is equal and opposite the force experienced by the one or more actuators 21, 22, 23, and thus the one or more actuators 21, 22, 23 remain stationary.

[0445] Referring now to Figures 50-52, the instrument 14 may also include a guidance array 1600. The guidance array 1600 provides an operator with visual indication of the pose of the tool support 18 relative to the hand-held portion 16 during operation of the instrument 14, providing visual indication to the operator of required changes in pitch orientation, roll orientation, and z-axis translation of the hand-held portion 16 to achieve the desired pose of the tool 20 while affording the plurality of actuators 21, 22, 23 with maximum adjustability to maintain the tool 20 on a target plane. The guidance array 1600 includes a tool alignment member 1602 removably or permanently coupled to the tool support 18 and a handle alignment member 604 removably or permanently coupled to the hand-held portion 16 for guiding the user as to how to move the hand-held portion 16 to provide the instrument 14 with sufficient adjustability by keeping the actuators 21, 22, 23 near their home positions or other predetermined positions. In some configurations, at least a portion of the tool alignment member 1602 and at least a portion of the handle alignment member 604 may be aligned when the actuators 21, 22, 23 are in their respective home positions.

[0446] Referring to Figures 51 and 52, the sterilization container 1200 may define a second void 1208. The second void 1208 may be configured to receive the tool alignment member 1602 and the handle alignment member 1604 when the tool alignment member 1602 and the handle alignment member 1604 are removed from the instrument 14 to facilitate sterilization of the tool alignment member 1602 and the handle alignment member 1604. It is contemplated that additional components of the instrument 14 may be removable from the instrument 14 and that the sterilization container 1200 may define additional voids configured to receive the additional components to facilitate sterilization of the additional components.

[0447] CLAUSES:

I. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine a state of the surgical tool in a known coordinate system, and determine a position and/or orientation of a reference coordinate system relative to the known coordinate system; activate guided mode based on a first relationship criteria between the state of the surgical tool and the reference coordinate system; and deactivate guided mode based on a second relationship criteria between the state of the surgical tool and the reference coordinate system, wherein the first relationship criteria and the second relationship criteria are different. II. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of the hand-held portion or the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of the hand-held portion or the tool support; determine a motor status; select an actuator/joint threshold based on the pose of the hand-held portion or the tool support, a boundary, and the motor status; determine a value of the actuator/joint of the actuator assembly; control the tool drive motor based on the actuator/joint threshold and the actuator position/joint angle value. III. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of the hand-held portion or the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of the hand-held portion or the tool support; determine a motor status; based on the motor status, select one of a first drive motor control criterion and a second drive motor control criterion wherein the first drive motor control criterion includes actuator position/joint angle of at least one actuator or joint actuator assembly and the second drive motor control criterion is based on a boundary; and control the tool drive motor based on the selected drive motor control criterion. IV. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a pose of the surgical tool and a target pose of the surgical tool, control the plurality of actuators to position the surgical tool in the plurality of controlled degrees of freedom based on the pose of the tool and the target pose of the surgical tool; and determine a motor status of the tool drive motor; select a boundary based on the motor status; and control the tool drive motor based the pose of the surgical tool in the at least one uncontrolled degree of freedom and based on a pose of the selected boundary. V. A computer

implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: control the plurality of actuators to position the surgical tool in the plurality of controlled degrees of freedom based on the pose of the surgical tool and the target pose of the surgical tool; and determine a motor status of the tool drive motor; select a distance parameter on the motor status; and control the tool drive motor based the pose of the surgical tool in the at least one uncontrolled degree of freedom and the selected distance parameter. VI. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a first target pose of the saw blade; determine a motor status at a first time; determine a pose of the hand-held portion or blade support at the first time; determine a procedure status based on the first target pose of the saw blade, the motor status at the first time, and the pose of the hand-held portion or blade support at the first time; limit an ability to select a second target pose of the saw blade based on the procedure status. VII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to:

determine, in a known coordinate system, a first target pose of the saw blade; determine a motor status at a first time; determine the motor status at a second time; determine a pose of the hand-held portion or blade support at the first time determine a pose of the hand-held portion or blade support at a second time, wherein at the first time, the instrument is in a unguided mode and at the first time, the instrument is a guided mode; and determine a procedure status based on the motor status of the saw drive motor at the first time, the motor status of the saw drive motor at the second time, the first target pose of the saw blade, the pose of the hand-held portion or blade support at the first time, and the pose of the hand-held portion or blade support at the second time. VIII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine a pose of the tool based on the first tracker and a pose of a portion of a patient's anatomy based on the second tracker; control the plurality of actuators to position the surgical tool based on the pose of the tool and the pose of the portion of the patient's anatomy; determine that an occlusion event has occurred for one of the first tracker and the second tracker; control the tool drive motor based the occlusion event. IX. A

computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a pose of the tool based on the first tracker and a pose of a portion of the patient's anatomy based on the second

tracker; control the plurality of actuators to position the surgical tool based on the pose of the surgical tool and the pose of the portion of the patient's anatomy; determine a motor status; determine that a tracking status for at least one of the first tracker and the second tracker; based on the motor status and the tracking status, select one of a first drive motor control criterion and a second drive motor control criterion; wherein the first drive motor control criterion includes a first time period; and the second drive motor control criterion includes a second time period, wherein the first time period is different than the second time period; and control the tool drive motor based on the selected drive motor control criterion. X. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine a pose of the hand-held portion or tool support and a target pose of the surgical tool, control the plurality of actuators to position the surgical tool based on the pose of the hand-held portion or tool support and the target pose of the surgical tool; receive an input signal that is indicative of a desire to move the plurality of actuators to a home state of the instrument, determine an initial state of the instrument based on the input signal; and control the system based on the initial state of the instrument. XI. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine a target pose of the surgical tool in a known coordinate system; determine a pose of the hand-held portion or tool support in the known coordinate system; generate a guide constraint based on the target pose of the surgical tool, the pose of the hand-held portion or tool support, and a guide constraint tuning parameter, wherein the guide constraint tuning parameter has a first value; generate a joint centering constraint based on a position of at least one of the plurality of actuators, a centering position for at least one actuator of the plurality of actuators, and a joint centering tuning parameter, wherein the joint centering tuning parameter has a second value and determine a commanded joint position of each of the plurality of actuators based on the guide constraint while the system is operating in a guided mode; and determine a commanded joint position based on the joint centering constraint when in transitioning from the guided mode to an unguided mode, wherein the value of the joint centering tuning parameter is different than the value of the guide constraint tuning parameter. XII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine, in a known coordinate system, a pose of the hand-held portion or tool support and a target pose of the surgical tool, wherein in a guided mode, the control system is configured to control the plurality

of actuators to position the surgical tool based on the pose of the hand-held portion or tool support and the target pose of the surgical tool; receive an input signal to transition to between the guided mode and an unguided mode wherein the instrument assumes a home state, in response to receiving the input signal: determine a velocity based on the target pose of the surgical tool and a pose of the hand-held portion or tool support; control the plurality of actuators to move at a first velocity based on the velocity and a first velocity threshold during a first time period; and control the plurality of actuators to move at a second velocity based on the velocity and a second velocity threshold during a second time period, the first velocity threshold being greater than the second velocity threshold. XIII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to: determine a target pose of the saw blade in a known coordinate system; determine a state of the saw blade in the known coordinate system; determine a value of a tuning parameter based receipt of an input signal to transition between an unguided mode where instrument assumes a home state to a guided mode; wherein the guided mode, the plurality of actuators are controlled to align the saw blade based on a guide constraint; generate the guide constraint based on the target pose of the saw blade and the pose of the hand-held portion or tool support and based on the value of the tuning parameter; calculate a constraint force adapted to move a virtual saw blade based on the guide constraint; simulate dynamics of the virtual saw blade in a virtual simulation based on the constraint force, and to output a commanded pose based on the virtual simulation; and control each of plurality of actuators based on the commanded pose. XIV. A hand-held robotic surgical system, the hand-held robotic surgical system comprising: a hand-held robotic surgical instrument, the hand-held robotic surgical instrument comprising: a hand-held portion, a tool support movably coupled to the hand-held portion, the tool support including a tool mount for supporting a tool, and an actuator assembly operatively interconnecting the tool support and the hand-held portion, the actuator assembly including at least one actuator, the actuator assembly configured to move the tool support relative to the hand-held portion in a plurality of degrees of freedom; and a controller configured to control the actuator assembly to move tool support relative to the hand-held portion and configured to operate the hand-held robotic surgical instrument in at least the following operating modes: a working mode where the controller controls the actuator assembly such that the tool is aligned with a target virtual object, and a sterilization mode where the controller controls the actuator assembly to move the tool support relative to the hand-held portion into a pose that is suitable for

sterilization; wherein the controller is configured to transition the hand-held robotic surgical instrument to the sterilization mode in response to an input signal. XV. The hand-held robotic surgical system of claim XIV, further comprising a sterilization container formed to allow sterilant to enter and residual sterilant to exit, the sterilization container defining a void configured to receive the hand-held robotic surgical instrument when the hand-held robotic surgical instrument is in the sterilization mode so that the hand-held robotic surgical instrument is capable of being subjected to a sterilization process, the sterilization container including a base and lid that couple to one another to define the void. XVI. The hand-held robotic surgical system of claim XIV, wherein the sterilization container includes a tray sized to be removably received by the sterilization container, the tray defining the void configured to receive the hand-held robotic surgical instrument. XVII. The hand-held robotic surgical system of claim XV, wherein the actuator assembly includes a plurality of actuators, and each of the plurality of actuators are configured to move between a first position defining an actuator upper limit and a second position defining an actuator lower limit to move the tool support relative to the hand-held portion, wherein a home position is a nominal position between the first position and the second position of each of the plurality of actuators. XVIII. The hand-held robotic surgical system of claim XVII, wherein each of the actuators of the actuator assembly do not extend greater than within 25% of the second position of each of the actuators when the hand-held robotic surgical instrument is in the sterilization mode such that the size of the hand-held robotic surgical instrument is reduced so as to be received in the void of the sterilization container. XIX. The hand-held robotic surgical system of claim XVIII, wherein the hand-held robotic surgical instrument is capable of moving the tool support relative to the hand-held portion into a pose where the hand-held robotic surgical instrument is sized such that the hand-held robotic surgical instrument cannot be received in the void when operating in the working mode. XX. The hand-held robotic surgical system of claim XVII, wherein each of the actuators of the actuator assembly do not extend greater than within 25% of the first position of each of the actuators when the hand-held robotic surgical instrument is in the sterilization mode such that the size of the hand-held robotic surgical instrument is increased so as to facilitate the flow of sterilant through the hand-held robotic surgical instrument. XXI. The hand-held robotic surgical system of claim XX, wherein the actuator assembly includes a first actuator and a second actuator each configured move between a first position defining an actuator upper limit and a second position defining an actuator lower limit, wherein the first

actuator does not extend greater than within 25% of the first position and the second actuator does not extend greater than within 25% of the second position when the hand-held robotic surgical instrument is in the sterilization mode. XXII. The hand-held robotic surgical system of claim XIV, wherein the input signal is generated from an input device configured to be actuated by a user. XXIII. The hand-held robotic surgical system of claim XXII, wherein: the input device is a power input device configured to be actuated by a user to generate the input signal, and the controller is configured to transition the hand-held robotic surgical system to the sterilization mode in response to the input signal and subsequently initiate a shut down procedure of the hand-held robotic surgical instrument. XXIV. The hand-held robotic surgical system of claim XXIII, wherein the power input device is arranged on at least one of the hand-held robotic surgical instrument and a surgical console. XXV. The hand-held robotic surgical system of claim XIV, further comprising a tool tracker coupled to the hand-held robotic surgical instrument and a localizer configured to monitor the tool tracker to determine a position and/or orientation of the hand-held robotic surgical instrument in a known coordinate system, wherein the input signal is based on the position and/or orientation of the tool tracker. XXVI. The hand-held robotic surgical system of claim XXV, wherein the controller is configured to select the operating mode of the hand-held robotic surgical instrument and generate the input signal based on the position and/or orientation of the hand-held robotic surgical instrument relative to a reference location in the known coordinate system. XXVII. The hand-held robotic surgical system of claim XIV, further comprising a tool tracker coupled to the hand-held robotic surgical instrument, a patient tracker configured to be fixed to a target anatomy of a patient, and a localizer configured to monitor the tool tracker and the patient tracker to determine a position and/or orientation of the hand-held robotic surgical instrument and the patient anatomy in a known coordinate system, wherein the input signal is based on the position and/or orientation of the tool tracker and the position and/or orientation of the patient tracker. XXVIII. The hand-held robotic surgical system of claim XXVII, wherein the controller is configured to select the operating mode of the hand-held robotic surgical instrument and generate the input signal based on the position and/or orientation of the hand-held robotic surgical instrument relative to a reference location in the known coordinate system. XXIX. The hand-held robotic surgical system of claim XXVIII, wherein: the controller is configured to calculate an angular parameter of the hand-held robotic surgical instrument based on the orientation of the hand-held robotic surgical instrument relative to the reference location in the

known coordinate system; the controller is configured to compare the angular parameter to at least one threshold angle; and the input signal is based on the comparison. XXX. The hand-held robotic surgical system of claim XXVIII, wherein: the controller is configured to calculate a distance parameter of the hand-held robotic surgical instrument based on the position of the hand-held robotic surgical instrument and a position of the reference location in the known coordinate system; the controller is configured to compare the distance parameter to at least one threshold distance; and the input signal is based on the comparison. XXXI. The hand-held robotic surgical system of claim XXX, wherein the position of the reference location in the known coordinate system is based on a position of a patient's anatomy, and the position of the hand-held robotic surgical instrument is based on a tool center point of the hand-held robotic surgical instrument. XXXII. The hand-held robotic surgical system of claim XXX, wherein: the at least one threshold distance includes a sterilization mode threshold distance; and the controller is configured to transition the hand-held robotic surgical instrument to the sterilization mode in response to the distance parameter exceeding the sterilization mode threshold distance. XXXIII. The hand-held robotic surgical system of claim XXX, wherein the actuator assembly includes a plurality of actuators, and each of the plurality of actuators are configured to move between a first position defining an actuator upper limit and a second position defining an actuator lower limit to move the tool support relative to the hand-held portion, wherein a home position is a nominal position between the first position and the second position of each of the plurality of actuators, wherein the controller is configured to transition each actuator of the plurality of actuator to their home positions in response to a second input signal. XXXIV. The hand-held robotic surgical system of claim XXXIII, wherein: the at least one threshold distance includes a home mode threshold distance; the controller is configured to compare the distance parameter to the home mode threshold distance; and the second input signal is based on the comparison. XXXV. The hand-held robotic surgical system of claim XXX, wherein: the at least one threshold distance includes a working mode threshold distance; and controller is configured to transition the hand-held robotic surgical instrument to the working mode in response to the distance parameter being within the working mode threshold distance. XXXVI. The hand-held robotic surgical system of claim XVII, wherein the controller is configured to perform a homing procedure to establish a home position of each actuator of the actuator assembly. XXXVII. The hand-held robotic surgical system of claim

XXXVI, wherein the controller is configured to generate the input signal to operate the hand-held robotic surgical instrument in the sterilization mode after the homing procedure is complete.

XXXVIII. The hand-held robotic surgical system of claim XIV, wherein the controller is in communication with a surgical console, and the controller is configured generate the input signal to transition the hand-held robotic surgical instrument in the sterilization mode when the controller detects an error. XXXIX. The hand-held robotic surgical system of claim XXXVIII, wherein the error is a communication error between the hand-held robotic surgical instrument and the surgical console. XL. The hand-held robotic surgical system of claim XXXIX, wherein the error is a line of sight error where a localizer configured to monitor a tool tracker and a patient tracker loses line of sight with one of the tool tracker and the patient tracker. XLI. The hand-held robotic surgical system of claim XXXIX, wherein the error is a failure of an application running on the surgical console. XLII. The hand-held robotic surgical system of claim XXXIX, wherein the error is an overcurrent condition of a drive motor of the hand-held robotic surgical instrument. XLIII. The hand-held robotic surgical system of claim XXXIX, wherein the error is a jammed condition of a drive motor of the hand-held robotic surgical instrument. XLIV. The hand-held robotic surgical system of claim XXXIX, wherein the error is an invalid sensor condition of a sensor of the hand-held robotic surgical instrument. XLV. The hand-held robotic surgical system of claim XXXIX, wherein the error is a timeout error where a user has not interacted with at least one of the hand-held robotic surgical instrument and the surgical console for at least a prescribed time period.

XLVI. The hand-held robotic surgical system of claim XIV, wherein the target virtual object is a target plane of a target anatomy of a patient. XLVII. A hand-held robotic surgical system, the hand-held robotic surgical system comprising: a hand-held robotic surgical instrument, the hand-held robotic surgical instrument comprising: a hand-held portion; a tool support movably coupled to the hand-held portion, the tool support including a tool mount for supporting a tool; an actuator assembly operatively interconnecting the tool support and the hand-held portion, the actuator assembly including at least one actuator, the actuator assembly configured to move the tool support relative to the hand-held portion in a plurality of degrees of freedom; and a controller configured to control the actuator assembly to move tool support relative to the hand-held portion and configured to operate the hand-held robotic surgical instrument in at least the following operating modes: a working mode where the controller controls the actuator assembly such that the tool is aligned with a target virtual object as a user operates on a patient, a sterilization mode where the

controller controls the actuator assembly to move the tool support relative to the hand-held portion into a sterilization pose that is suitable for sterilization, and a freeze mode where the controller controls the actuator assembly to maintain the pose of the tool support relative to the hand-held portion in a freeze pose as a user operates on a patient; wherein the controller is configured to transition the hand-held robotic surgical instrument between at least the working mode, the sterilization mode, and the freeze mode in response to an input signal. XLVIII. The hand-held robotic surgical system of claim XLVII, wherein the at least one actuator of the actuator assembly is non-back drivable such that the tool support only moves relative to the hand-held portion in response to the controller commanding the actuator to move. XLIX. The hand-held robotic surgical system of claim XLVII, wherein: the freeze pose of the tool support relative to the hand-held portion is the same as the sterilization pose; and in response to receiving the input signal commanding the controller to transition the hand-held robotic surgical instrument to the freeze mode, the controller is configured to control the actuator assembly to move the tool support relative to the hand-held portion into the sterilization pose before controlling the actuator assembly to maintain the pose of the tool support relative to the hand-held portion in the freeze pose as a user operates on a patient. L. The hand-held robotic surgical system of claim XLVII, further comprising a sterilization container formed to allow sterilant to enter and residual sterilant to exit, the sterilization container defining a void configured to receive the hand-held robotic surgical instrument when the hand-held robotic surgical instrument is in the sterilization pose so that the hand-held robotic surgical instrument is capable of being subjected to a sterilization process, the sterilization container including a base and lid that couple to one another to define the void. LI. The hand-held robotic surgical system of claim L, wherein the actuator assembly includes a plurality of actuators, and each of the plurality of actuators are configured to move between a first position defining an actuator upper limit and a second position defining an actuator lower limit to move the tool support relative to the hand-held portion, wherein a home position is a nominal position between the first position and the second position of each of the plurality of actuators. LII. The hand-held robotic surgical system of claim LI, wherein each of the actuators of the actuator assembly do not extend greater than within 25% of the second position of each of the actuators when the hand-held robotic surgical instrument is in the sterilization mode such that the size of the hand-held robotic surgical instrument is reduced so as to be received in the void of the sterilization container. LIII. The hand-held robotic surgical system of claim LII, wherein the hand-

held robotic surgical instrument is capable of moving the tool support relative to the hand-held portion into a pose where the hand-held robotic surgical instrument is sized such that the hand-held robotic surgical instrument cannot be received in the void when operating in the working mode. LIV. The hand-held robotic surgical system of claim XV, further comprising a tool alignment member coupled to and extending from the tool support, and a handle alignment member coupled to and extending from the hand-held portion, wherein at least a portion of the tool alignment member and at least a portion of the handle alignment member are aligned when the tool support has a desired range of motion relative to the hand-held portion. LV. The hand-held robotic surgical system of claim LIV, wherein the tool alignment member is removable from the tool support and the handle alignment member is removable from the hand-held portion, and the sterilization container defines a second void configured to receive the tool alignment member and the handle alignment member to facilitate sterilization of the tool alignment member and the handle alignment member. LVI. A hand-held medical robotic system for use with a surgical tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators; a localizer; a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of one of the surgical tool, hand-held portion and the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; determine an actuator position/joint angle value; and determine a motor status of the tool drive motor; control the tool drive motor based on the actuator position/joint angle value and the motor status. LVII. The system of claim LVI, wherein the control system is configured to determine a first actuator/joint threshold based on the motor status, and the control system is further configured to control the tool drive motor based on the actuator position/joint angle value, the first actuator/joint threshold and the motor status. LVIII. The system of claim LVII, wherein the control system is further configured to determine a second actuator/joint threshold and control the tool drive motor based on the second actuator/joint threshold and the actuator position/joint angle value, wherein the second

actuator/joint threshold is different than the first actuator/joint threshold. LIX. The system of any one of claims LVII-LVIII, wherein the first actuator/joint threshold is a first actuator threshold, and wherein the control system is configured to control the tool drive motor based on the actuator position, the first actuator threshold, and the motor status. LX. The system of any one of claims LVIII-LIX, wherein the second actuator/joint threshold is a second actuator threshold and the control system is configured to control the tool drive motor based on the second actuator threshold and the actuator position value and the motor status, wherein the second actuator threshold is different than the first actuator threshold. LXI. The system of any one of claims LVII-LX, wherein the plurality of actuators include a first actuator and a second actuator, wherein the control system determines a first actuator threshold and a second actuator threshold for the first actuator and for the second actuator, and the control system is configured to control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the first actuator and control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the second actuator. LXII. The system of claim LXI, wherein at least one of the first actuator threshold and the second actuator threshold are different for the first actuator and the second actuator. LXIII. The system of any one of claims LVIII-LXII, wherein the motor status is selected from permissive state and a restricted state, wherein in the permissive state, the tool drive motor is permitted to run and in the restricted state, the tool drive motor is restricted from running. LXIV. The system of claim LXIII, wherein the control system is configured to control the tool drive motor based on the first actuator/joint threshold and the actuator position/joint value when the motor status is determined to be in the permissive state; and wherein the control system is configured control the tool drive motor based on the second actuator/joint threshold and the actuator /joint value when the motor status is determined to be in a restricted state. LXV. The system of claim LXIV, wherein the first actuator/joint threshold and the second actuator/joint threshold are further defined as a ranges of values, and the range of values included in the first actuator/joint threshold is larger than, and encompasses, the range of values included in the second actuator/joint threshold. LXVI. The system of any one of claims LVI-LXV, wherein the actuator position/joint angle value is a current measured position, previous measured position of at least one actuator, a commanded position or combinations thereof or a current measured angle, a previous measured angle, a commanded angle, or combinations thereof. LXVII. The system of any one of claims LXIII-LXVI, wherein the control

system being configured to control the drive motor is further configured to stop the drive motor based on the first actuator/joint threshold and the actuator position/joint angle value when the motor status is in the permissive state , and the control system is configured to stop the drive motor based on the second actuator/joint threshold and the actuator position/joint angle value when the motor status is in the restricted state. LXVIII. The system of any one of claims LXIII-LXVII, wherein the control system being configured to control the drive motor is further configured to stop the drive motor when the actuator position/joint angle value is outside of a range of the first actuator/joint threshold when the motor status is in the permissive state , and the control system is configured to stop the drive motor when the actuator position/joint angle value is outside of range of the second actuator/joint threshold when the motor status is in the restricted state. LXIX. The control system of any one of claims LVI-LXVIII, wherein the control system is configured to determine, in a known coordinate system, a target pose of the surgical tool and a pose of the surgical tool, and control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool. LXX. The system of any one of claims LVI-LXIX, wherein the surgical tool is a saw blade. LXXI. The control system of any one of claims LVI-LXX, wherein the target pose is a target plane. LXXII. The system of any one of claims LVI-LXXI, wherein the control system is further configured to control the tool drive motor based on the pose of the surgical tool and a boundary. LXXIII. A hand-held medical robotic system for use with surgical tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators; a localizer; a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of one of the surgical tool, hand-held portion and the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; determine a motor status; select an actuator/joint threshold based on the pose of one of the surgical tool, hand-held portion and the tool support, a boundary, and the motor status; determine a value of the actuator position/joint angle of the actuator assembly; control the tool drive motor based on the

actuator/joint threshold and the actuator position/joint angle value. LXXIV. The system of claim LXXIII, wherein the control system is configured to select a first actuator/joint threshold when the pose of surgical tool is proximal the boundary and select a second actuator/joint threshold when the pose of the surgical tool is distal the boundary, with the first actuator/joint threshold being different from the second actuator/joint threshold. LXXV. The system of claim LXXIV, wherein the motor status is selected from permissive state and a restricted state, wherein in the permissive state, the tool drive motor is permitted to run and in the restricted state, the tool drive motor is restricted from running, and wherein the control system is configured to select the second actuator/joint threshold when the surgical tool is within the boundary and wherein the tool drive motor is in the restricted state. LXXVI. The system of claim LXXV, wherein the control system is configured to select the first actuator/joint threshold when the surgical tool is outside of the boundary and wherein the tool drive motor is in the permissive state. LXXVII. The system of any one of claims LXXV-LXXVI, wherein the control system is configured to select the first actuator/joint threshold when the surgical tool is outside of the boundary and wherein the tool drive motor is in the restricted state. LXXVIII. The system of any one of claims LXXV-LXXVII, wherein the control system is configured to select the first actuator/joint threshold when the surgical tool is outside of the boundary and wherein the tool drive motor is in the restricted state. LXXIX. The system of any one of claims LXXV-LXXVIII, wherein the control system is configured to transition the drive motor to the restricted state based on a state of the surgical tool and the boundary. LXXX. The system of any one of claims LXXIII-LXXIX, wherein the instrument weighs less than 6 lbs. LXXXI. The system of any one of claims LXXIII-LXXIX, wherein the surgical tool is a saw blade. LXXXII. The system of any one of claims LXXIII-LXXXI, wherein the boundary is based on a planned pose of an implant. LXXXIII. The system of claim LXXXII, wherein the target pose of the tool is based on the planned pose of the implant. LXXXIV. The system of any one of claims LXXIV-LXXXIII, wherein the first actuator/joint threshold is a first actuator threshold, and wherein the control system is configured to control the tool drive motor based on the actuator position value, and the first actuator threshold. LXXXV. The system of any one of claims LXXIV-LXXXIV, wherein the first actuator/joint threshold is a first actuator threshold, and wherein the control system is configured to control the tool drive motor based on the actuator position and the first actuator threshold. LXXXVI. The system of any one of claims LXXIV-LXXXV, wherein the second actuator/joint threshold is a second actuator

threshold and the control system is configured to control the tool drive motor based on the second actuator threshold and the actuator position value, wherein the second actuator threshold is different than the first actuator threshold. LXXXVII. The system of claims LXXIII-LXXXVI, wherein the plurality of actuators include a first actuator and a second actuator, wherein the control system determines a first actuator threshold and a second actuator threshold for the first actuator and for the second actuator, and the control system is configured to control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the first actuator and control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the second actuator. LXXXVIII. The system of any one of claims LXXIII-LXXXVII, wherein the second actuator/joint threshold is a second actuator threshold, and the control system is configured to control the tool drive motor based on the second actuator threshold and the actuator position value, wherein the second actuator threshold is different than the first actuator threshold. LXXXIX. The system of any one of claims LXXIII-LXXXVIII, wherein the plurality of actuators include a first actuator and a second actuator, wherein the control system determines a first actuator threshold and a second actuator threshold for the first actuator and for the second actuator, and the control system is configured to control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the first actuator and control the drive motor based on the actuator position value, the first actuator threshold, and the second actuator threshold for the second actuator. XC. A hand-held medical robotic system for use with a saw blade, the system comprising : an instrument comprising; a hand-held portion to be held by a user; a blade support coupled to the hand-held portion, the blade support comprising a saw drive motor to drive motion of the saw blade; an actuator assembly operatively interconnecting the blade support and the hand-held portion to move the blade support to move the saw blade in a plurality of degrees of freedom relative to the hand-held portion to place the saw blade at a desired pose, the actuator assembly including a plurality of actuators; a localizer; and a control system coupled to the plurality of actuators and the localizer, the control system configured to: determine, in a known coordinate system, a first target pose of the saw blade; determine a motor status at a first time; determine a pose of one of the saw blade, hand-held portion and the blade support at the first time; determine a procedure status based on the first target pose of the saw blade, the motor status at the first time, and the pose of one of the saw blade, hand-held portion and the blade support at the first time; and

limit an ability to select a second target pose of the saw blade based on the procedure status. XCI. The system of claim XC, wherein the control system is configured to enable the second target pose of the saw blade based on the procedure status. XCII. The system of claim XCI, wherein the first target pose of the saw blade is associated with a distal femur cut or a tibia cut, and wherein the second target pose is associated with one or more of the following cuts: anterior cortex cut, a posterior condyle cut, a posterior chamfer cut, or an anterior chamfer cut. XCIII. The system of any one of claims XC-XCII, wherein the motor status is based on parameter of the saw drive motor. XCIV. The system of any one of claims XC-XCIII, wherein the control system is configured to determine the procedure status based on the first target pose of the saw blade, the motor status at the first time, a the motor status at a second time, the pose of the and the pose of one of the saw blade, hand-held portion and blade support at the first time, and the pose of the and the pose of one of the saw blade, hand-held portion and the blade support at the second time. XCV. The system of any one of claims XC-XCIV, wherein the control system is configured to determine the procedure status based on the first target pose of the saw blade, the motor status at the first time, and a time duration that the pose of the hand-held portion or blade support is a particular pose. XCVI. The system of any one of claims XC-XCV, wherein the control system is configured to determine the procedure status based on the motor status of the saw drive motor at the first time, the first target pose of the saw blade and the pose of the hand-held portion or blade support at the first time and based on an input signal. XCVII. The system of claim XCVI, further comprising a user input device configured to provide the input signal. XCVIII. The system of any one of claims XC-XCVII, wherein the first target pose includes a first region to be cut, and a second region to be cut, the first region being spatially separate from the second region, wherein the control system is configured to determine the procedure status based on a status of the first region, a status of the second region, and wherein the control system is configured to determine a status of the first region and the second regions separately based on the pose of the saw blade, the hand-held portion or the blade support and the motor status at each pose. XCIX. The system of claim XCVIII, wherein the control system is further configured to determine a pose of the saw blade, blade support or the hand-held portion at a second time, and wherein the control system is configured to determine the status of the first region based on the pose of the blade support or hand-held portion and the motor status at the first time and determine the status of the first region based on the pose of the blade support and the hand-held portion and the motor status of the second time. C. The system of claim

XCIX, wherein a patient image includes a first plurality of voxels and a second plurality of voxels and wherein the first region is associated with the first plurality of voxels, and wherein the second region is associated with the second plurality of voxels. CI. The system of any one of claims XCIX-C, wherein a patient model includes the first region to be cut and the second region to be cut. CII. The system of any one of claims XCIX-CI, wherein the control system is configured to determine the procedure status based on the status of the first region and the status of the second region. CIII. The system of any one of claims XC-CII, wherein the instrument weighs less than 6 lbs. CIV. A hand-held medical robotic system for use with a saw blade, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a blade support coupled to the hand-held portion, the blade support comprising a saw drive motor to drive motion of the saw blade; an actuator assembly operatively interconnecting the blade support and the hand-held portion to move the blade support to move the saw blade in a plurality of degrees of freedom relative to the hand-held portion to place the saw blade at a desired pose, the actuator assembly including a plurality of actuators; a localizer; and a control system coupled to the plurality of actuators and the localizer, the control system configured to: determine, in a known coordinate system, a first target pose of the saw blade; determine a motor status at a first time; determine the motor status at a second time; determine a pose one of the saw blade, hand-held portion or the blade support at the first time; determine a pose of the saw blade, hand-held portion or the blade support at a second time, wherein at the first time, the instrument is in an unguided mode and at the first time, the instrument is a guided mode; and determine a procedure status based on the motor status of the saw drive motor at the first time, the motor status of the saw drive motor at the second time, the first target pose of the saw blade, the pose of the hand-held portion or blade support at the first time, and the pose of the saw blade, hand-held portion or blade support at the second time. CV. The system of claim CIV, wherein the control system is configured to limit an ability to select a second target pose of the saw blade based on the procedure status. CVI. The system of claim CV, wherein the control system is configured to enable the second target pose of the saw blade based on the procedure status. CVII. The system of claim CV, wherein the first target pose of the saw blade is associated with a distal femur cut or a tibia cut, and wherein the second target pose is associated with one or more of the following cuts: anterior cortex cut, a posterior condyle cut, a posterior chamfer cut, or an anterior chamfer cut. CVIII. The system of any one of claims CIV-CVII, wherein the motor status is based on parameter of the saw drive motor. CIX. The system of any one of claims CIV-

CVIII, wherein the control system is configured to determine the procedure status based on the first target pose of the saw blade, the motor status at the first time, a the motor status at a second time, the pose of the and the pose of one of the saw blade, hand-held portion and the blade support at the first time, and the pose of the and the pose of one of the saw blade, hand-held portion and the blade support at the second time. CX. The system of any one of claims CIV-CIX, wherein the control system is configured to determine the procedure status based on the first target pose of the saw blade, the motor status at the first time, and a time duration that the pose of the hand-held portion or blade support is a particular pose. CXI. The system of any one of claims CIV-CX, wherein the control system is configured to determine the procedure status based on the motor status of the saw drive motor at the first time, the first target pose of the saw blade and the pose of the hand-held portion or blade support at the first time and based on an input signal. CXII. The system of any one of claims CIV-CXI further comprising a user input device configured to provide the input signal. CXIII. The system of any one of claims CIV-CXII, wherein the first target pose includes a first region to be cut, and a second region to be cut, the first region being spatially separate from the second region, wherein the control system is configured to determine the procedure status based on a status of the first region, a status of the second region, and wherein the control system is configured to determine a status of the first region and the second regions separately based on the pose of the saw blade, the hand-held portion or the blade support and the motor status at each pose. CXIV. The system of claim CXIII, wherein the control system is further configured to determine a pose of the saw blade, blade support or the hand-held portion at a second time, and wherein the control system is configured to determine the status of the first region based on the pose of the blade support or hand-held portion and the motor status at the first time and determine the status of the first region based on the pose of the blade support and the hand-held portion and the motor status of the second time. CXV. The system of claim CXIII, wherein a patient image includes a first plurality of voxels and a second plurality of voxels and wherein the first region is associated with the first plurality of voxels, and wherein the second region is associated with the second plurality of voxels. CXVI. The system of any one of claims CXIII-CXV, wherein a patient model includes the first region to be cut and the second region to be cut. CXVII. The system of any one of claims XCIII-CXVI, wherein the control system is configured to determine the procedure status based on the status of the first region and the status of the second region. CXVIII. The system of any one of claims CIV-CXVII, wherein the instrument weighs less

than 6 lbs. CXIX. The system of any one of claims CIV-CXVIII, wherein .a second target pose includes a third region to be cut, and a fourth region to be cut, the third region being spatially separate from the fourth region, wherein the control system is configured to determine the procedure status based on a status of the third region, a status of the third region, and wherein the control system is configured to determine a status of the third region and the fourth regions separately based on the pose of the saw blade, the hand-held portion or the blade support and the motor status at each pose. CXX. A computer implemented method or software product for controlling a hand-held surgical robot including a plurality of actuators and a tool drive motor to position a surgical tool, the method /product including instructions to: determine a target pose of the surgical tool in a known coordinate system; determine a pose of one of the surgical tool, hand-held portion, and the tool support in the known coordinate system; generate a guide constraint based on the target pose of the surgical tool, and the pose of the hand-held portion or tool support, wherein the guide constraint includes at least one guide constraint direction and a at least one guide constraint error measured along each guide constraint direction; determine a commanded joint position of each of the plurality of actuators based on the guide constraint; and control the tool drive motor based on the guide constraint direction and the guide constraint error. CXXI. A computer implemented method or software product for controlling a hand-held surgical robot including a plurality of actuators and a tool drive motor to position a surgical saw blade, the method /product including instructions to: receive a planned pose of a surgical implant; determine a plurality of target cutting planes based on the planned pose of the surgical implant; determine a position of an instrument; set a boundary based on the position of the instrument, the boundary being associated with one of the plurality of target cutting planes; control a saw drive motor based on the set boundary; and control a plurality of actuators to align the saw blade to one of the target cutting planes. CXXII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including instructions to plan a virtual boundary for of the hand-held surgical robot comprising the steps: receiving a planned pose of a surgical implant relative to a bone in a known coordinate system; determine a plurality of target cutting planes based on the planned pose of the surgical implant in the known coordinate system; determining a pose of the bone; determining a position of a pointer in a desired location relative to the bone for a cut depth limit; and set a boundary associated with one of the plurality of target cutting planes based on the position of the pointer. CXXIII. A computer implemented method or software product

for controlling a hand-held surgical robot, the method /product including: determine, in a known coordinate system, a target pose of a tool and a pose of a hand-held portion of the hand-held surgical robot; estimate an amount of external effort applied between a tool support of the hand-held surgical robot and the hand-held portion of the hand-held surgical robot; and control an indicator based on the estimated amount of external effort applied, wherein the estimated amount of effort is a force or a torque. CXXIV. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including: determine, in a known coordinate system, a target pose of a tool and a pose of a hand-held portion of the hand-held surgical robot; estimate an amount of external effort applied between a tool support of the hand-held surgical robot and the hand-held portion of the hand-held surgical robot; and control a user interface based on the estimated amount of external effort applied, wherein the estimated amount of effort is a force or a torque. CXXV. A computer implemented method or software product for controlling a hand-held surgical robot including a hand-held portion, a tool platform, a plurality of actuators and a tool drive motor, the method /product including: determine, in a known coordinate system, a target pose of a tool the hand-held surgical robot; estimate an amount of external effort applied between a tool support of the hand-held surgical robot and the hand-held portion of the hand-held surgical robot; and control drive motor based on the estimated amount of effort applied, wherein the estimated amount of effort is a force or a torque. CXXVI. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including: determine, in a known coordinate system, a first target pose of a saw blade; determine a pose of the saw blade, a hand-held portion of the hand-held surgical robot and a blade support of the hand-held surgical robot at a first time; determine a procedure status based on the first target pose of the saw blade, and the pose of one of the saw blade, hand-held portion and the blade support at the first time; and limit an ability to select a second target pose of the saw blade based on the procedure status. CXXVII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including: determine, in a known coordinate system, a state of a surgical tool and a target pose of the surgical tool; control a plurality of actuators of the hand-held surgical robot to position the surgical tool based on the state of the surgical tool and the target pose of the surgical tool; and determine a motor status of a tool drive motor; select a guide constraint error threshold on the motor status; and control the tool drive motor based on a guide constraint error threshold, a guide constraint direction and a guide constraint error

CXXVIII. A computer implemented method or software product for controlling a hand-held surgical robot, the method /product including: determine, in a known coordinate system, a state of a surgical tool and a target pose of the surgical tool; control a plurality of actuators of the hand-held surgical robot to position the surgical tool based on the state of the surgical tool and the target pose of the surgical tool; and determine a motor status of a tool drive motor; select a error threshold on the motor status; and control the tool drive motor based on an error threshold and an error.

CXXIX. A hand-held medical robotic system for use with a surgical tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators; a localizer; a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of one of the surgical tool, hand-held portion and the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; and determine a motor status of the tool drive motor; control the tool drive motor based on a workspace limit, a pose of one of the surgical tool, hand-held portion, and the tool support and the motor status. CXXX. A hand-held medical robotic system for use with surgical tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators; a localizer; a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to: determine, in a known coordinate system, a target pose of the surgical tool and a pose of one of the surgical tool, hand-held portion and the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; determine a motor status; select a workspace limit based on the pose of one of the surgical tool, hand-held portion and the tool support, a boundary, and the motor status; control the

tool drive motor based on the workspace limit and a pose of one of the surgical tool, hand-held portion, and the tool support. CXXXI. A hand-held medical robotic system for use with surgical tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators; a localizer; a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to: determine, in a known coordinate system, a target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support; determine a motor status; based on the motor status, select one of a first drive motor control criterion and a second drive motor control criterion wherein the first drive motor control criterion includes a workspace limit and the second drive motor control criterion is based on a boundary; and control the tool drive motor based on the selected drive motor control criterion. CXXXII. A hand-held medical robotic system for use with a saw blade, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the tool; an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the tool in a plurality of degrees of freedom relative to the hand-held portion to place the tool at a desired pose, the actuator assembly including a plurality of actuators; a localizer; and a control system coupled to the plurality of actuators and the localizer, the control system configured to: determine, in a known coordinate system, a first target pose of the tool; determine a motor status at a first time; determine a pose of one of the tool, hand-held portion and the blade support at the first time; determine a procedure status based on the first target pose of the tool, the motor status at the first time, and the pose of one of the tool, hand-held portion and the blade support at the first time; and limit an ability to select a second target pose of the tool based on the procedure status. CXXXIII. A hand-held medical robotic system for use with a tool, the system comprising: an instrument comprising; a hand-held portion to be held by a user; a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the tool; an

actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the tool in a plurality of degrees of freedom relative to the hand-held portion to place the tool at a desired pose, the actuator assembly including a plurality of actuators; a localizer; and a control system coupled to the plurality of actuators and the localizer, the control system configured to: determine, in a known coordinate system, a first target pose of the tool; determine a pose of one of the tool, hand-held portion and the tool support at a first time; determine a procedure status based on the first target pose of the tool, and the pose of one of the tool, hand-held portion and the tool support at the first time; and limit an ability to select a second target pose of the tool based on the procedure status. CXXXIV. A method of controlling a hand-held robotic surgical robot, the hand-held surgical robot including a plurality of actuators, a tool drive motor and a tool, the method comprising; determining a target pose of the tool in a known coordinate system; determining a state of the tool in the known coordinate system; controlling the plurality of actuators to position the tool on a desired plane based on the state of the tool and the target pose of the tool; and permitting the tool drive motor to run when a position of one or more of the plurality of actuators is coincident with a joint limit for that actuator. CXXXV. A method of controlling a hand-held robotic surgical robot, the hand-held surgical robot including a plurality of actuators, a tool drive motor and a tool, the method comprising; determining a target pose of the tool in a known coordinate system; determining a state of the tool in the known coordinate system; controlling the plurality of actuators to position the tool on a desired plane based on the state of the tool and the target pose of the tool; and permitting the tool drive motor to run when a position of one or more of the plurality of actuators would result in the instrument encountering a workspace limit.

CLAIMS

What is claimed is:

1. A hand-held medical robotic system for use with a surgical tool, the system comprising:

an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion to support a surgical tool, the tool support comprising a tool drive motor;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to place the surgical tool, the actuator assembly including a plurality of actuators;

a localizer;

a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to:

determine a state of the surgical tool in a known coordinate system, and

determine a position and/or orientation of a reference coordinate system relative to the known coordinate system;

activate a guided mode based on a first relationship criteria between the state of the surgical tool and the reference coordinate system; and

deactivate the guided mode based on a second relationship criteria between the state of the surgical tool and the reference coordinate system,

wherein the first relationship criteria and the second relationship criteria are different.

2. The system of claim 1, wherein the guided mode is defined as a mode operable to control the plurality of actuators to align the surgical tool with a virtual object.

3. The system of claim 2, wherein the guided mode includes activation of a guide constraint configured to control the plurality of actuators to align the surgical tool with the virtual object.

4. The system of claim 3, wherein the control system further comprises:

a constraint solver to calculate a constraint force adapted to move a virtual surgical tool towards a target pose based on the guide constraint;

a virtual simulator to simulate dynamics of the virtual surgical tool in a virtual simulation based on the constraint force and to output a commanded pose; and

the control system is further configured to control each of the actuators based on the commanded pose.

5. The system of any one of claims 1-4, wherein the reference coordinate system is coincident with the known coordinate system.

6. The system of any one of claims 1-5, wherein the first relationship criteria is based on a first virtual object, and the second relationship criteria is based on a second virtual object, and the first and second virtual objects are different, wherein the pose of the first virtual object and the second virtual object are defined in the reference coordinate system.

7. The system of claim 6, wherein the first virtual object is smaller than the second virtual object, and wherein the first and second virtual objects each define volumetric regions.

8. The system of claim 7, wherein the first relationship criteria is based on the pose of the surgical tool and based on the first virtual object, and wherein the second relationship criteria is based on the pose of the surgical tool and based on the second virtual object.

9. The system of any one of claims 1-8, wherein the first relationship criteria is based on determining a first distance parameter based on the state of the surgical tool and the reference coordinate system and the second relationship criteria is based on a second distance parameter based on the state of the surgical tool and the reference coordinate system, with the first distance parameter different from the second distance parameter.

10. The system of any one of claims 6-8, wherein the first virtual object is based on a mesh.

11. The system of any one of claims 1-10, wherein the reference coordinate system is defined relative to a patient tracker.

12. The system of any one of claims 1-11, wherein the reference coordinate system is based on a target pose of the surgical tool.

13. The system of any one of claims 1-12, wherein the state of the tool is a pose of the tool.

14. The system of any one of claims 1-13, wherein the control system is further configured to control each of the plurality of the actuators such that the instrument returns to a home state

based on a based on a third relationship criteria between the state of the surgical tool and the reference coordinate system.

15. The system of claim 14, wherein the control system determines the third relationship criteria based on whether the guided mode is activated.

16. The system of any one of claims 1-15, wherein the surgical tool is a saw blade.

17. The system of any one of claims 1-16, wherein the instrument weighs less than 6 lbs.

18. A hand-held medical robotic system for use with surgical tool, the system comprising: an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the surgical tool, the actuator assembly including a plurality of actuators;

a localizer;

a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to:

determine, in a known coordinate system, a target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support;

control each of the plurality of actuators based on the target pose of the surgical tool and the pose of one of the surgical tool, hand-held portion and the tool support;

determine a motor status;

based on the motor status, select one of a first drive motor control criterion and a second drive motor control criterion wherein the first drive motor control criterion includes actuator position/joint angle of at least one actuator or joint of the actuator assembly and the second drive motor control criterion is based on a boundary; and

control the tool drive motor based on the selected drive motor control criterion.

19. The system of claim 18, wherein the control system is configured to select the first drive motor control criterion when the motor status is in a restricted state, and in the restricted state, the tool drive motor is restricted from running.

20. The system of claim 19, wherein the control system is configured to select the second drive motor control criterion when the motor status is in a permissive state, wherein in the permissive state, the tool drive motor is permitted to run.

21. The system of any one of claims 18-20, wherein the first drive motor control criterion is includes the actuator position/joint angle and an actuator/joint threshold.

22. The system of any one of claims 18-21, wherein the control system is configured to determine a transition in the motor status, and wherein the control system is configured to select one of the first drive motor control criterion and the second drive motor control criterion based on the transition.

23. The system of any one of claims 18-21, wherein the second control motor criterion is based on the boundary and the pose of the surgical tool.

24. The system of any one of claims 20-23, wherein when the second drive motor control criterion is selected, the control system is configured to transition the tool drive motor from the permissive state to the restricted state based on the boundary and the pose of the surgical tool.

25. The system of any one of claims 18-24, wherein the boundary is based on a planned pose of an implant.

26. The system of claim 25, wherein the target pose of the tool is based on the planned pose of the implant.

27. The system of any one of claims 24-26, wherein the first drive motor control criterion is based on the actuator position/joint angle of at least one actuator or joint of the actuator assembly and a first actuator/joint threshold, and wherein the control system is configured to control the tool drive motor based on the actuator position/joint angle of the at least one actuator or joint of the actuator assembly and the first actuator threshold.

28. The system of claim 27, wherein the first actuator/joint threshold is further defined as a range of values.

29. The system of any one of claims 27-28, wherein the first actuator/joint threshold is a first actuator threshold, and wherein the control system is configured to control the tool drive motor based on the actuator position and the first actuator threshold.

30. The system of any one of claims 27-29, wherein the control system being configured to control the drive motor is further configured to transition the drive motor to the permissive state based on the first actuator/joint threshold and the actuator position/joint angle value when the motor status is in the restricted state.

31. The system of any one of claims 27-30, wherein the control system being configured to control the drive motor is further configured to transition the drive motor to the permissive state when the actuator position/joint angle value is within of a range of the first actuator/joint threshold when the motor status is in the restricted state.

32. The system of any one of claims 27-31, wherein the instrument weighs less than 6 lbs.

33. The system of any one of claims 27-32, wherein the surgical tool is a saw blade.

34. A hand-held medical robotic system for use with a surgical tool, the system comprising:
an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the surgical tool;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool in a plurality of controlled degrees of freedom relative to the hand-held portion to place the surgical tool at a desired pose, the actuator assembly being incapable of repositioning the surgical tool in at least one uncontrolled degree of freedom, the actuator assembly including a plurality of actuators;

a localizer; and

a control system coupled to the plurality of actuators and the localizer, the control system configured to:

determine, in a known coordinate system, a state of the surgical tool and a target pose of the surgical tool,

control the plurality of actuators to position the surgical tool in the plurality of controlled degrees of freedom based on the state of the tool and the target pose of the surgical tool; and

determine a motor status of the tool drive motor;

select a boundary based on the motor status; and

control the tool drive motor based the state of the surgical tool in the at least one uncontrolled degree of freedom and based on the selected boundary.

35. The system of claim 34, wherein the motor status is selected from permissive state and a restricted state, wherein in the permissive state, the tool drive motor is permitted to run and in the restricted state, the tool drive motor is restricted from running, and wherein the boundary is further characterized as a first boundary, and wherein the control system is configured to select from the first boundary and a second boundary, and wherein the control system is configured to select the second boundary when the tool drive motor is in the restricted state, and wherein the control system is configured to select the first boundary when the tool drive motor is in a permissive state.

36. The system of claim 35, wherein the control system is configured to control the tool drive motor by stopping the tool drive motor based on the state of the surgical tool in the at least one uncontrolled degree of freedom and based on the selected boundary.

37. The system of any one of claims 34-36, wherein the instrument weighs less than 6 lbs.

38. The system of any one of claims 34-37, wherein the surgical tool is a saw blade.

39. The system of any one of claims 35-38, wherein the first boundary is defined by a first virtual object, and the second boundary is defined by a second virtual object, wherein the first and second virtual objects are different.

40. The system of claim 39, wherein the first virtual object is a first plane and the second virtual object is a second plane, and the first plane is parallel to the second plane.

41. The system of claim 40, wherein the control system is configured to control the tool drive motor by transitioning the tool drive motor to the restricted state from the permissive state based on the state of the tool and the first virtual object, and the control system is configured to control the tool drive motor by transitioning the tool drive motor from the restricted state based on the state of the tool and the second virtual object.

42. The system of any one of claims 35-41, wherein the first boundary is based on a planned pose of an implant.

43. The system of claim 42, wherein the target pose of the tool is based on planned pose of the implant.

44. A hand-held medical robotic system for use with a surgical tool, the system comprising:

an instrument comprising;

- a hand-held portion to be held by a user;
- a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the surgical tool;
- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool in a plurality of controlled degrees of freedom relative to the hand-held portion to place the surgical tool at a desired pose, the actuator assembly being incapable of repositioning the surgical tool in at least one uncontrolled degree of freedom, the actuator assembly including a plurality of actuators;
- a localizer; and
- a control system coupled to the plurality of actuators and the localizer, the control system configured to: determine, in a known coordinate system, a state of the surgical tool and a target pose of the surgical tool,
- control the plurality of actuators to position the surgical tool in the plurality of controlled degrees of freedom based on the state of the surgical tool and the target pose of the surgical tool; and
- determine a motor status of the tool drive motor;
- select a distance parameter on the motor status; and
- control the tool drive motor based the state of the surgical tool in the at least one uncontrolled degree of freedom and the selected distance parameter.

45. The system of claim 44, wherein the motor status is selected from permissive state and a restricted state, wherein in the permissive state, the tool drive motor is permitted to run and in the restricted state, the tool drive motor is restricted from running, wherein the distance parameter is characterized as a first distance parameter, and wherein the control system is configured to select the first distance parameter when the tool drive motor is in a permissive state, and wherein the control system is configured to select a second distance parameter when the tool drive motor is in the restricted state, and wherein the first and second distance parameters are different.

46. The system of claim 45, wherein the control system is configured to control the tool drive motor by stopping the tool drive motor based on the state of the surgical tool in the at least uncontrolled degree of freedom and based on the selected distance parameter.

47. The system of any one of claims 44-46, wherein the instrument weighs less than 6 lbs.

48. The system of any one of claims 44-47, wherein the surgical tool is a saw blade.

49. The system of any one of claims 45-48, wherein the first distance parameter is based on a planned pose of an implant.

50. The system of claim 49, wherein the target pose of the tool is based on the planned pose of the implant.

51. A hand-held medical robotic system for use with a surgical tool, the system comprising: an instrument comprising:

- a hand-held portion to be held by a user;

- a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the tool;

- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool in a plurality of degrees of freedom relative to the hand-held portion to place the surgical tool at a desired pose, the actuator assembly including a plurality of actuators;

- a first tracker for being coupled to a tool;

- a second tracker for being coupled to a patient;

- a localizer; and

- a control system coupled to the plurality of actuators and the localizer, the control system configured to:

- determine a pose of one of the surgical tool, hand-held portion and the tool support based on the first tracker and a pose of a portion of a patient's anatomy based on the second tracker;

- control the plurality of actuators to position the surgical tool based on the pose of one of the surgical tool, hand-held portion and the tool support and the pose of the portion of the patient's anatomy;

- determine that an occlusion event has occurred for one of the first tracker and the second tracker; and

control the tool drive motor based the occlusion event.

52. The system of claim 51, wherein the control system is configured to control the tool drive motor such that the tool drive motor is placed in a restricted state where the tool drive motor is restricted from running.

53. The system of claim 52, wherein the control system is configured to control the tool drive motor such that the tool drive motor is placed in a permissive state where the tool drive motor is permitted to run.

54. The system of claim 53, wherein the control system is further configured to select, based on a motor status, a first time period or a second time period, and the control the tool drive motor based on the occlusion event and based on the selected one of the first time period and the second time period.

55. The system of claim 54, wherein the control system is configured to select the first time period when the motor status is in the permissive state and select the second time period when the motor status is in the restricted state, and wherein the first time period is different than the second time period.

56. The system of claim 55, wherein the first tracker and the second tracker include optical tracking elements.

57. The system of any one of claims 55-56, wherein the first time period is longer than the second time period.

58. The system of any one of claims 55-57, wherein the control system is configured to transition the tool drive motor from the permissive state to the restricted state when the occlusion event has a duration that exceeds the first time period.

59. The system of any one of claims 55-58, wherein the control system is configured to transition the tool drive motor from the restricted state to the permissive state when there is no occlusion event for a duration that exceeds the second time period.

60. The system of any one of claims 56-59, wherein the optical tracking elements are LEDs.

61. The system of any one of claims 51-60, wherein the instrument weighs less than 6 lbs.

62. The system of any one of claims 51-61, wherein the surgical tool is a saw blade.

63. A hand-held medical robotic system for use with a surgical tool, the system comprising

:

an instrument comprising;

 a hand-held portion to be held by a user;

 a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the surgical tool;

 an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool in a plurality of degrees of freedom relative to the hand-held portion to place the surgical tool at a desired pose, the actuator assembly including a plurality of actuators;

 a first tracker for being coupled to the instrument;

 a second tracker coupled to a patient;

 a localizer; and

 a control system coupled to the plurality of actuators and the localizer,

the control system configured to:

 determine, in a known coordinate system, a pose of one of the surgical tool, hand-held portion and the tool support based on the first tracker and a pose of a portion of a patient's anatomy based on the second tracker;

 control the plurality of actuators to position the surgical tool based on the pose of one of the surgical tool, hand-held portion and the tool support and the pose of the portion of the patient's anatomy;

 determine a motor status;

 determine that a tracking status for at least one of the first tracker and the second tracker;

 based on the motor status and the tracking status, select one of a first drive motor control criterion and a second drive motor control criterion; wherein the first drive motor control criterion includes a first time period; and the second drive motor control criterion includes a second time period, wherein the first time period is different than the second time period; and

 control the tool drive motor based on the selected drive motor control criterion.

64. The system of claim 63, wherein the control system is configured to select the first drive motor control criterion when the motor status is in a permissive state and the tracking status is occluded for at least one of the first tracker and the second tracker, and in the permissive state, the tool drive motor is permitted to run.

65. The system of claim 64, wherein the control system is configured to select the second drive motor control criterion when the motor status is in a restricted state and the tracking status is unoccluded for at both the first tracker and the second tracker, and in the restricted state, the tool drive motor is restricted from running.

66. The system of any one of claims 63-65, wherein the first time period is smaller than the second time period.

67. The system of claim 65, wherein the control system is configured to control the tool drive motor based on a duration of the tracking status being occluded and the first time period.

68. The system of claim 67, wherein the control system is configured to set the tool drive motor to a restricted state when the duration of the tracking status being occluded exceeds the first time period.

69. The system of any one of claims 65-68, wherein the control system is configured to control the tool drive motor based on a duration of the tracking status being unoccluded and the second time period.

70. The system of claim 69, wherein the control system is configured to set the tool drive motor to a permissive state when the duration of the tracking status being unoccluded exceeds the second time period.

71. The system of any one of claims 63-70, wherein the instrument weighs less than 6 lbs.

72. The system of any one of claims 63-70, wherein the surgical tool is a saw blade.

73. A hand-held medical robotic system for use with a surgical tool, the system comprising:
an instrument comprising;

 a hand-held portion to be held by a user;

 a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;

 an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-

held portion, the actuator assembly including a plurality of actuators; a control system coupled to the plurality of actuators and the tool drive motor,
a localizer;

a control system coupled to the plurality of actuators and the localizer, the control system configured to:

determine a pose of one of the surgical tool, hand-held portion and the tool support and a target pose of the surgical tool,

control the plurality of actuators to position the surgical tool based on a pose of one of the surgical tool, hand-held portion and the tool support and the target pose of the surgical tool;

receive an input signal that is indicative of a desire to move the plurality of actuators to a home state of the instrument,

determine an initial state of the instrument based on the input signal; and

control the system based on the initial state of the instrument.

74. The system of claim 73, wherein the control system is configured to provide an indication to the user based on the initial state.

75. The system of claim 74, wherein the indication is a tactile alert, a visual alert, or an audio alert.

76. The system of any one of claims 73-75, wherein the control system is configured to control the tool drive motor based on the initial state of the instrument.

77. The system of any one of claims 73-76, wherein the control system is configured to control the system based on the initial state and a first virtual object.

78. The system of claim 77, wherein the control system is configured to determine a distance based on a pose of one of the surgical tool, hand-held portion and the tool support and control the system based on the initial state and the distance.

79. The system of any one of claims 73-78, wherein the control system is configured to control the system based on the initial state of the instrument based on determining a degree of alignment of the tool support relative to the hand-held portion based on the initial state and the home state of the instrument.

80. The system of claim 79, wherein the degree of alignment is calculated by determining a position of at least one actuator of the plurality of actuators at the initial state of the instrument and a position of the at least one actuator corresponding to the home state.

81. The system of any one of claims 79-80, the degree of alignment is calculated based on a pose of the surgical tool, tool support or hand-held portion while the instrument is in the initial state and the pose of the surgical tool, tool support or hand-held portion while the instrument is in the home state.

82. The system of any one of claims 79-81, wherein the control system is configured to provide an indication to the user based on the degree of alignment.

83. The system of claim 82, wherein the indication is a tactile alert, a visual alert, or an audio alert.

84. The system of any one of claims 79-83, wherein the control system is configured to control the tool drive motor based on the input signal and the degree of alignment

85. The system of any one of claims 79-84, wherein the control system is configured to set the tool drive motor to a restricted state based on the degree of alignment and an alignment threshold at the time of the control system receiving the input signal.

86. The system of claim 85, wherein the control system is configured to set the tool drive motor to the restricted state when the degree of alignment exceeds the alignment threshold at the time of the control system receiving the input signal.

87. The system of any one of claims 73-86, wherein the home state of the instrument is defined by each of the actuators being at a median position.

88. The system of any one of claims 73-87, wherein the home state of the instrument is defined by each of the actuators being at a position of 40-60 % of a range of motion of each actuator.

89. The system of any one of claims 79-88, wherein the control system is configured to control the system based on the degree of alignment and a virtual object.

90. The system of claim 89, wherein the control system is configured to determine a distance based on the pose of the surgical tool, hand-held portion or tool support and control the system based on the distance.

91. The system of any one of claims 79-90, wherein the initial state of the instrument is computed based on a commanded or measured pose of the tool support or hand-held portion.

92. The system of any one of claims 79-90, wherein the instrument weighs less than 6 lbs.

93. The system of any one of claims 79-92, wherein the surgical tool is a saw blade.

94. A hand-held medical robotic system for use with a surgical tool, the system comprising:

- an instrument comprising;

- a hand-held portion to be held by a user;

- a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;

- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion, the actuator assembly including a plurality of actuators;

- a localizer;

- a control system coupled to the plurality of actuators, the localizer, and the tool drive motor,

- the control system configured to:

- determine a target pose of the surgical tool in a known coordinate system;

- determine a pose of one of the surgical tool, hand-held portion and the tool support in the known coordinate system;

- generate a guide constraint based on the target pose of the surgical tool, the pose of the hand-held portion or tool support, and a guide constraint tuning parameter, wherein the guide constraint tuning parameter has a first value;

- generate a joint centering constraint based on a position of at least one of the plurality of actuators, a centering position for at least one actuator of the plurality of actuators, and a joint centering tuning parameter,

- wherein the joint centering tuning parameter has a second value and

- determine a commanded joint position of each of the plurality of actuators based on the guide constraint while the system is operating in a guided mode; and

- determine a commanded joint position based on the joint centering constraint when in transitioning from the guided mode to an unguided mode, wherein the value of the joint centering tuning parameter is different than the value of the guide constraint tuning parameter.

95. The system of claim 94, wherein the joint centering tuning parameter affects a stiffness or a damping of the joint centering constraint.

96. The system of any one of claims 94-95, wherein the target pose of the surgical tool is defined by a position in a first degree of freedom, a first angle, and a second angle in the known coordinate system.

97. The system of any one of claims 94-96, wherein the surgical tool is a saw blade.

98. The system of any one of claims 94-97, wherein the instrument weighs less than 6 lbs.

99. The system of any one of claims 94-98, further comprising an input device, the control system configured to transition from the guided mode to the unguided mode based on receipt of an input signal provided by the input device.

100. The system of any one of claims 94-99, further comprising an input device, the control system configured to transition from the unguided mode to the guided mode based on receipt of an input signal provided by the input device.

101. A hand-held medical robotic system for use with a surgical tool, the system comprising:

- an instrument comprising;

- a hand-held portion to be held by a user;

- a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;

- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion, the actuator assembly including a plurality of actuators

- a localizer;

- a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to:

- determine, in a known coordinate system, a pose of one of the surgical tool, hand-held portion and the tool support and a target pose of the surgical tool,

- wherein in a guided mode, the control system is configured to control the plurality of actuators to position the surgical tool based on a pose of one of the surgical tool, hand-held portion and the tool support and the target pose of the surgical tool;

receive an input signal to transition to between the guided mode and an unguided mode wherein the instrument assumes a home state,

in response to receiving the input signal:

determine a velocity based on the target pose of the surgical tool and a pose of the surgical tool, hand-held portion or tool support;

control the plurality of actuators to move at a first velocity based on the velocity and a first velocity threshold during a first time period; and

control the plurality of actuators to move at a second velocity based on the velocity and a second velocity threshold during a second time period, the first velocity threshold being greater or lesser than the second velocity threshold.

102. The system of claim 101, wherein the velocity is a commanded velocity or a measured velocity.

103. The system of any one of claims 101-102, wherein the instrument weighs less than 6 lbs.

104. The system of any one of claims 101-103, wherein the surgical tool is a saw blade.

105. The system of any one of claims 101-104, wherein the first velocity and the second velocity are defined with respect to a Cartesian reference frame.

106. The system of any one of claims 101-105, wherein the first velocity threshold and the second velocity threshold are obtained based a velocity limiting function that is function of an acceleration of the surgical tool.

107. The system of any one of claims 101-106, wherein the second velocity threshold results in a force that would not cause the hand-held portion of the instrument to move abruptly in a user's hand.

108. A hand-held medical robotic system for use with a surgical tool, the system comprising:

a hand-held instrument comprising:

a hand-held portion to be held by a user;

a blade support movably coupled to the hand-held portion to support the surgical tool, an actuator assembly operatively interconnecting the blade support and the hand-held portion, the actuator assembly including a plurality of actuators, the blade support including a saw drive motor,

a localizer, and

a control system configured to

determine a target pose of a saw blade in a known coordinate system;

determine a state of the saw blade in the known coordinate system;

determine a value of a tuning parameter based receipt of an input signal to transition between an unguided mode where instrument assumes a home state to a guided mode; wherein the guided mode, the plurality of actuators are controlled to align the saw blade based on a guide constraint;

generate the guide constraint based on the target pose of the saw blade and the pose of the hand-held portion or tool support and based on the value of the tuning parameter;

calculate a constraint force adapted to move a virtual saw blade based on the guide constraint;

simulate dynamics of the virtual saw blade in a virtual simulation based on the constraint force, and to output a commanded pose based on the virtual simulation; and

control each of plurality of actuators based on the commanded pose.

109. The system of claim 108, wherein the value of the tuning parameter is defined by a function of time.

110. The system of claim 109, wherein the function is initiated based on receipt of the input signal to transition between the unguided mode and the guided mode.

111. The system of any one of claims 109-110, wherein the function is defined such that the value of the tuning parameter changes over time.

112. The system of claim 111, wherein the function results in the tool support moving slower at a first time than at a second time, the second time being after the first time and the first time being after receipt of the input signal.

113. The system of any one of claims 108-112, wherein the instrument weighs less than 6 lbs.

114. The system of any one of claims 108-113, wherein the surgical tool is a saw blade.

115. A hand-held medical robotic system for use with a surgical tool, the system comprising:

- an instrument comprising;
 - a hand-held portion to be held by a user;
 - a tool support coupled to the hand-held portion to support a surgical tool, the tool support comprising a tool drive motor;
 - an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to place the surgical tool, the actuator assembly including a plurality of actuators;
 - a localizer;
 - a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to:
 - determine a state of the surgical tool, and
 - determine a position and/or orientation of a patient;
 - activate guided mode based on a first relationship criteria between the state of the surgical tool and the state of the patient or patient anatomy; and
 - deactivate guided mode based on a second relationship criteria between the state of the surgical tool and the patient,
 - wherein the first relationship criteria and the second relationship criteria are different.
- 116. A hand-held medical robotic system for use with a surgical tool, the system comprising:
 - an instrument comprising;
 - a hand-held portion to be held by a user;
 - a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;
 - an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion, the actuator assembly including a plurality of actuators;
 - a localizer;
 - a control system coupled to the plurality of actuators, the localizer, and the tool drive motor,

the control system configured to:

determine a target pose of the surgical tool in a known coordinate system;

determine a pose of one of the surgical tool, hand-held portion, and the tool support in the known coordinate system;

generate a guide constraint based on the target pose of the surgical tool, and the pose of the surgical tool, hand-held portion or tool support, wherein the guide constraint includes at least one guide constraint direction and a at least one guide constraint error measured along each guide constraint direction;

determine a commanded joint position of each of the plurality of actuators based on the guide constraint; and

control the tool drive motor based on the guide constraint direction and the guide constraint error.

117. The system of claim 116, wherein the control system is configured to generate a second guide constraint based on the target pose of the surgical tool and the pose of the hand-held portion or the tool support, wherein the guide constraint is a first guide constraint, the guide constraint direction is a first guide constraint direction and the guide constraint error is a first guide constraint error and wherein the first guide constraint direction is in a first degree of freedom and the second guide constraint has a second guide constraint direction in a second degree of freedom different from the first degree of freedom, and wherein the control system is configured to control the tool drive motor based on the first guide constraint and the second guide constraint.

118. The system of claim 117, wherein the control system is configured to control the tool drive motor based on the guide constraint error and a guide constraint error threshold.

119. The system of claim 118, wherein the first guide constraint direction is in a first degree of freedom, and wherein the first degree of freedom is a translation degree of freedom or an orientation of degree of freedom.

120. The system of claim 119, wherein first degree of freedom is a translation degree of freedom and wherein the guide constraint error threshold is a translation threshold.

121. The system of any one of claims 119-120, wherein the control system is configured to control the tool drive motor based on the guide constraint error, wherein the guide constraint error threshold is an error range.

122. The system of claim 21, wherein the error range is asymmetrical about a median value of zero.

123. The system of any one of claims 120-122, wherein the translation threshold is further defined as a first translation threshold and a second translation threshold, wherein the control system is configured to select one of the first translation threshold and the second translation threshold based on the pose of one of the surgical tool, hand-held portion, and the tool support in the known coordinate system, and wherein the first and second translation thresholds are different.

124. The system of any one of claims 116-123, wherein the control system is configured to receive a planned pose of an implant in the known coordinate system and wherein the target pose of the surgical tool is based on the planned pose of the implant.

125. The system of claim 124, wherein the target pose of the surgical tool is defined by a position in a first degree of freedom, a first angle, and a second angle in the known coordinate system.

126. The system of any one of claims 124-125, wherein the surgical tool is a saw blade.

127. The system of any one of claims 116-126, wherein the guide constraint direction is a unit vector that describes an axis of rotation or a direction of translation.

128. The system of claim 127, wherein the guide constraint error is an angle about the axis of rotation or a distance about the direction of translation.

129. A hand-held medical robotic system for use with a surgical tool, the system comprising:
an instrument comprising;

 a hand-held portion to be held by a user;

 a blade support coupled to the hand-held portion to support a saw blade, the blade support comprising a saw drive motor;

 an actuator assembly operatively interconnecting the blade support and the hand-held portion to move the blade support in a plurality of degrees of freedom relative to the hand-held portion to place the saw blade, the actuator assembly including a plurality of actuators;

 a localizer;

 a second instrument;

 a control system coupled to the plurality of actuators, the localizer, and the saw drive motor, the control system configured to:

 receive a planned pose of a surgical implant;

- determine a plurality of target cutting planes based on the planned pose of the surgical implant;
 - determine a position of the second instrument;
 - set a boundary based on the position of the second instrument, the boundary being associated with one of the plurality of target cutting planes;
 - control the saw drive motor based on the set boundary; and
 - control the plurality of actuators to align the saw blade to one of the target cutting planes.
130. The system of claim 129, wherein the boundary is a three-dimensional object.
131. The system of claim 130, wherein the three-dimensional object intersects one of the target cutting planes.
132. The system of any one of claims 129-131, wherein the second instrument is a pointer.
133. A method of virtually planning a virtual boundary for of a surgical instrument for a bone on a patient, the method comprising the steps:
- receiving a planned pose of a surgical implant relative to the bone in a known coordinate system;
 - determine a plurality of target cutting planes based on the planned pose of the surgical implant in the known coordinate system;
 - determining a pose of the bone;
 - positioning a pointer in a desired location relative to the bone for a cut depth limit;
 - determining a position of the pointer; and
 - set a boundary associated with one of the plurality of target cutting planes based on the position of the pointer.
134. The method of claim 133, wherein the boundary is a three-dimensional object.
135. The method of claim 134, wherein the three-dimensional object intersects one of the target cutting planes.
136. The method of any one of claims 134-135, wherein the three-dimensional object is perpendicular to one of the target cutting planes.
137. The method of any one of claims 133-136, wherein the step of positioning a pointer is further defined as positioning the pointer to contact a surface of a tibia.
138. A hand-held medical robotic system for use with a tool, the system comprising:

an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion to support the tool, the tool support comprising a tool drive motor;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the tool, the actuator assembly including a plurality of actuators;

a localizer;

a control system coupled to the plurality of actuators, the localizer, and the tool drive motor, the control system configured to

determine, in a known coordinate system, a target pose of the tool and a pose of the hand-held portion;

estimate an amount of external effort applied between the tool support and the hand-held portion; and

control an indicator based on the estimated amount of external effort applied, wherein the estimated amount of effort is a force or a torque.

139. The system of claim 138, wherein the control system is configured to control the indicator based on the estimated amount of external force and a force threshold.

140. The system of any one of claims 138-139, wherein the control system is configured to control the indicator based on the estimated amount of external force and a force threshold and an error counter.

141. The system of any one of claim 138-140, wherein the control system is configured to control the indicator based on the amount of external force and based on a time threshold.

142. The system of any one of claims 139-141, wherein estimated amount of external force comprises a first force component and a second force component, the first force component having a first direction and the second force component having a second direction, the first direction being different than the second direction, and wherein the force threshold includes a first force threshold and a second force threshold, wherein the control system is configured to control the indicator based on the first force component and the first force threshold, control the indicator based on the second force component and the second force threshold, or control the indicator based on the first

force component, the second force component, the first force threshold, and the second force threshold.

143. The system of claim 142, wherein the first and second directions are defined in the known coordinate system.

144. The system of any one of claims 139-143, wherein estimated amount of external force comprises a first force component and a second force component, the first force component corresponding to a first actuator of the plurality of actuators and the second force component corresponding to a second actuator of the plurality of actuators, the first actuator being different than the second actuator, and wherein the force threshold includes a first force threshold and a second force threshold, wherein the control system is configured to control the indicator based on the first force component and the first force threshold, control the indicator based on the second force component and the second force threshold, or control the indicator based on the first force component, the second force component, the first force threshold, and the second force threshold.

145. The system of any one of claims 137-144, wherein the indicator is selected from a visual indicator, an audible indicator, or a tactile indicator.

146. The system of any one of claims 137-144, wherein the instrument includes one or more current sensors configured to detect an amount of current supplied to each of the plurality of actuators; the control system is configured to estimate an amount of external effort applied between the tool support and the hand-held portion based on an output of the one or more current sensors.

147. The system of any one of claims 137-146, wherein the instrument includes one or more force or torque sensors configured to detect an amount of force or torque applied, and wherein the control system is configured to estimate the amount of external effort applied between the tool support and the hand-held portion based on an output of the one or more force or torque sensors.

148. A hand-held medical robotic system for use with a tool, the system comprising:

- an instrument comprising;

- a hand-held portion to be held by a user;

- a tool support coupled to the hand-held portion to support the tool, the tool support comprising a tool drive motor and a surgical tool;

- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the tool, the actuator assembly including a plurality of actuators;

a localizer;
a control system coupled to the plurality of actuators, the localizer, and the tool drive motor,
the control system configured to
 determine, in a known coordinate system, a target pose of the tool and a pose of the
hand-held portion;
 estimate an amount of external effort applied between the tool support and the hand-
held portion; and
 control a user interface based on the estimated amount of external effort applied,
wherein the estimated amount of effort is a force or a torque.

149. The system of claim 148, wherein the control system is configured to control the user interface to prompt a user to check a tool to instrument registration based on the estimated amount of external effort applied.

150. The system of any one of claims 148-149, wherein the control system is configured to control the user interface to initiate a tool to instrument registration workflow based on the estimated amount of external effort applied.

151. A hand-held medical robotic system for use with a tool, the system comprising:

an instrument comprising;
 a hand-held portion to be held by a user;
 a tool support coupled to the hand-held portion to support the tool, the tool support comprising a tool drive motor;
 an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion to align the tool, the actuator assembly including a plurality of actuators;
a localizer;
a control system coupled to the plurality of actuators, the localizer, and the tool drive motor,
the control system configured to
 determine, in a known coordinate system, a target pose of the tool and a pose of the
hand-held portion;
 determine, in a known coordinate system, a target pose of the tool and a pose of the
hand-held portion;

estimate an amount of external effort applied between the tool support and the hand-held portion; and

control drive motor based on the estimated amount of effort applied, wherein the estimated amount of effort is a force or a torque.

152. A hand-held medical robotic system for use with a saw blade, the system comprising: an instrument comprising;

a hand-held portion to be held by a user;

a blade support coupled to the hand-held portion, the blade support comprising a saw drive motor to drive motion of the saw blade;

an actuator assembly operatively interconnecting the blade support and the hand-held portion to move the blade support to move the saw blade in a plurality of degrees of freedom relative to the hand-held portion to place the saw blade at a desired pose, the actuator assembly including a plurality of actuators;

a localizer; and

a control system coupled to the plurality of actuators and the localizer,

the control system configured to:

determine, in a known coordinate system, a first target pose of the saw blade;

determine a pose of one of the saw blade, hand-held portion and the blade support at a first time;

determine a procedure status based on the first target pose of the saw blade, and the pose of one of the saw blade, hand-held portion and the blade support at the first time; and

limit an ability to select a second target pose of the saw blade based on the procedure status.

153. A hand-held medical robotic system for use with a surgical tool, the system comprising :

an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the surgical tool;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool in a plurality of controlled degrees of freedom relative to the hand-held portion to place the surgical tool at a desired pose, the actuator assembly being incapable of repositioning the surgical tool in at least one uncontrolled degree of freedom, the actuator assembly including a plurality of actuators;

a localizer; and

a control system coupled to the plurality of actuators and the localizer, the control system configured to:

determine, in a known coordinate system, a state of the surgical tool and a target pose of the surgical tool;

control the plurality of actuators to position the surgical tool in the plurality of controlled degrees of freedom based on the state of the surgical tool and the target pose of the surgical tool; and

determine a motor status of the tool drive motor;

select a guide constraint error threshold on the motor status; and

control the tool drive motor based on a guide constraint error threshold, a guide constraint direction and a guide constraint error.

154. A hand-held medical robotic system for use with a surgical tool, the system comprising :

an instrument comprising;

a hand-held portion to be held by a user;

a tool support coupled to the hand-held portion, the tool support comprising a tool drive motor to drive motion of the surgical tool;

an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support to move the surgical tool relative to the hand-held portion to place the surgical tool at a desired pose in one or more degrees of freedom, the actuator assembly including a plurality of actuators;

a localizer; and

a control system coupled to the plurality of actuators and the localizer, the control system configured to:

determine, in a known coordinate system, a state of the surgical tool and a target pose of the surgical tool,

control the plurality of actuators to position the surgical tool based on the state of the surgical tool and the target pose of the surgical tool; and

determine a motor status of the tool drive motor;

determine an error value between the state of the surgical tool and the target pose of the surgical tool in at least one degree of freedom;

based on the motor status, select an error threshold for the at least one degree of freedom; and

control the tool drive motor based on the selected error threshold and the error value.

155. The system of claim 154, wherein the state of the tool is selected from a current position of the tool or a previously commanded position of the tool.

156. The system of claim 155, wherein the error threshold is an error range, and wherein the control system is configured to control the tool drive motor based on the selected error range and based on the error value.

157. The system of claim 156, wherein the motor status is selected from permissive state and a restricted state, wherein in the permissive state, the tool drive motor is permitted to run and in the restricted state, the tool drive motor is restricted from running, and wherein the error threshold is further characterized as a first error range, and wherein the control system is configured to select from the first error range and a second error range, and wherein the control system is configured to select the second error range when the tool drive motor is in the restricted state, and wherein the control system is configured to select the first error range when the tool drive motor is in a permissive state.

158. The system of claim 156, wherein the at least one degree of freedom is an elevation degree of freedom.

159. The system of claim 158, wherein the at least one degree of freedom is a first degree of freedom and the error value is a first value, the control system is configured to determine a second error value in a second degree of freedom based on the target pose of the surgical tool and the pose of the surgical tool, hand-held portion or the tool support, wherein the second degree of freedom is different from the first degree of freedom, and wherein the control system is configured

to control the tool drive motor based on the first error value and a first error threshold and control the tool drive motor based on the second error value and a second error threshold.

160. A hand-held medical robotic system for use with a surgical tool, the system comprising:

- an instrument comprising;

- a hand-held portion to be held by a user;

- a tool support coupled to the hand-held portion to support the surgical tool, the tool support comprising a tool drive motor;

- an actuator assembly operatively interconnecting the tool support and the hand-held portion to move the tool support in a plurality of degrees of freedom relative to the hand-held portion, the actuator assembly including a plurality of actuators;

- a localizer;

- a control system coupled to the plurality of actuators, the localizer, and the tool drive motor,

- the control system configured to:

- determine, in a known coordinate system, a target pose of the tool in a known coordinate system;

- determine a state of one of the surgical tool in the known coordinate system;

- control the plurality of actuators to position the surgical tool based on the state of the surgical tool and the target pose of the surgical tool;

- determine an error value between the state of the surgical tool and the target pose of the surgical tool in at least one degree of freedom; and

- control the tool drive motor based on an error threshold and the error value for the at least one degree of freedom.

161. The system of claim 160, wherein the control system is configured to maintain a motor status of the tool drive motor in a permissive state when a position of one or more plurality of actuators is coincident with a joint for that actuator.

162. A method of controlling a hand-held robotic surgical robot, the hand-held surgical robot including a plurality of actuators, a saw drive motor and a surgical saw blade, the method comprising;

- determining a target pose of the saw blade in a known coordinate system;

determining a state of the surgical saw blade in the known coordinate system;
controlling the plurality of actuators to position the surgical saw blade on a desired plane based on the state of the surgical saw blade and the target pose of the surgical saw blade; and
permitting the saw drive motor to run when a position of one or more of the plurality of actuators is coincident with a joint limit for that actuator.

163. The method of claim 162, wherein the step of permitting is further defined as permitting the saw drive motor to run without consideration of the position of one or more of the plurality of actuators.

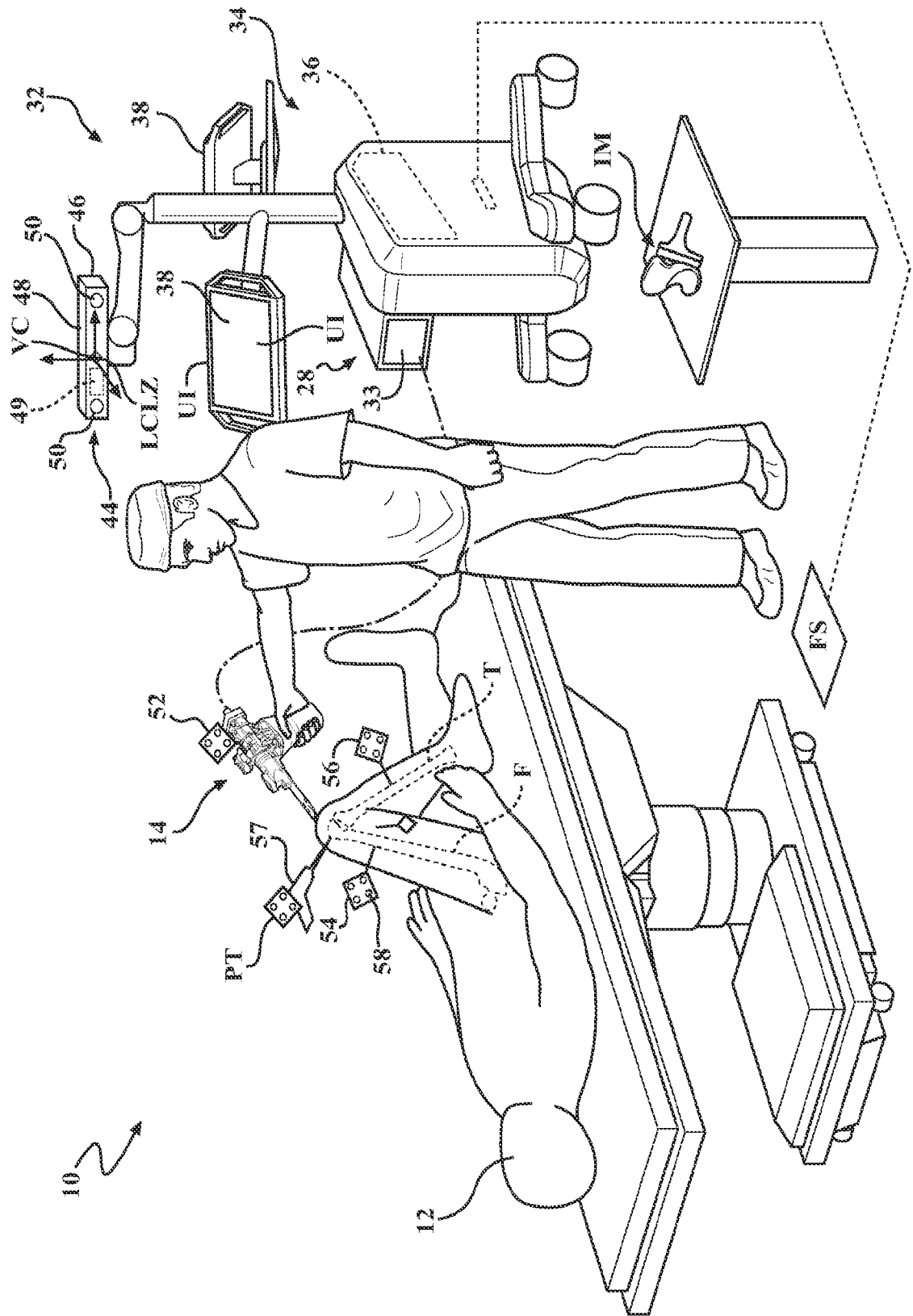
164. The method of claim 162, wherein the position of the actuator is a measured position, a commanded position, a previous measured position, or a previous commanded position.

165. The method of claim 162, wherein the step of permitting is further defined as permitting the saw drive motor to run so long as the saw blade does not violate a distal boundary and so long as the saw blade is within bone.

166. The method of claim 165, wherein the step of permitting is further defined as permitting the saw drive motor to run so long as the saw blade is close to the desired plane.

167. The method of claim 165, wherein the step of permitting is further defined as permitting the saw drive motor so long as the saw blade is within an error threshold in one or more degrees of freedom.

168. The method of claim 165, wherein the step of permitting is further defined as permitting the saw drive motor so long as the saw blade within an error threshold in each of at least three or more degrees of freedom.



LIGHT

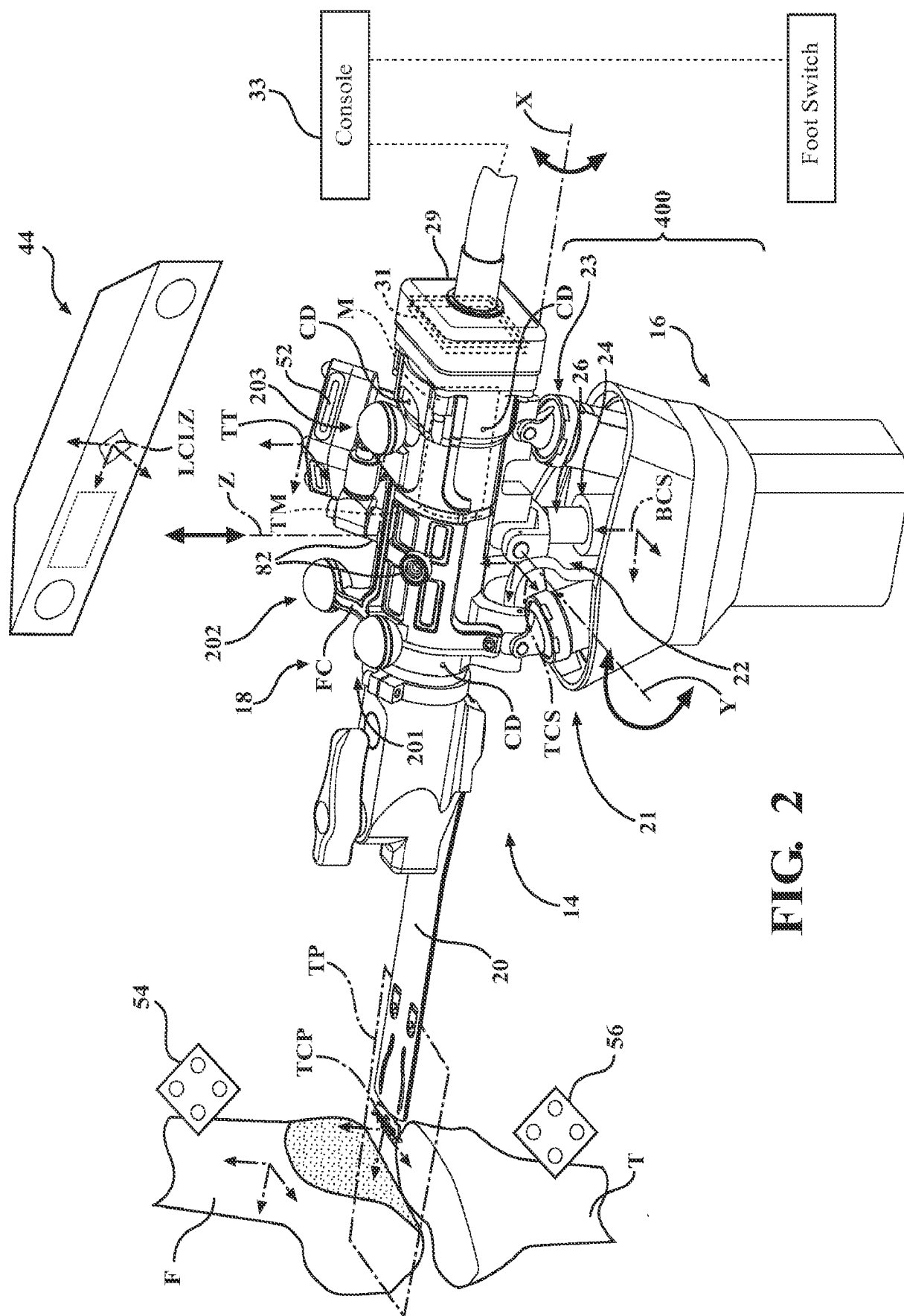
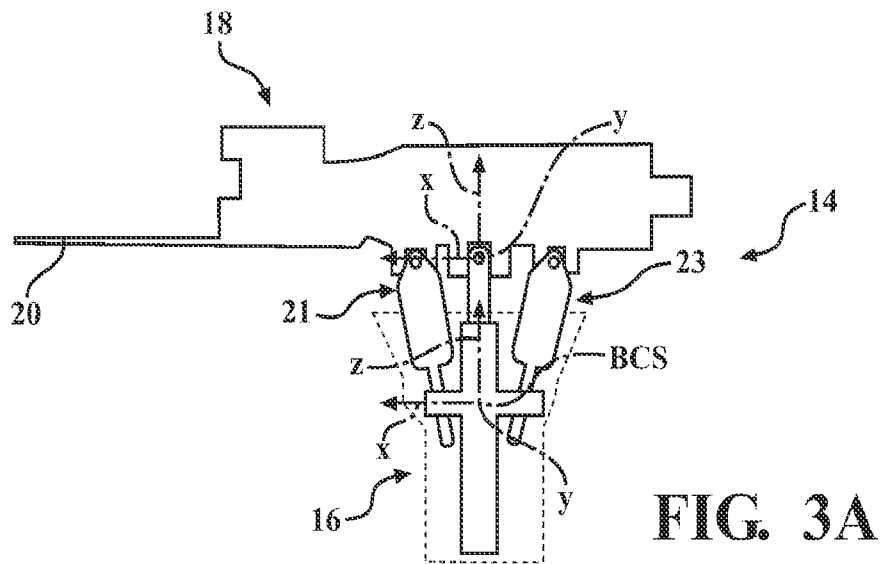
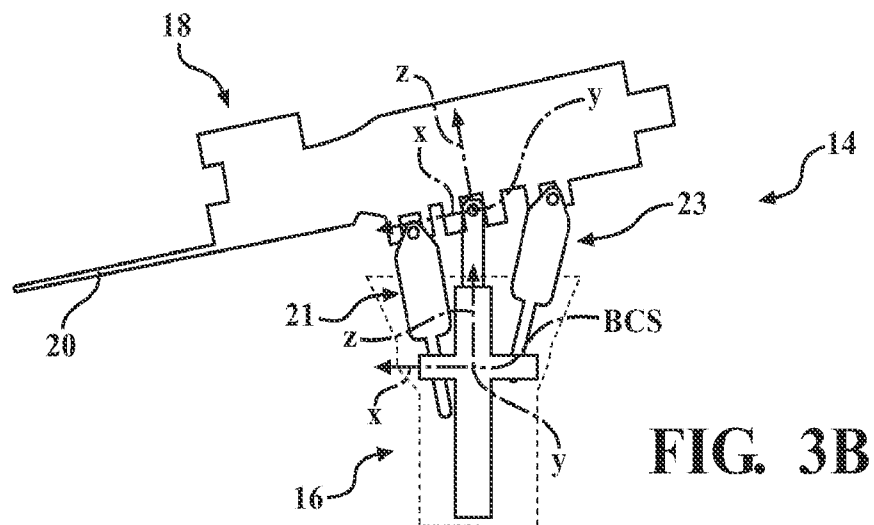
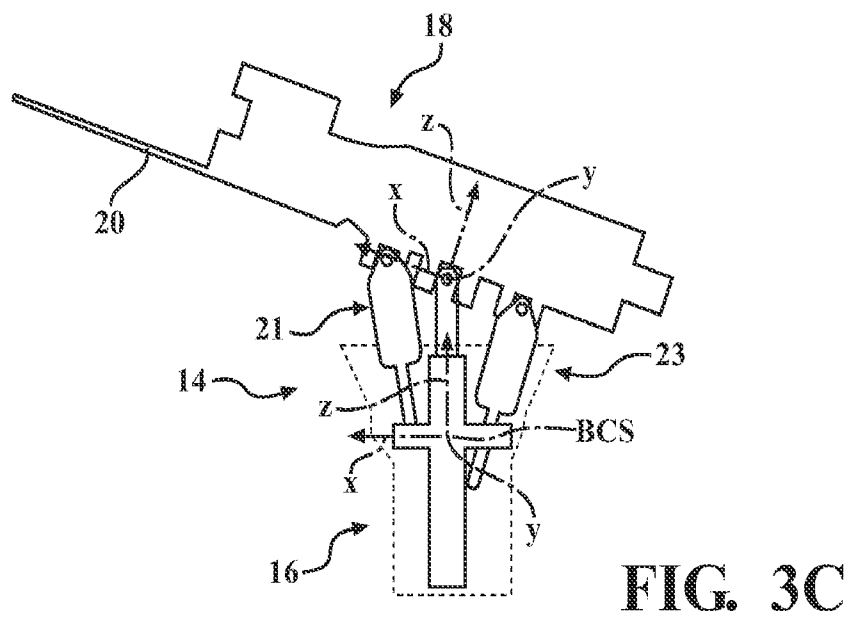


FIG. 2



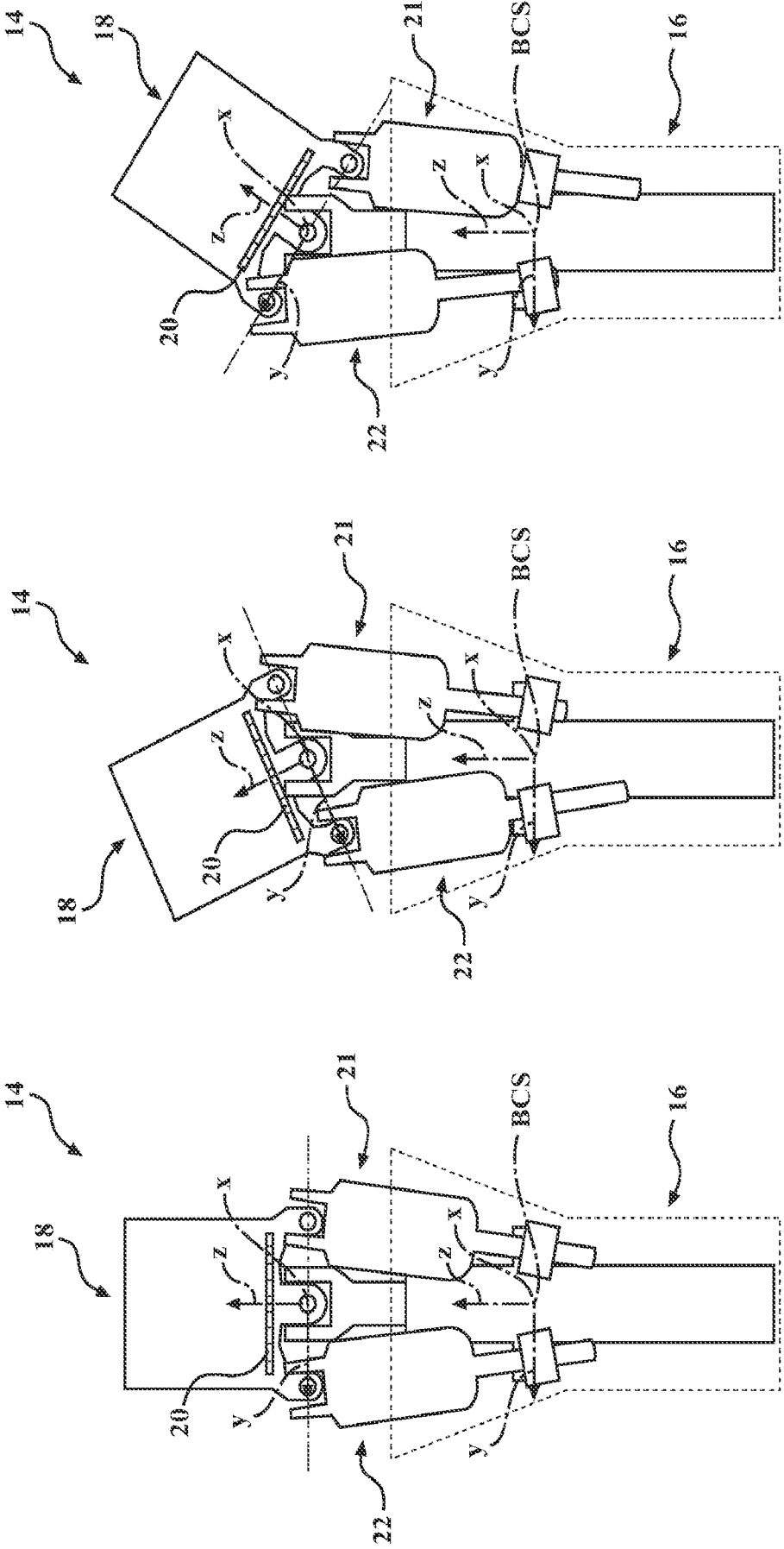
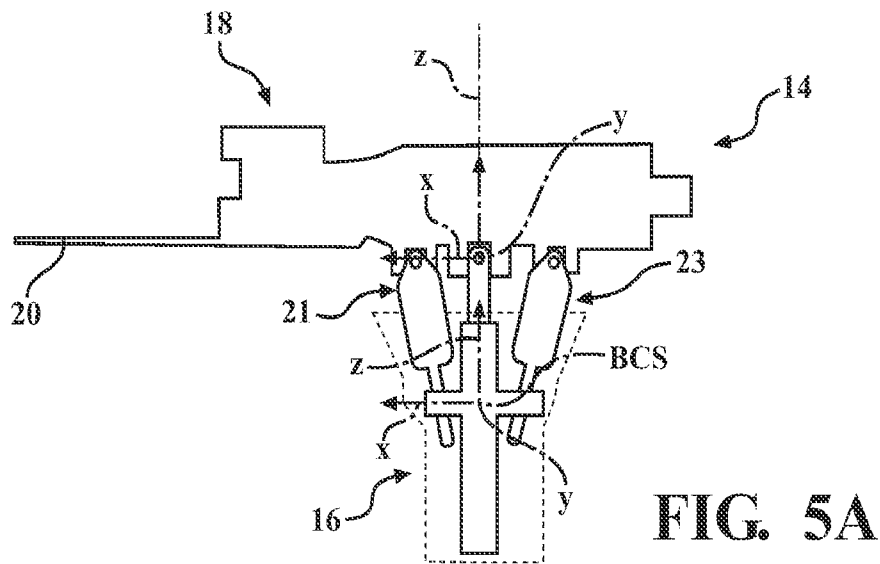
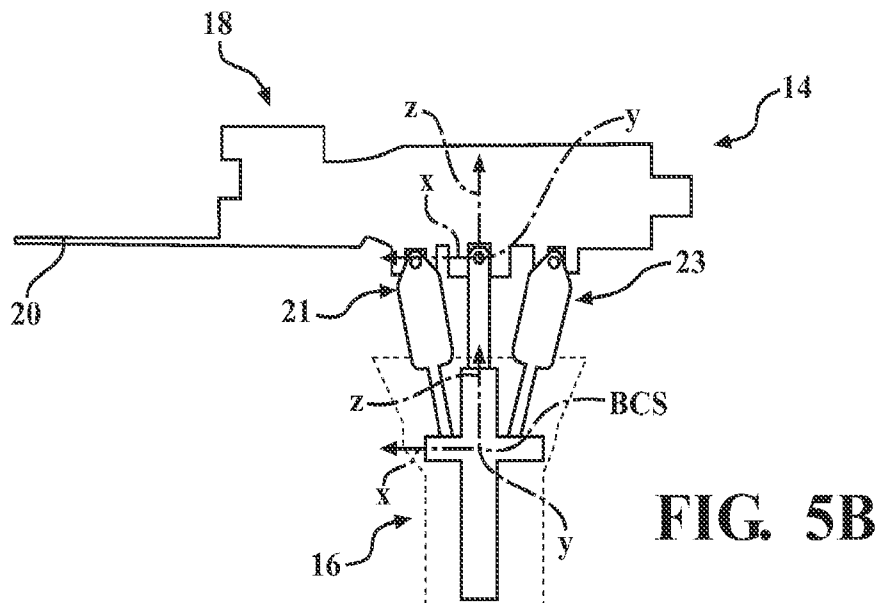
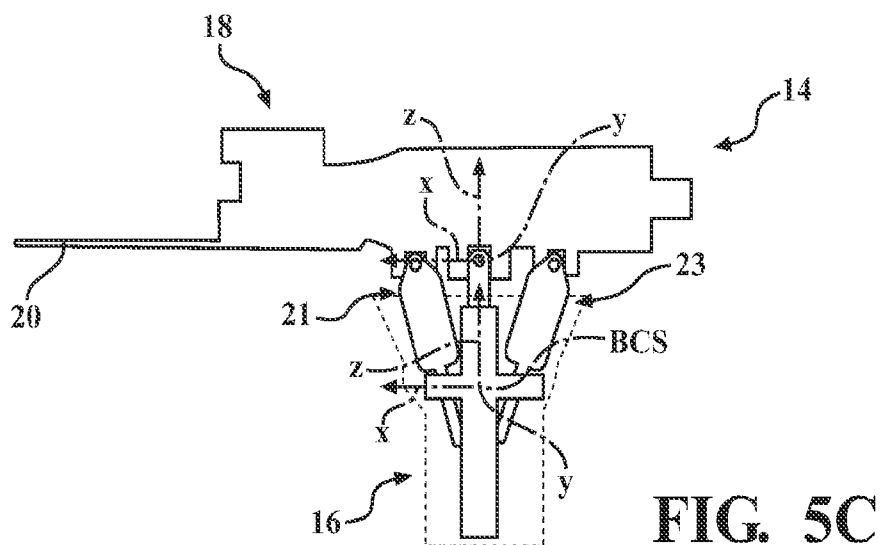
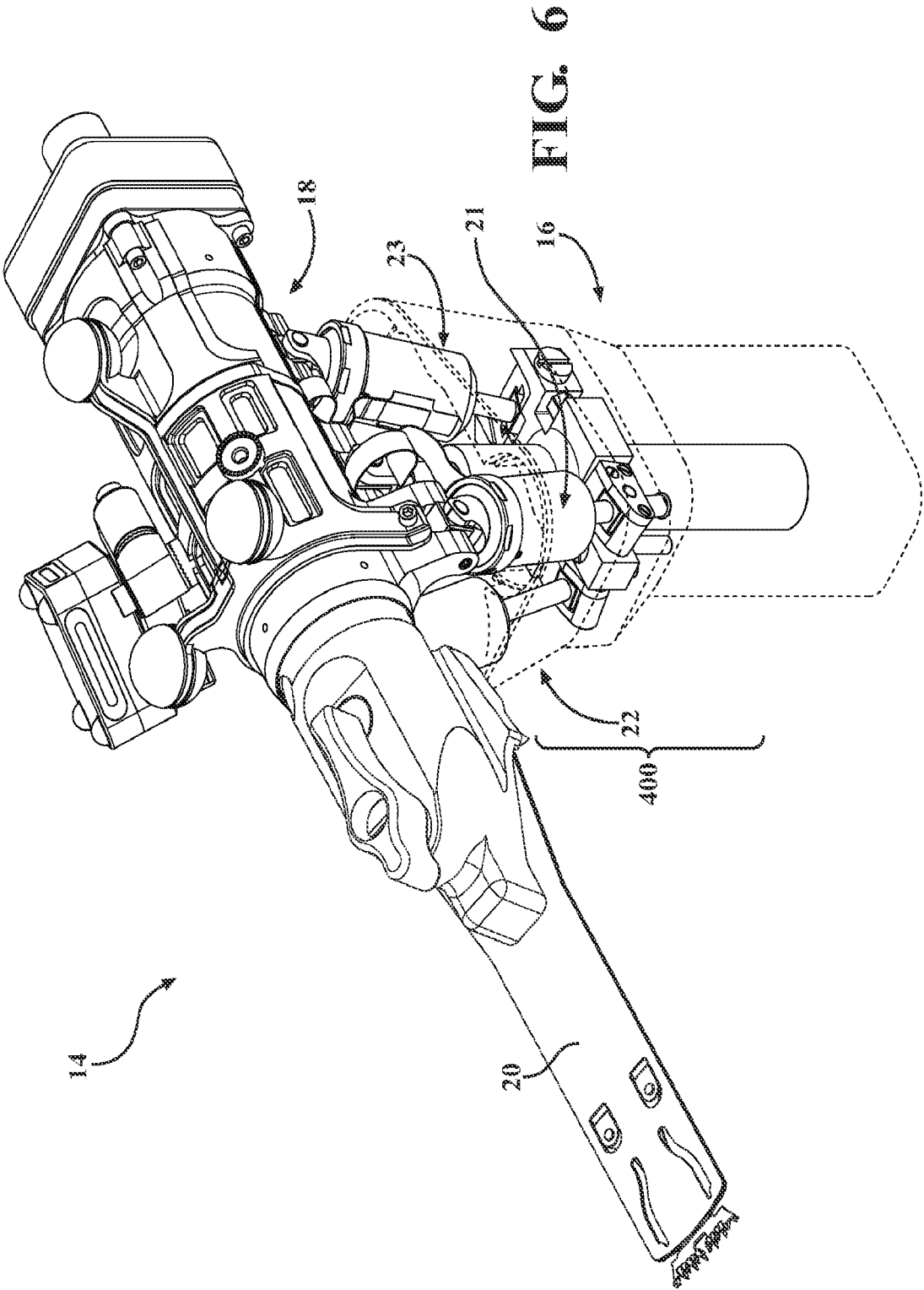


FIG. 4C

FIG. 4B

FIG. 4A

**FIG. 5A****FIG. 5B****FIG. 5C**



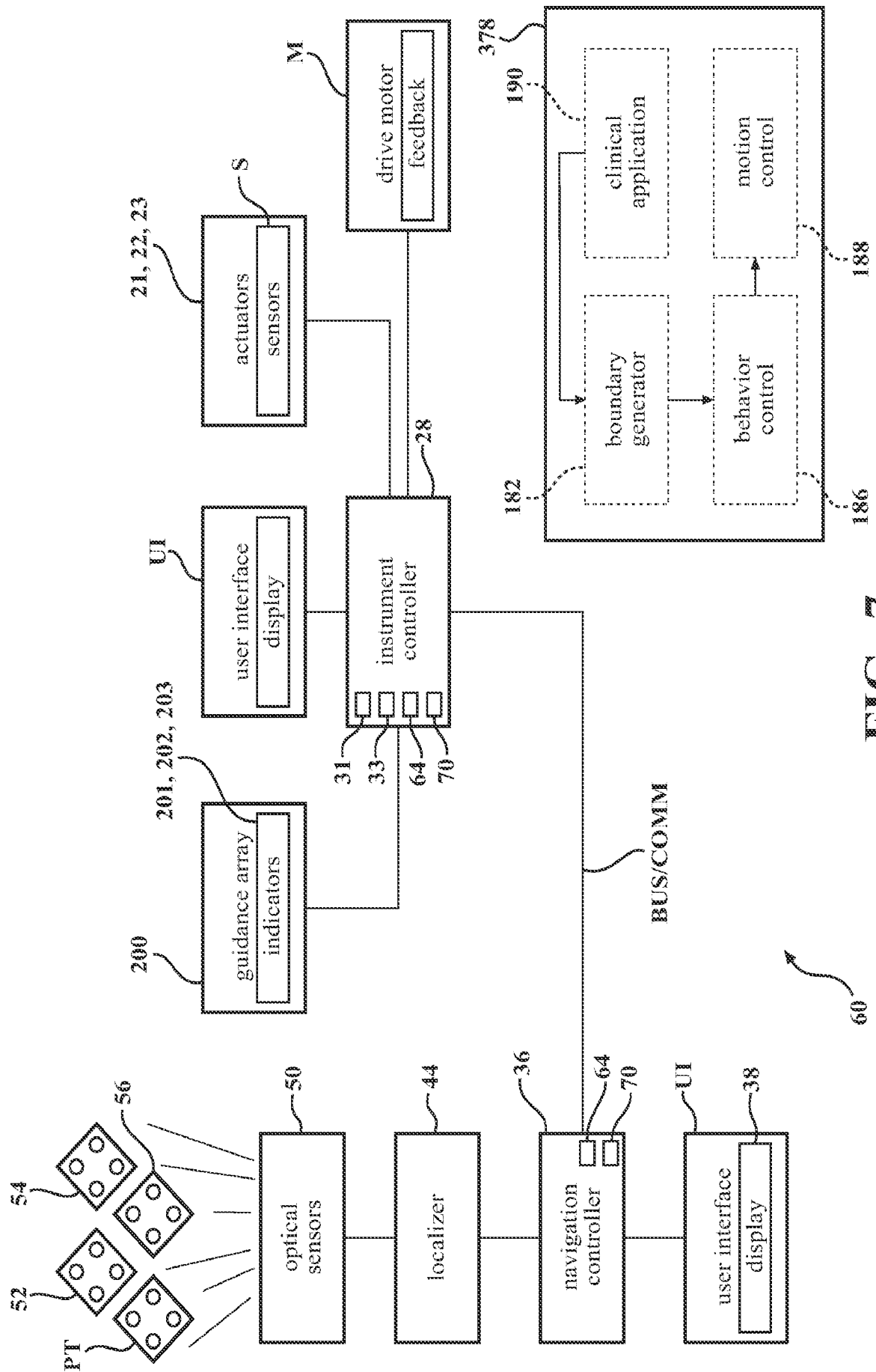
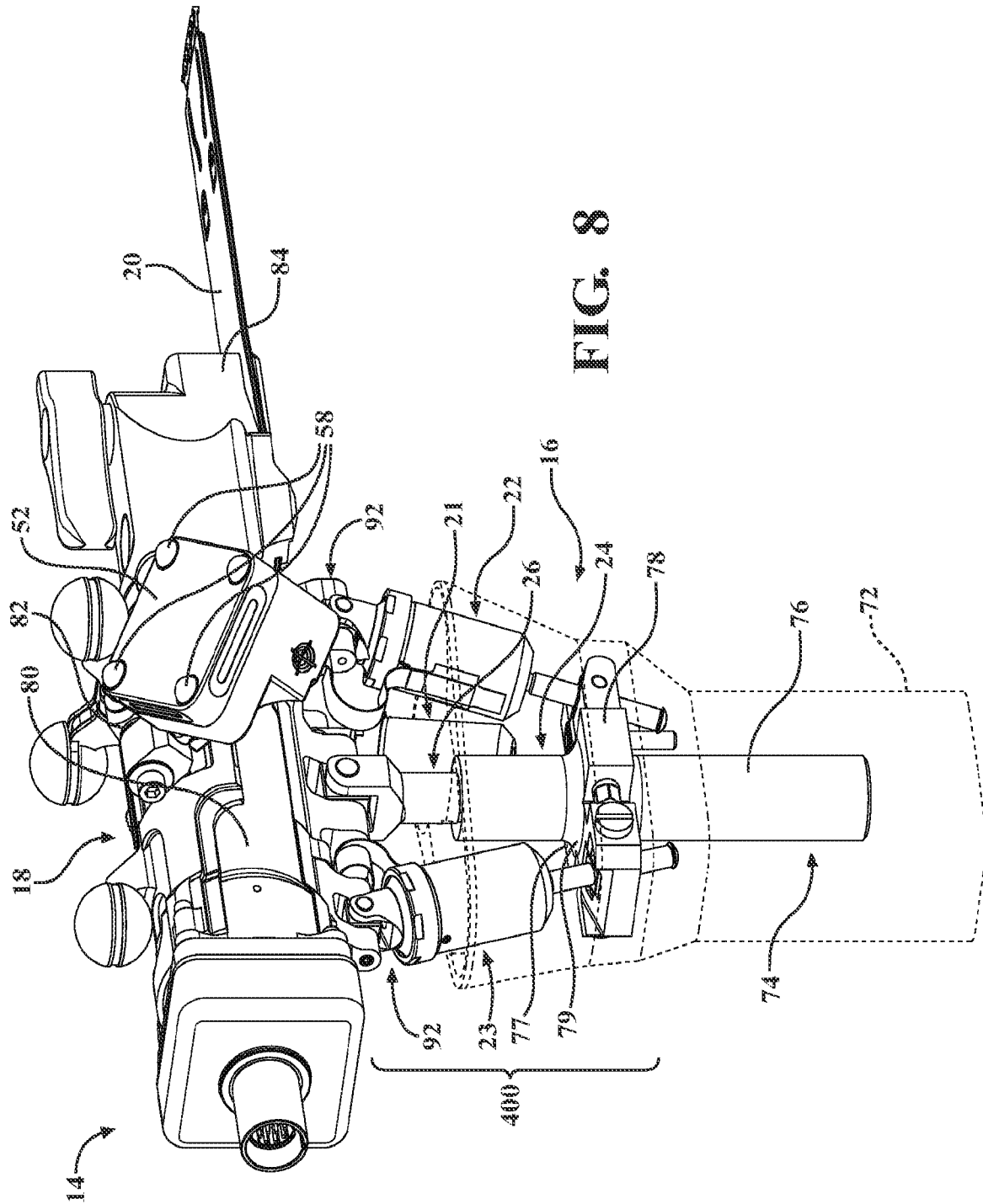
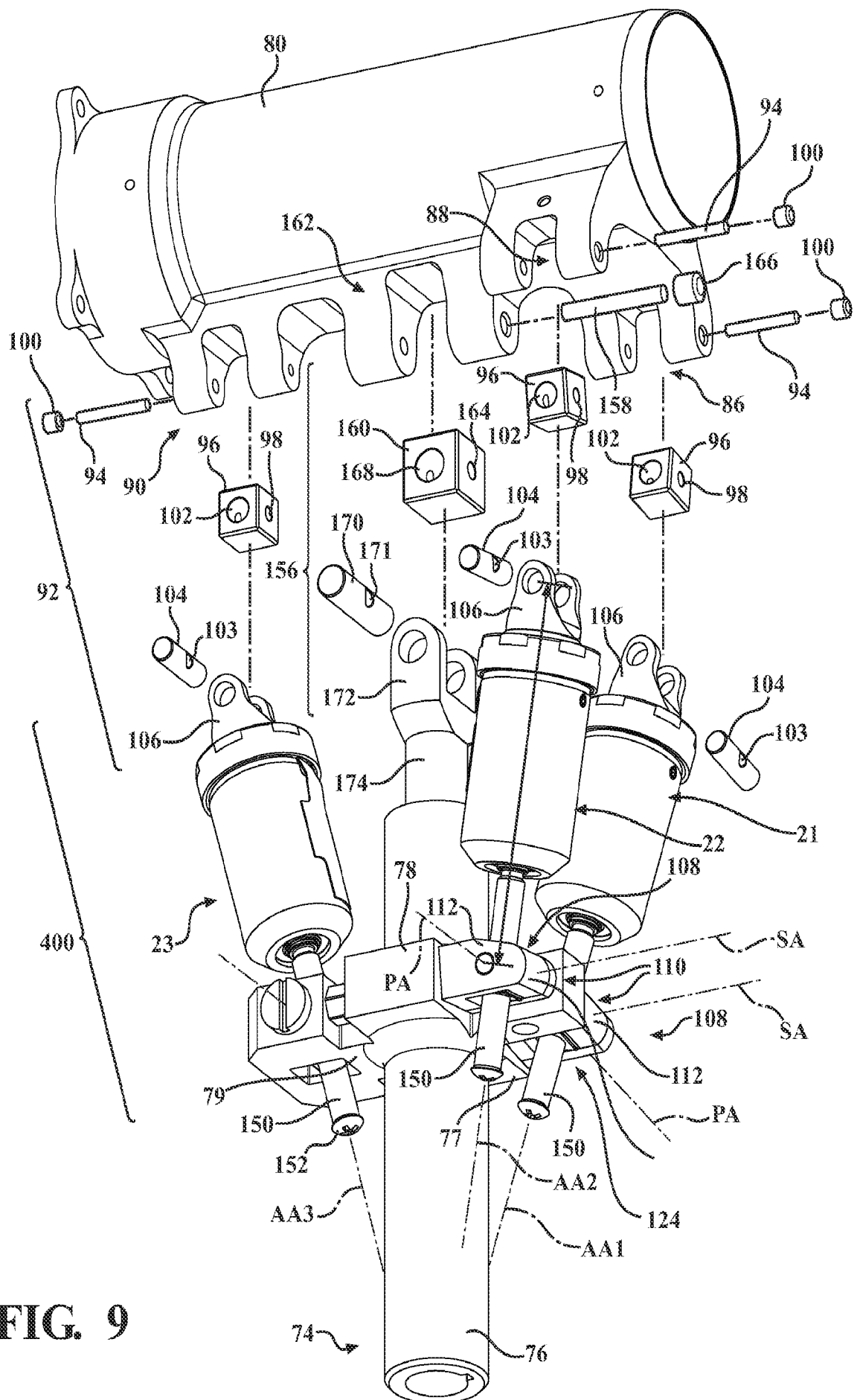


FIG. 7



**FIG. 9**

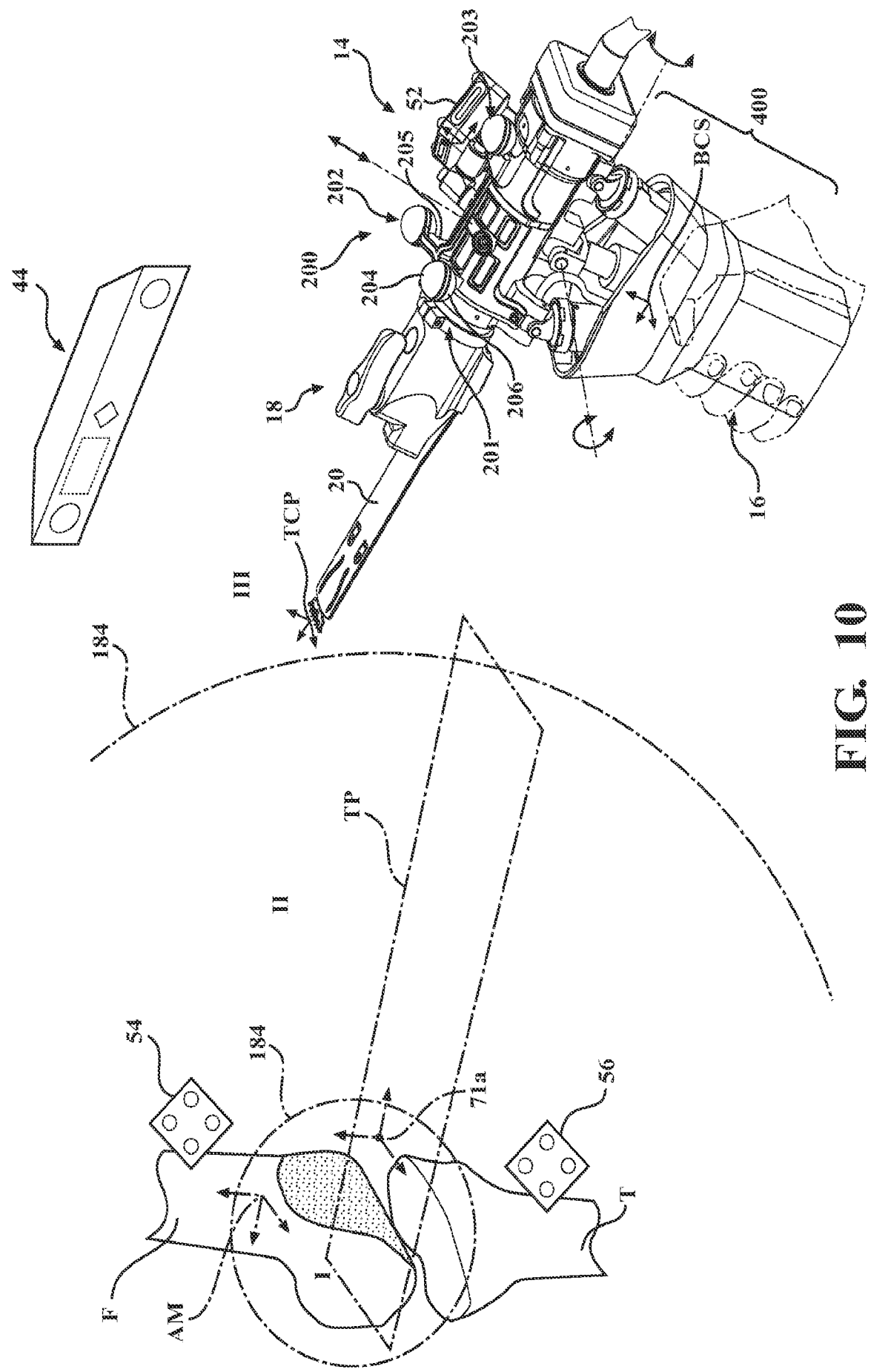


FIG. 10

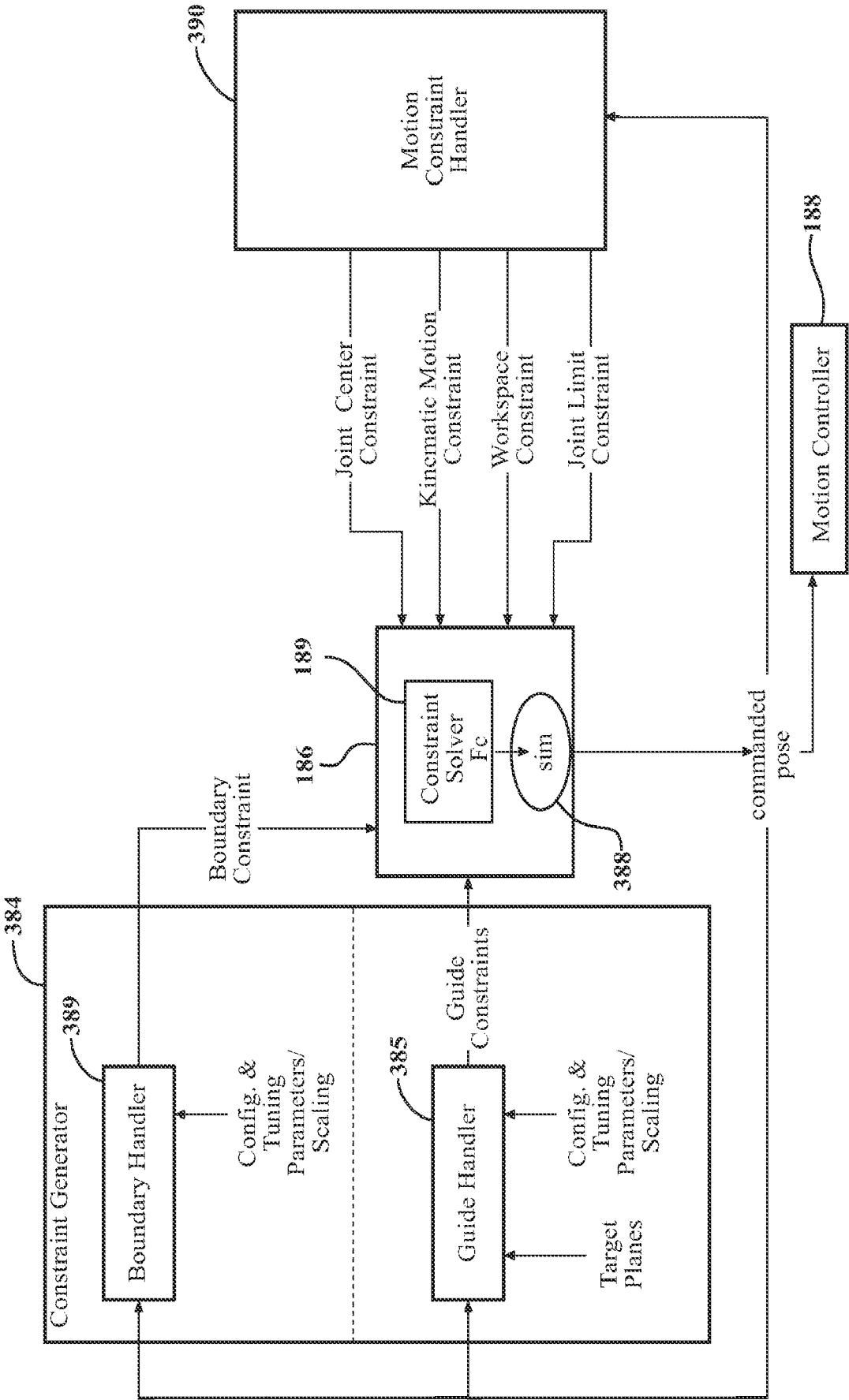


FIG. 11

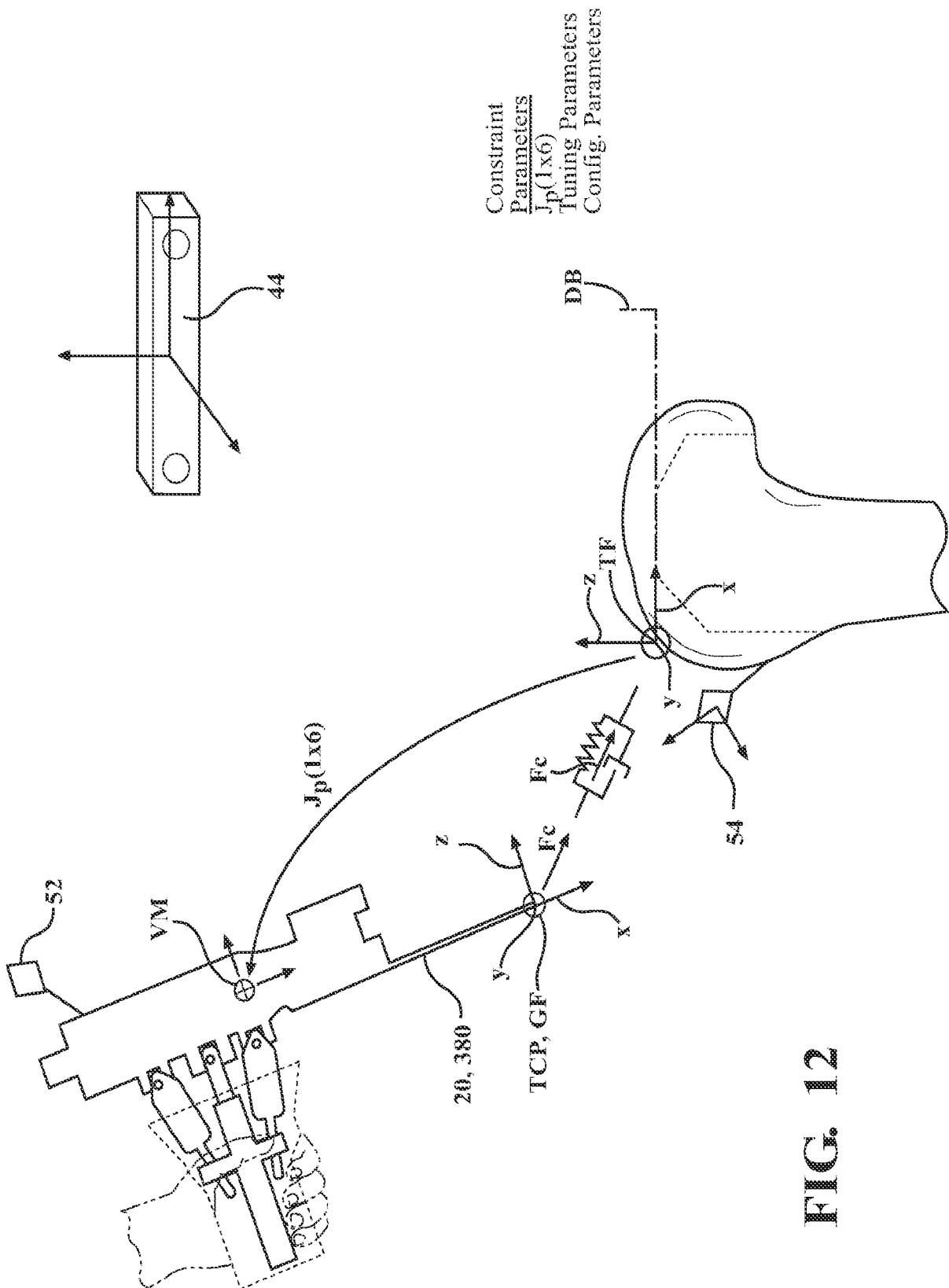


FIG. 12

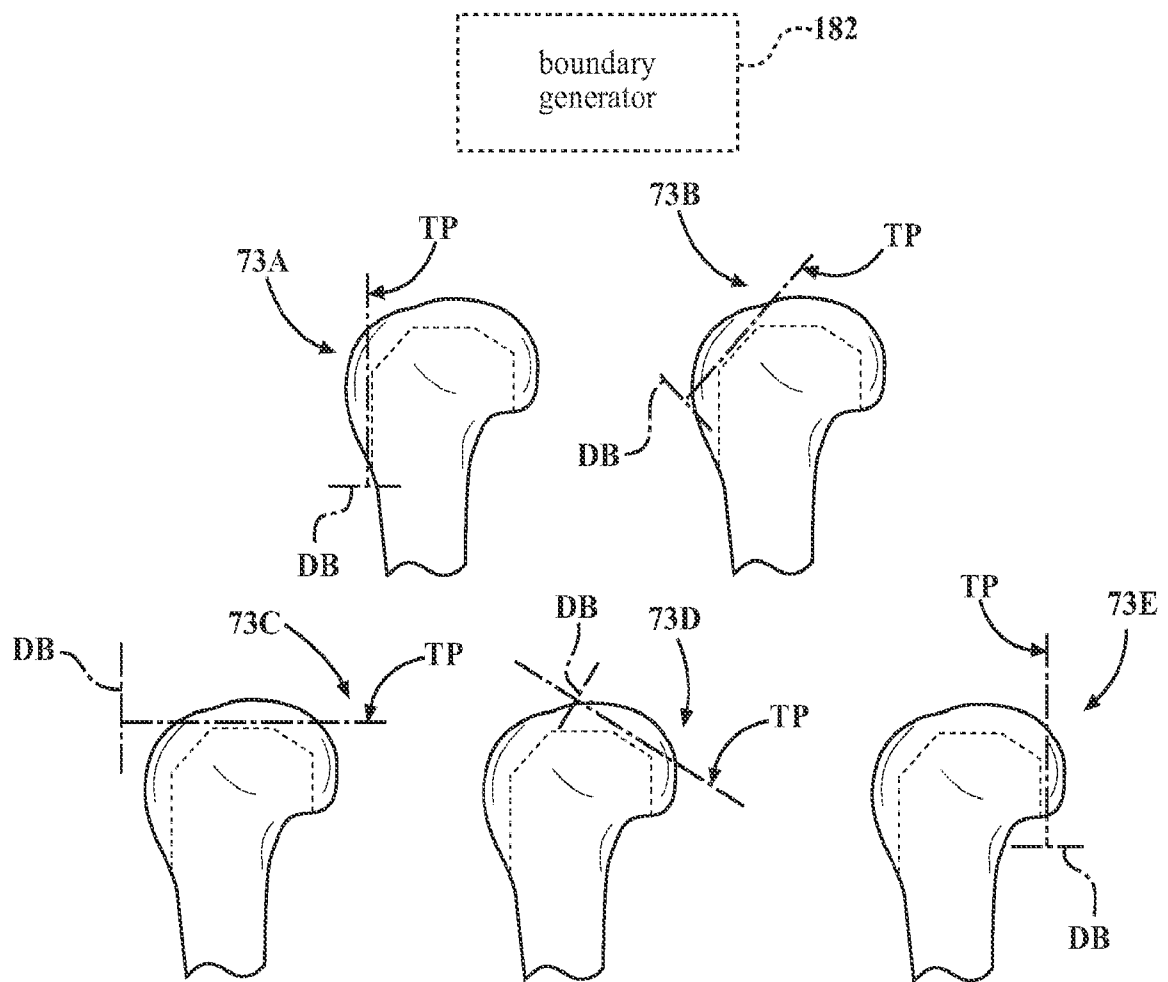
**FIG. 13**

FIG. 14

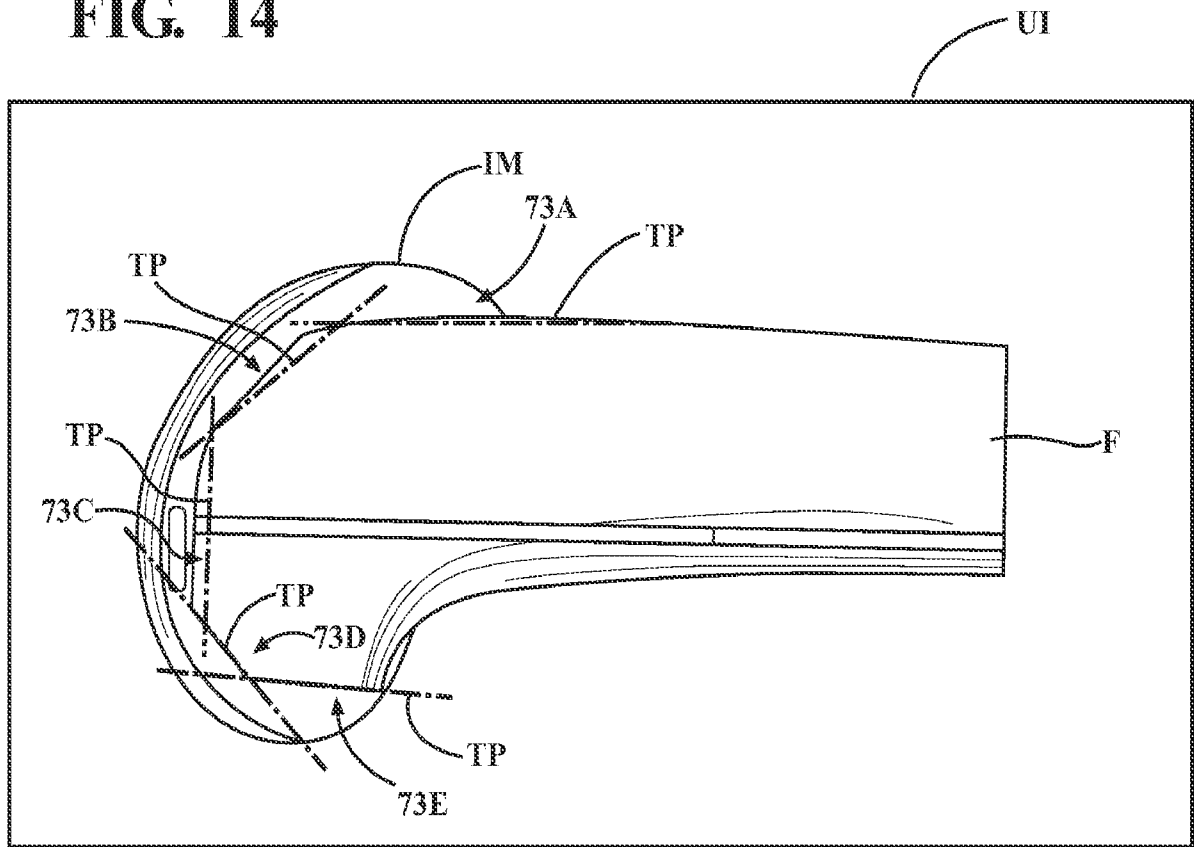
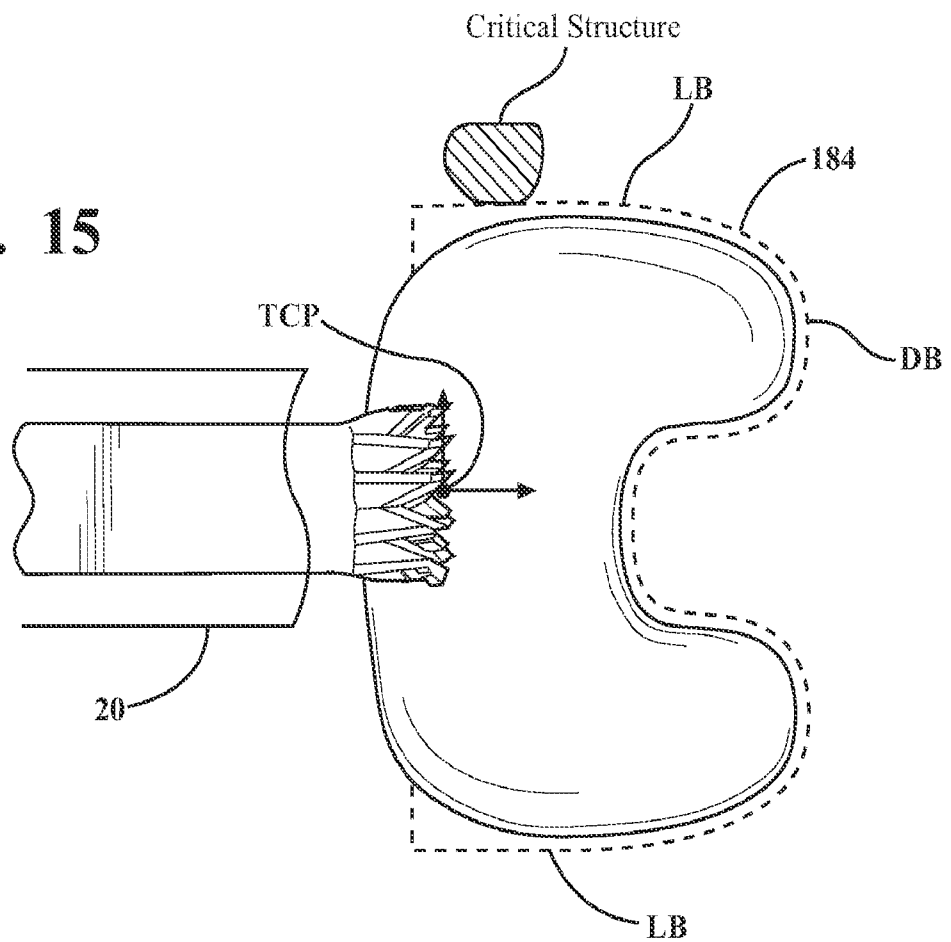
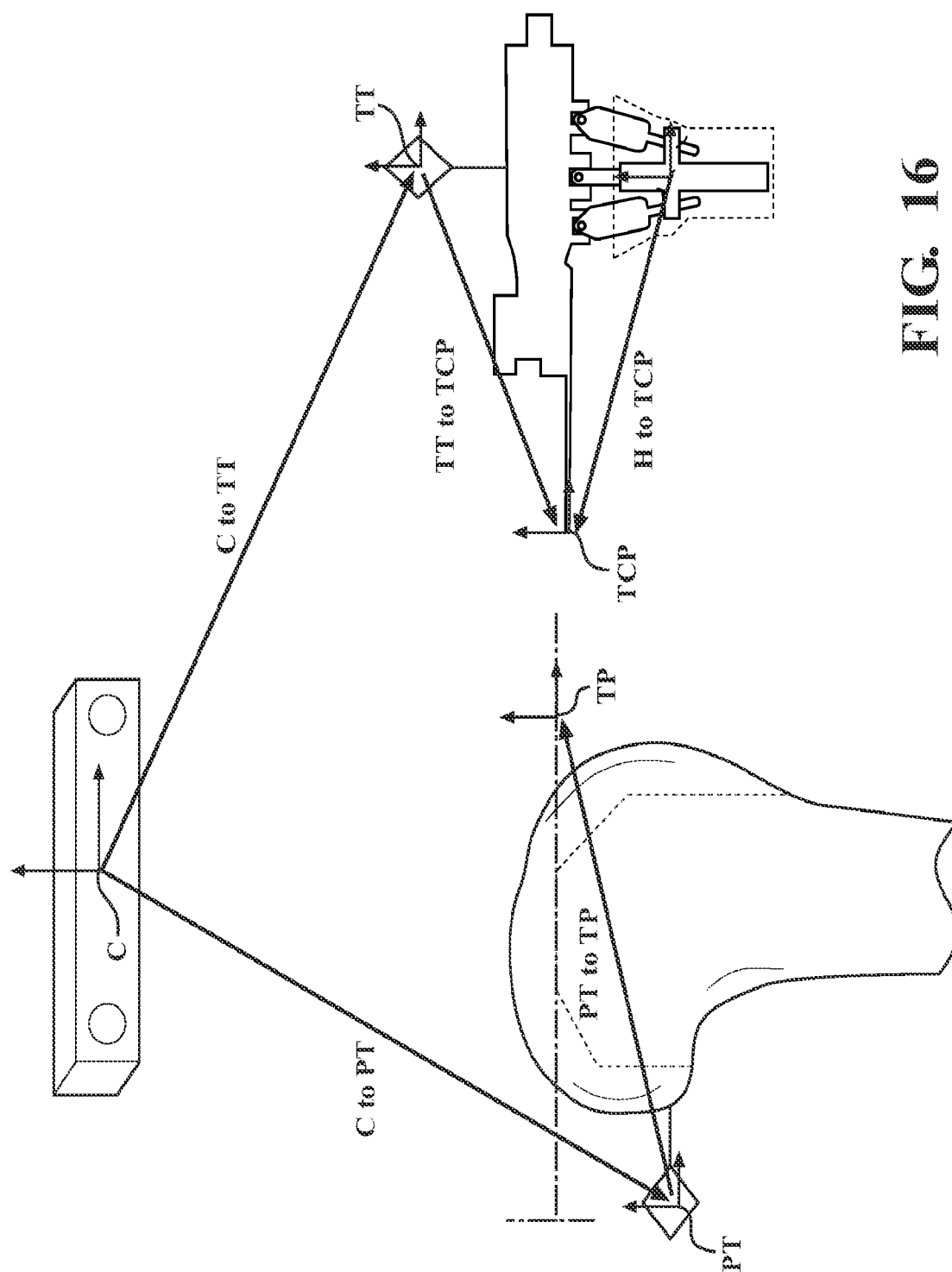


FIG. 15



**FIG. 16**

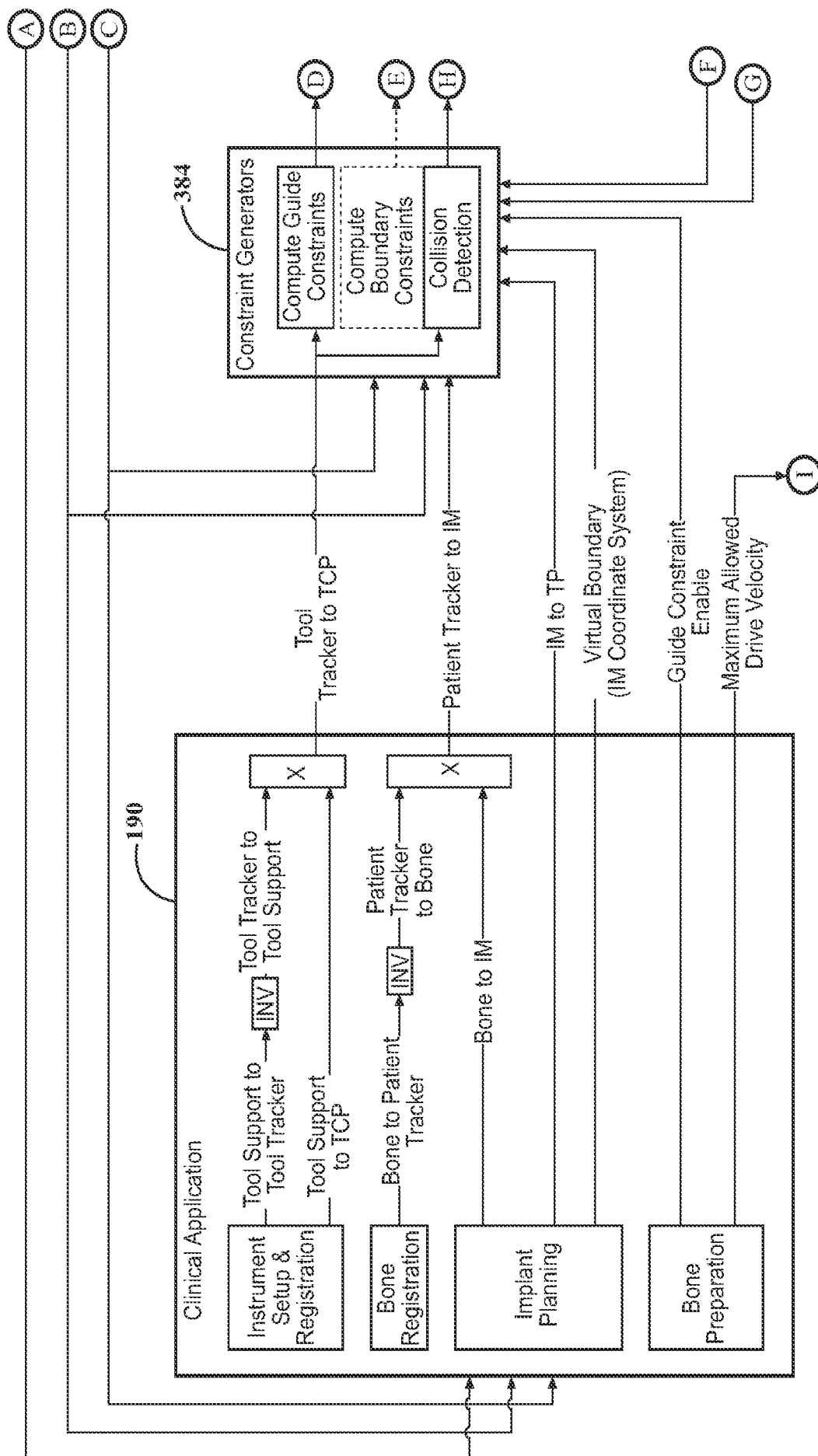


FIG. 17A

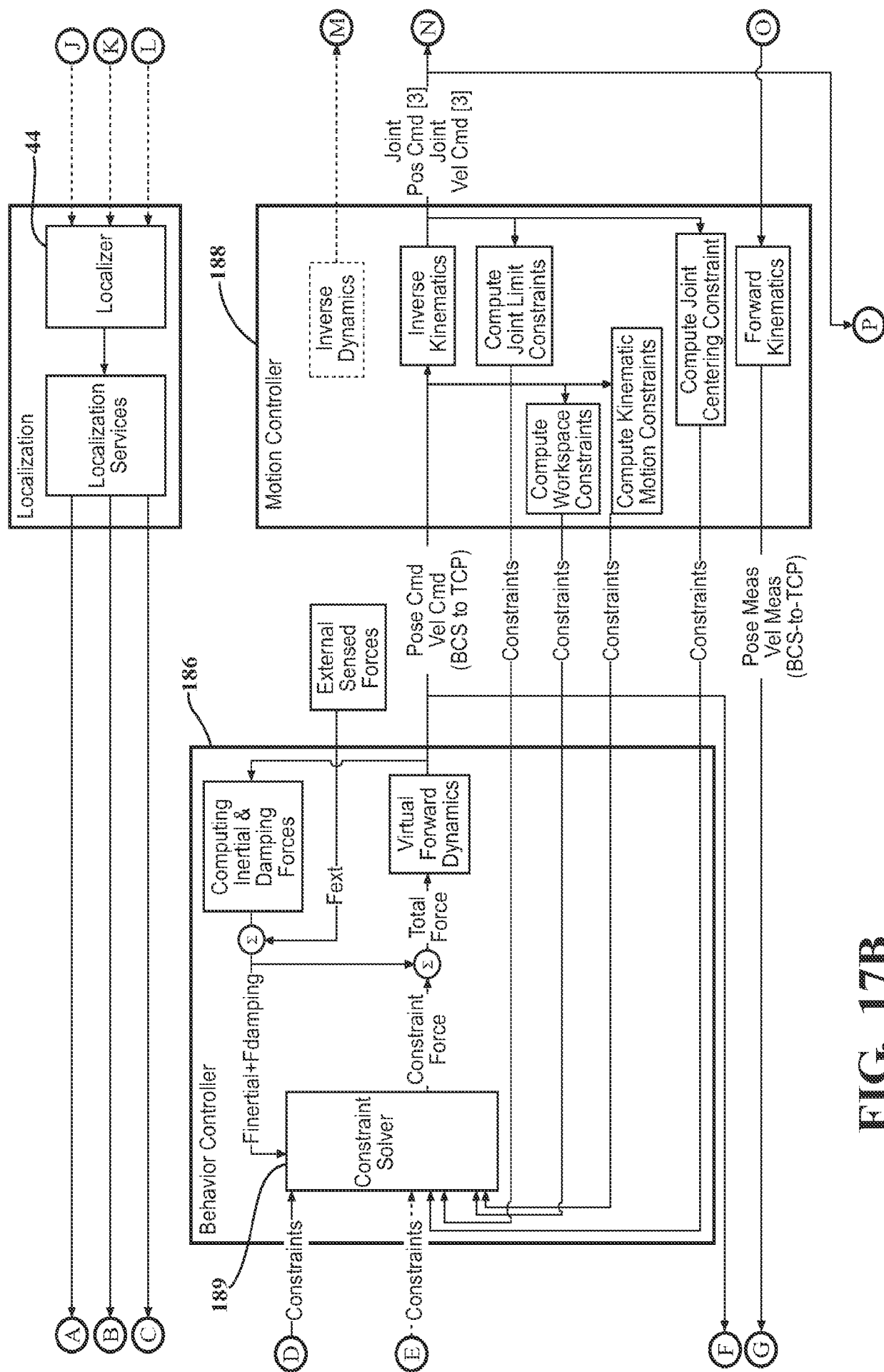


FIG. 17B

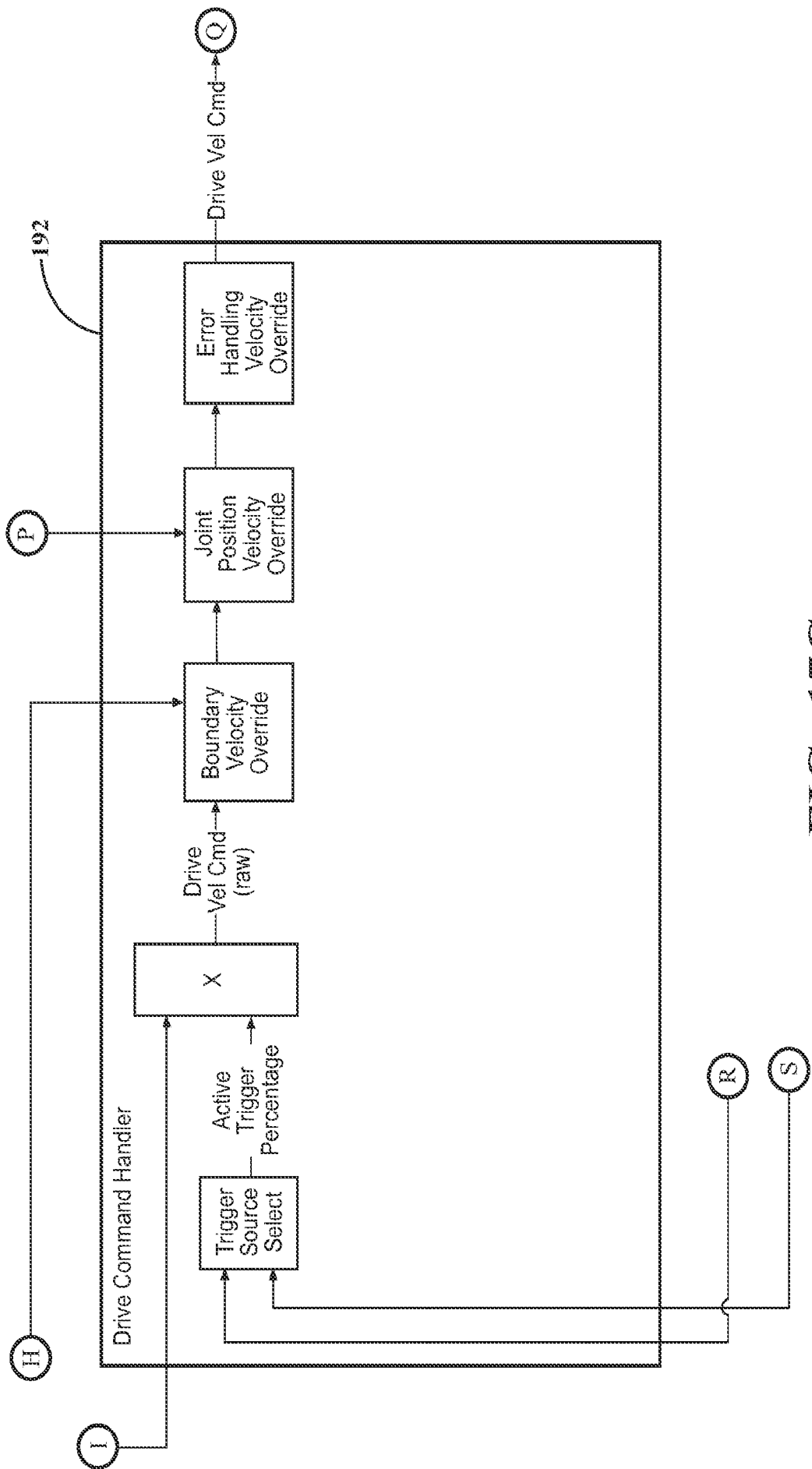


FIG. 17C

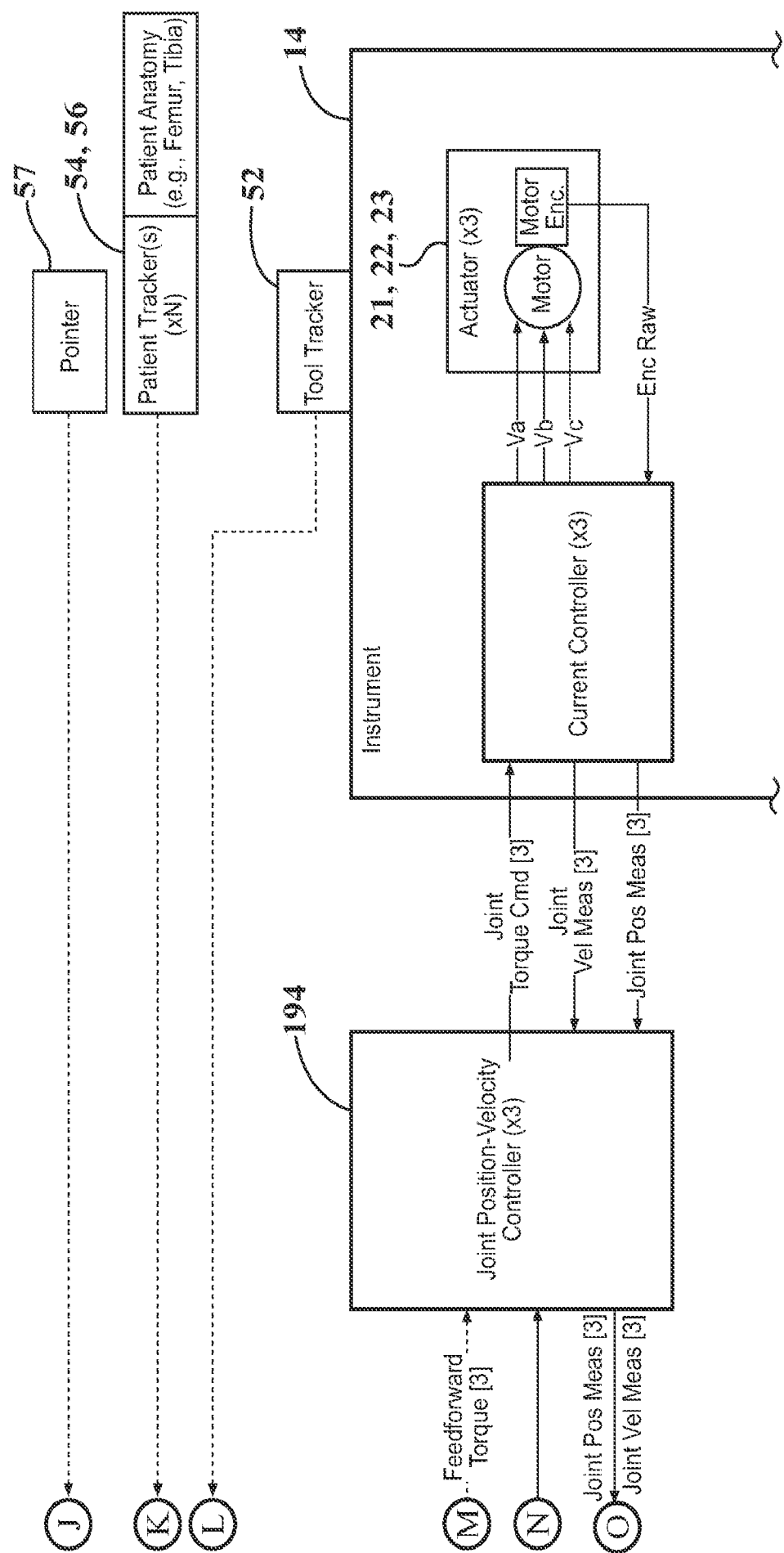


FIG. 17D

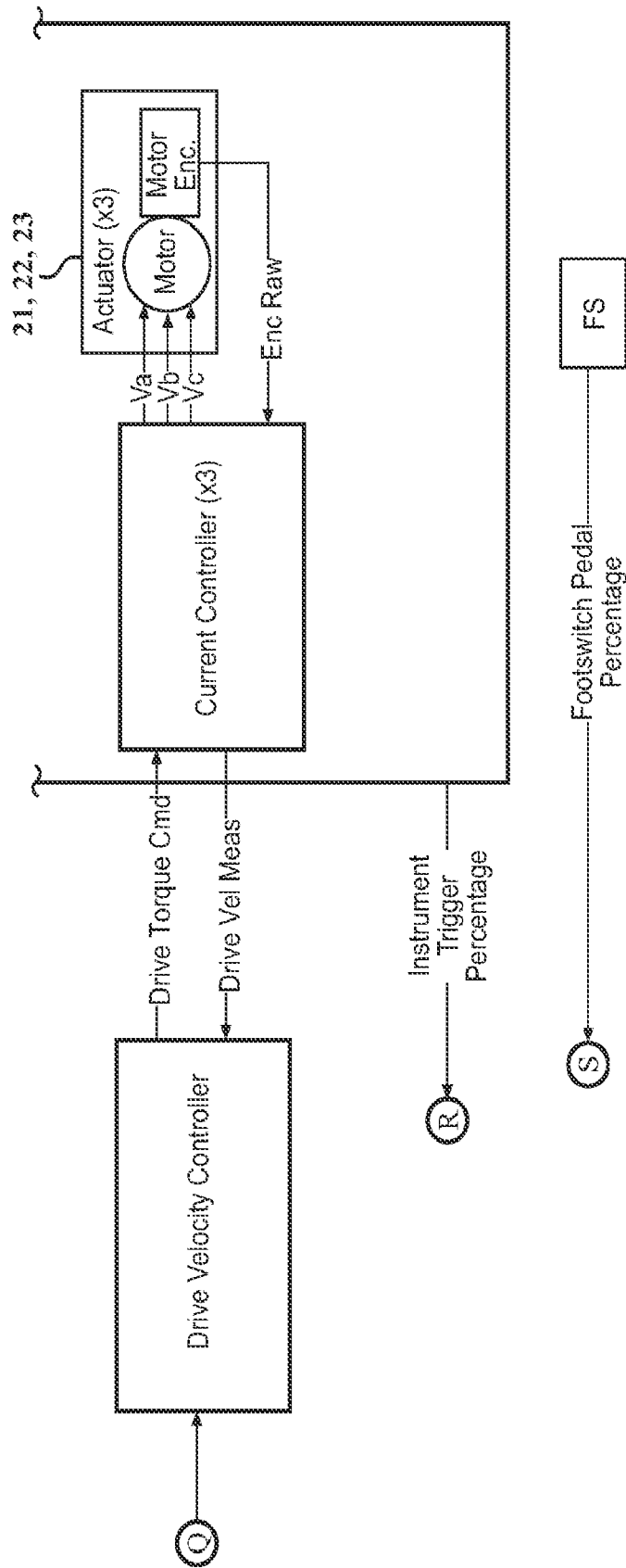


FIG. 17E

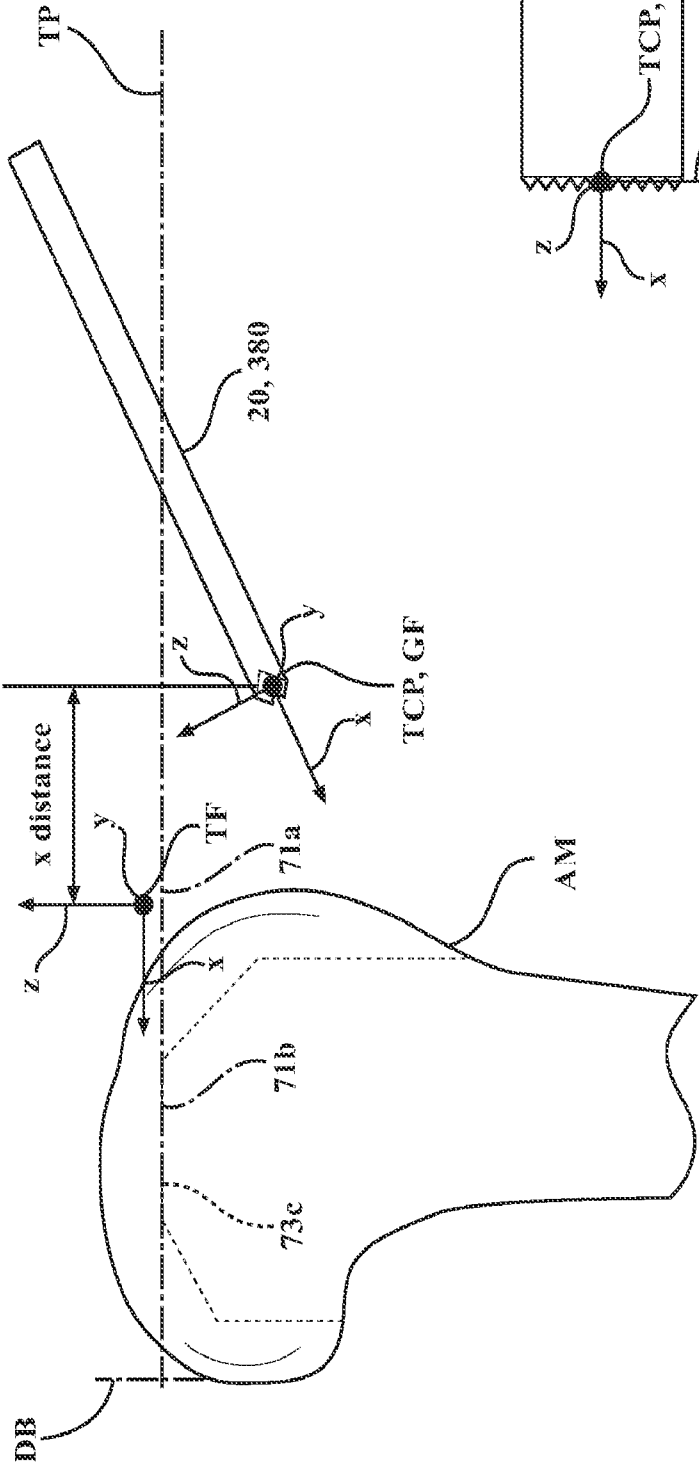


FIG. 18

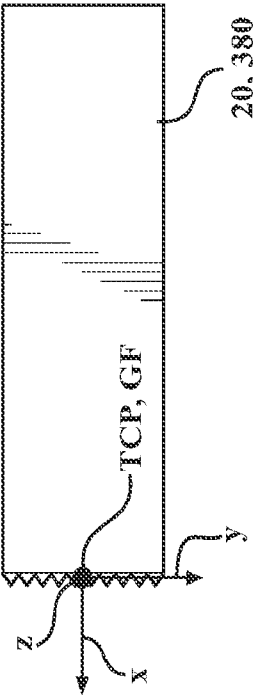


FIG. 19

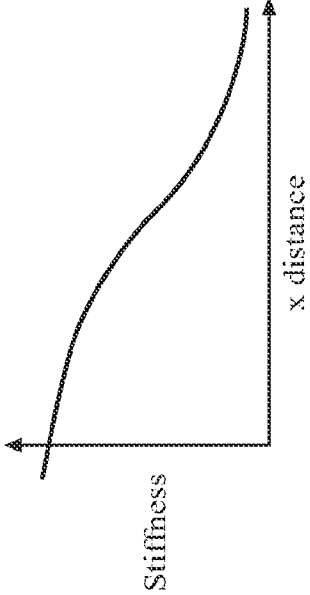


FIG. 20

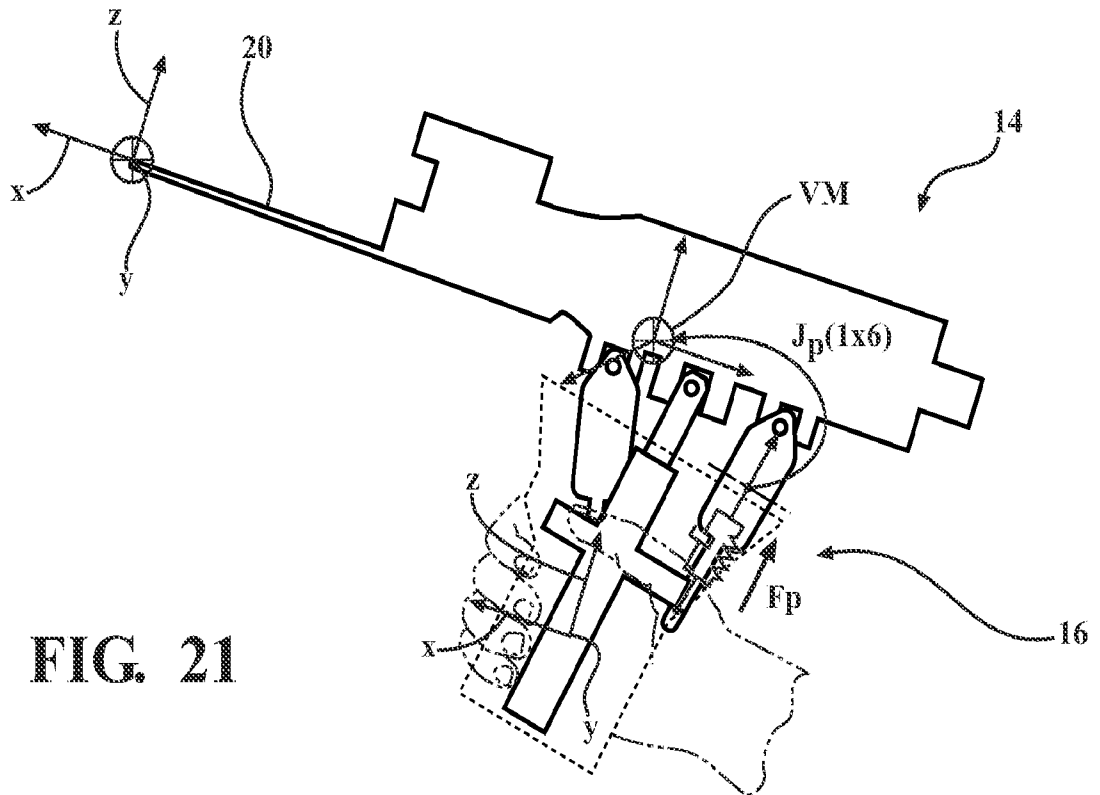


FIG. 21

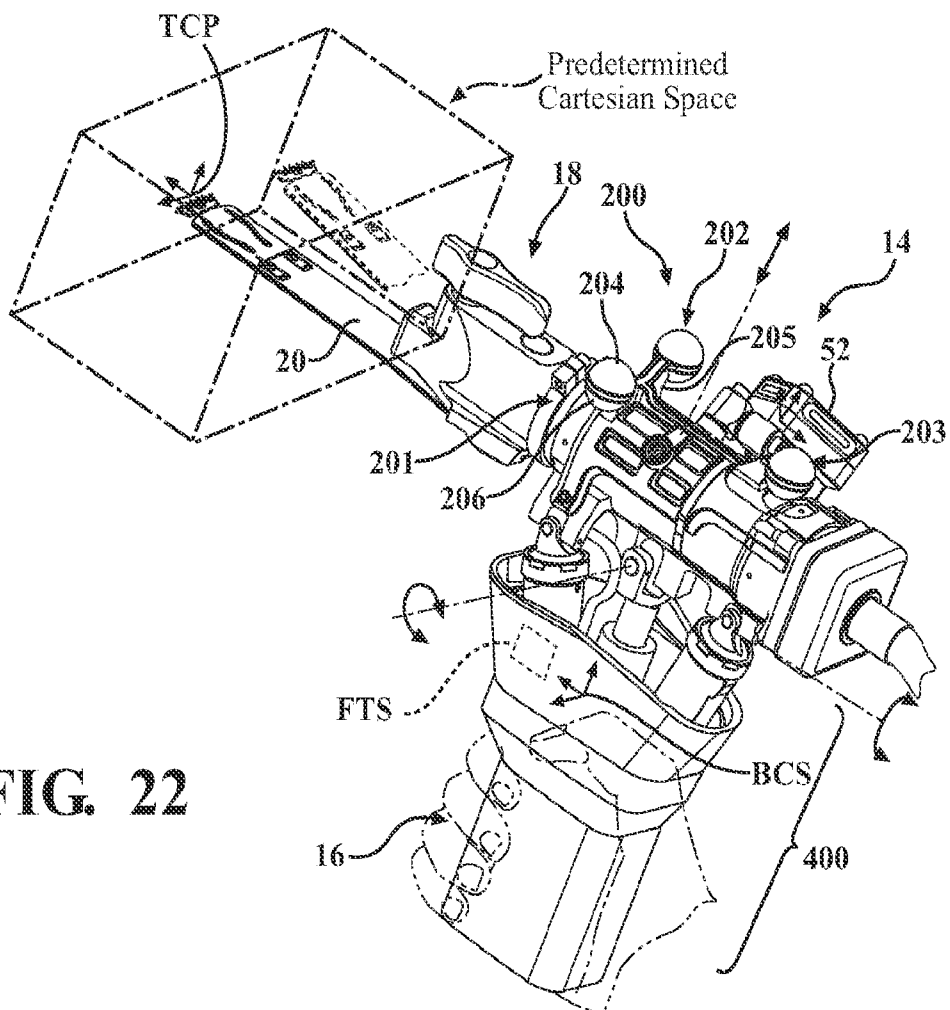


FIG. 22

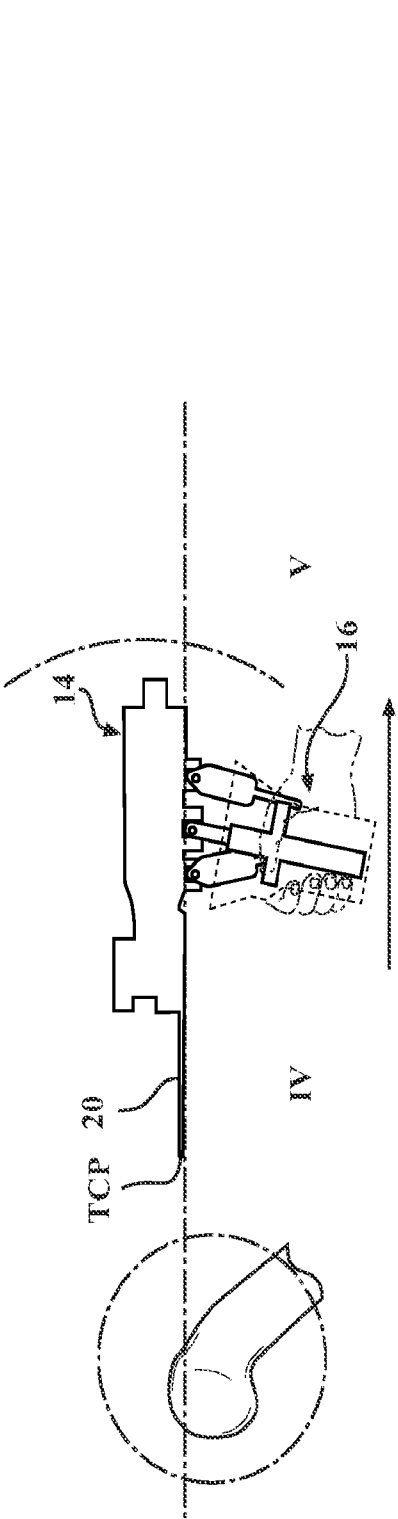


FIG. 23A

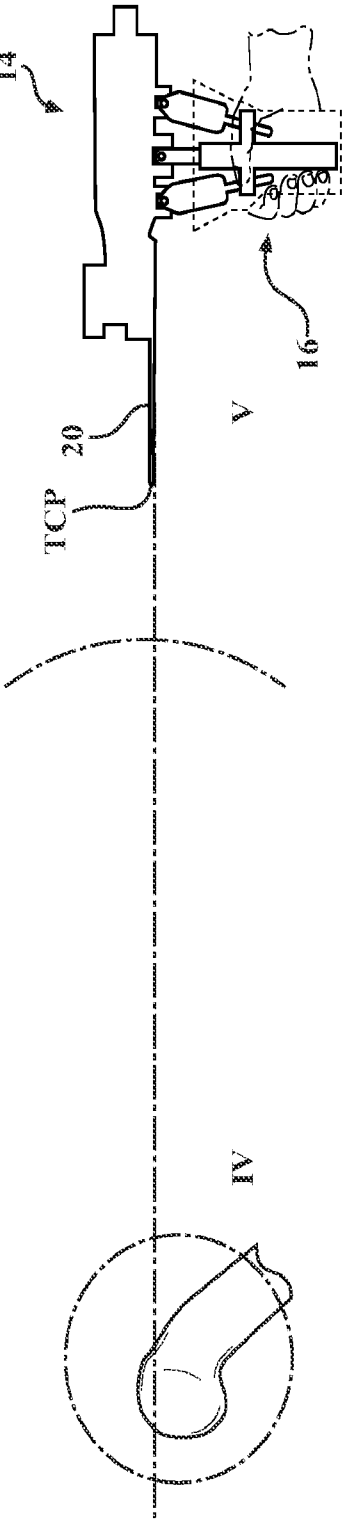


FIG. 23B

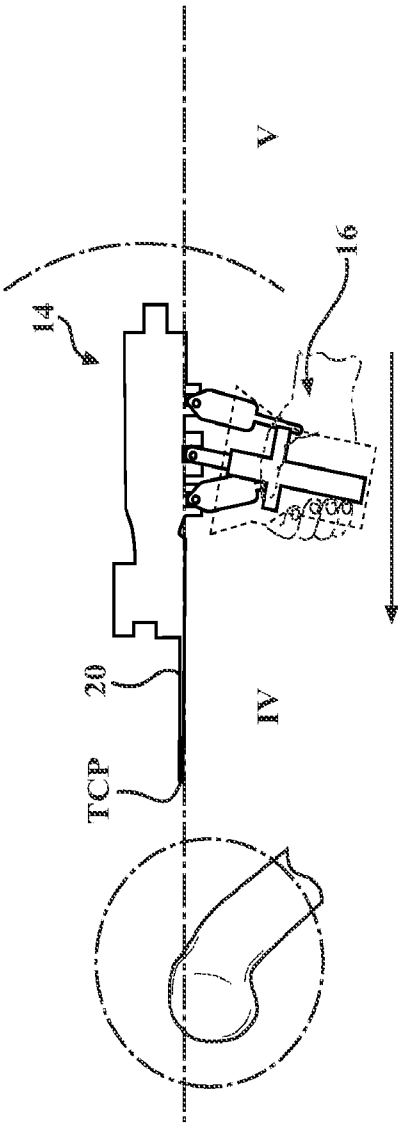


FIG. 23C

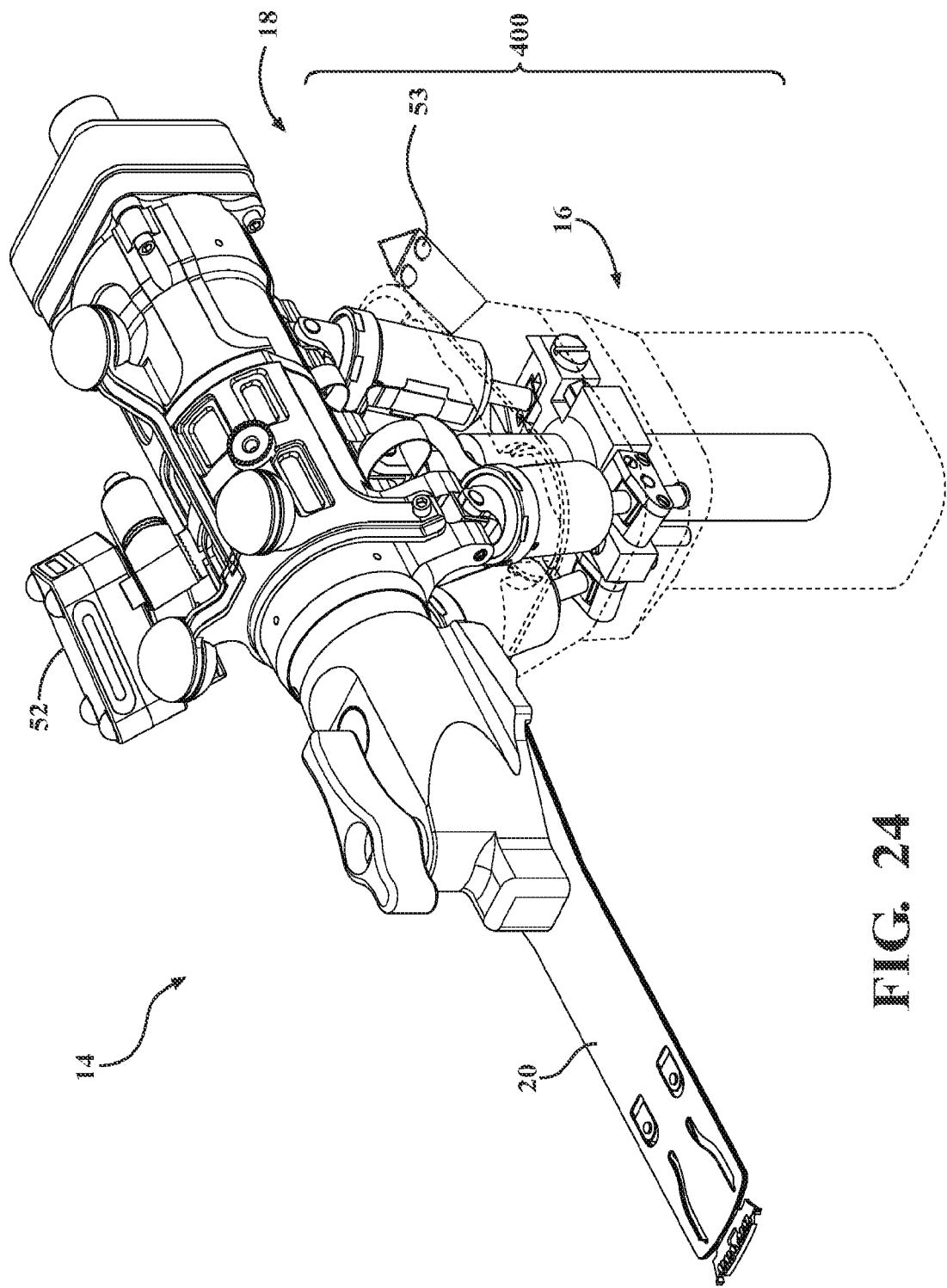


FIG. 24

Contrain Equation

Calculate force for each constraint (F_{p_i}) in constraint space by solving system of n linear equations ($Ax = b \rightarrow x = A^{-1}b = F = (M^{-1}J^{-1}a)$)

$$Fp = \left(J_p M^{-1} J_p^T + \frac{C}{\Delta t}\right)^{-1} \left(\frac{v_{p2}}{\Delta t} - \frac{J_p^v c_{g1}}{\Delta t} - \frac{\varepsilon \Delta d}{\Delta t^2} - \left(J_p M^{-1} + \frac{C}{\Delta t} J_p^{-T}\right) (F_{inertial} + F_{damping} + F_{c_{gext}})\right) \geq 0$$

FIG. 25

Forward Dynamics Algorithm

Configuration Parameters:

Mass matrix, M_{6DOF} [6x6] combination of Mass and Inertia [3x3] matrices

Velocity Limits, V_{max}, ω_{max}

Inputs:

initial pose, ⁰T(t₀)

initial velocity, ⁿv(t₀)

total force applied at CG, ⁿF_{total}

time interval, dT

Outputs:

final pose, ⁰T(T₀ + dT)

final velocity, ⁿv(t₀ + dT)

FIG. 26

Forward Dynamics Algorithm

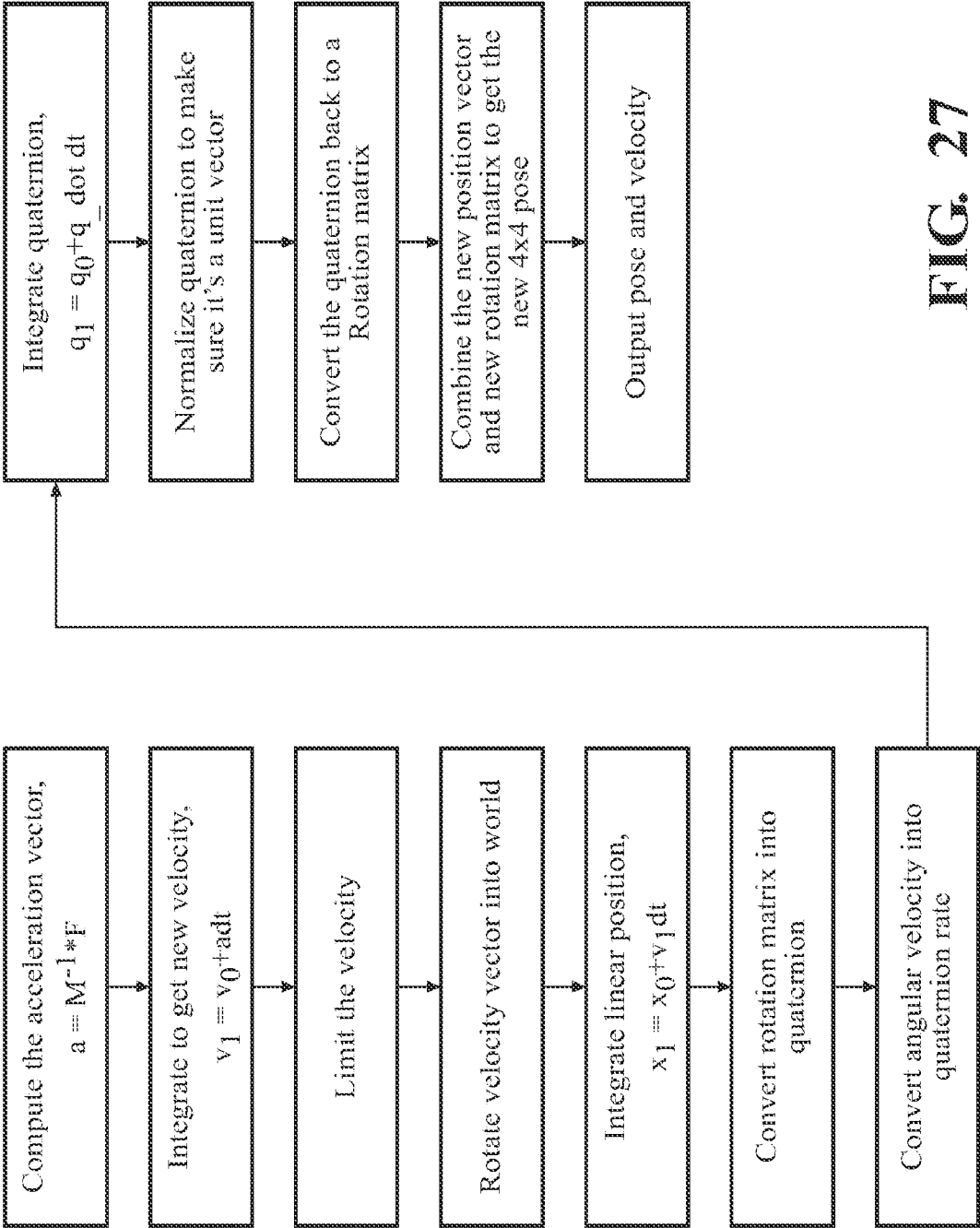


FIG. 27

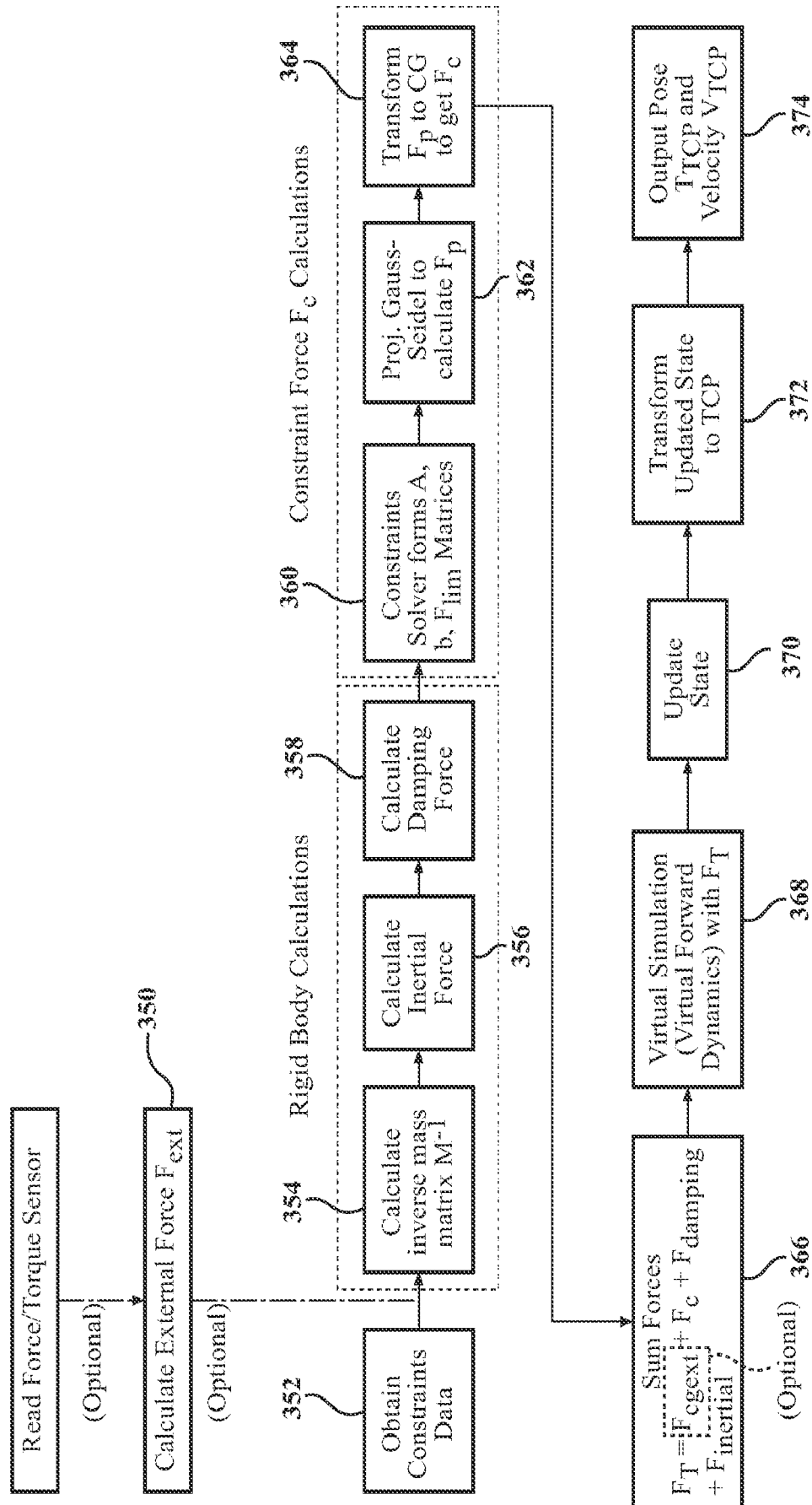


FIG. 28

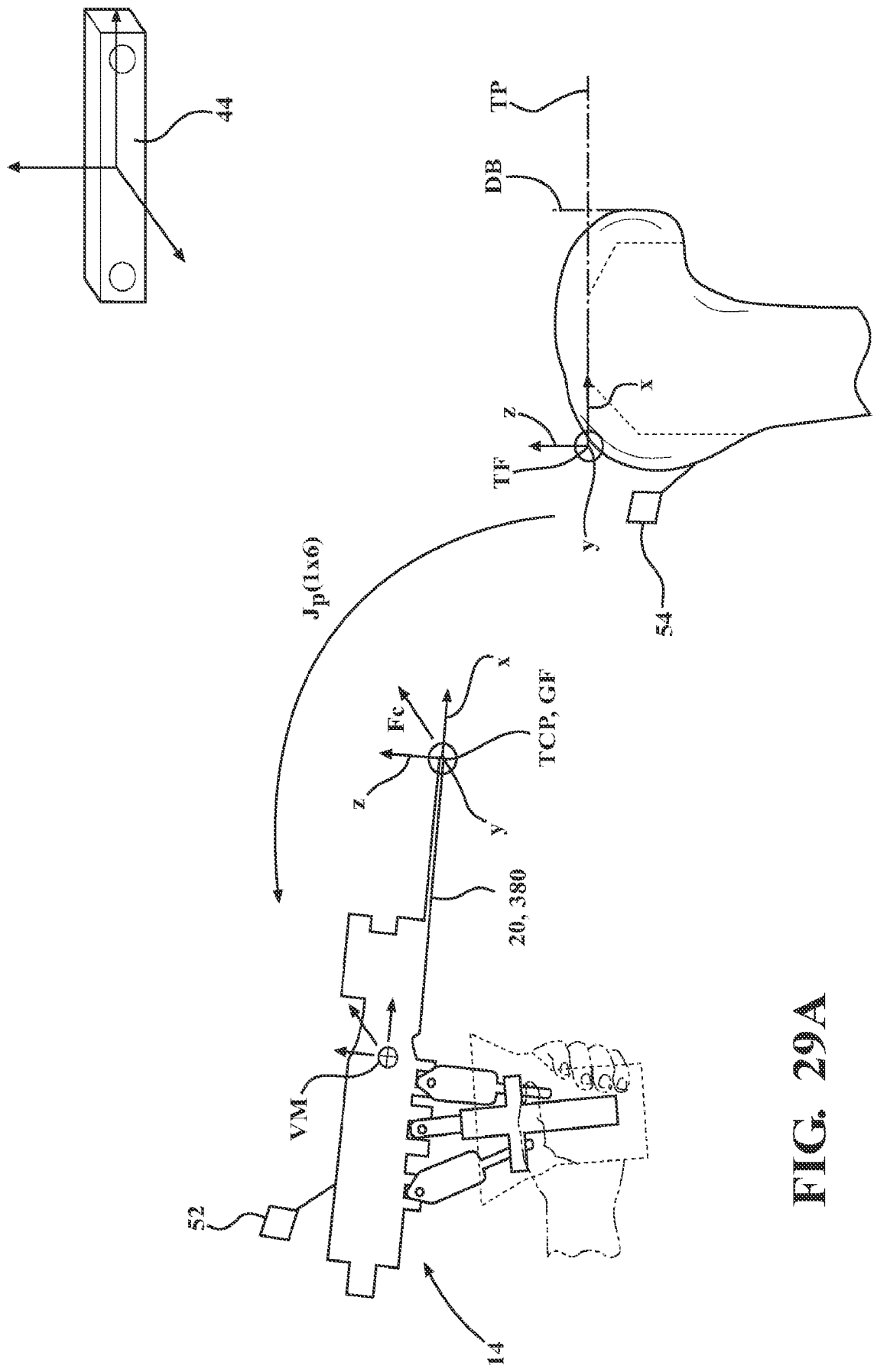


FIG. 29A

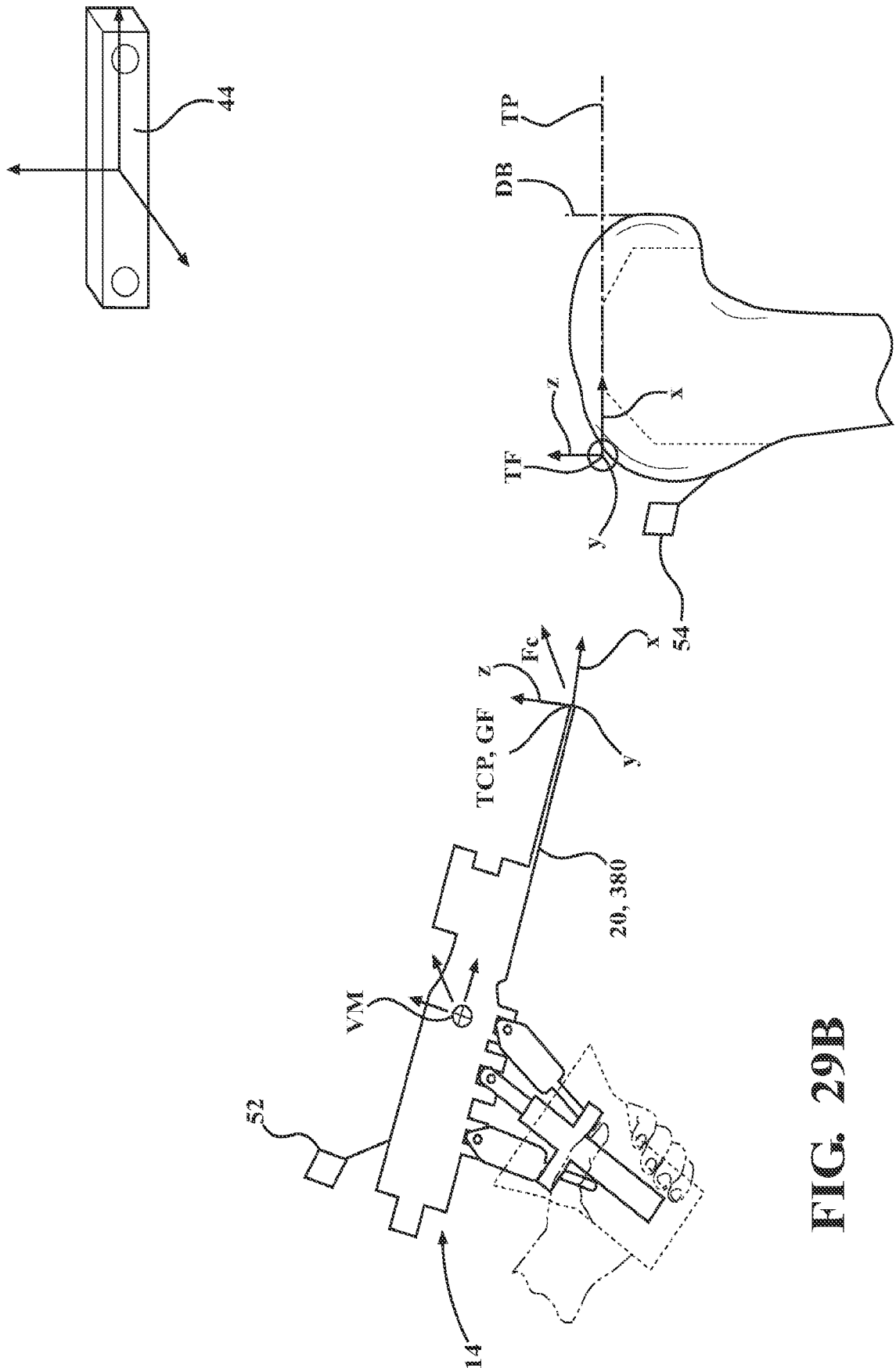
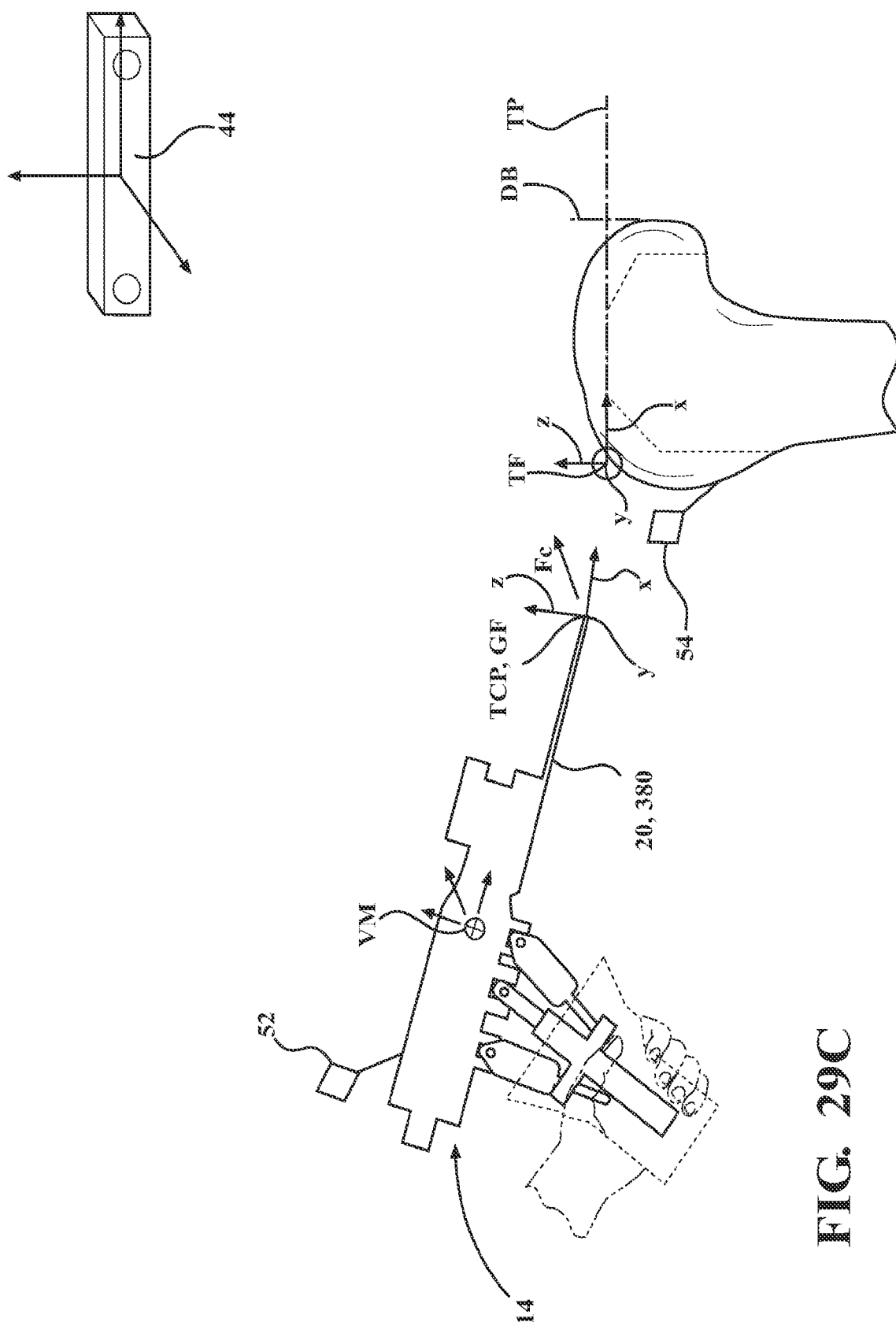
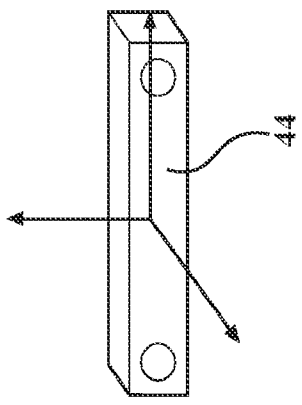
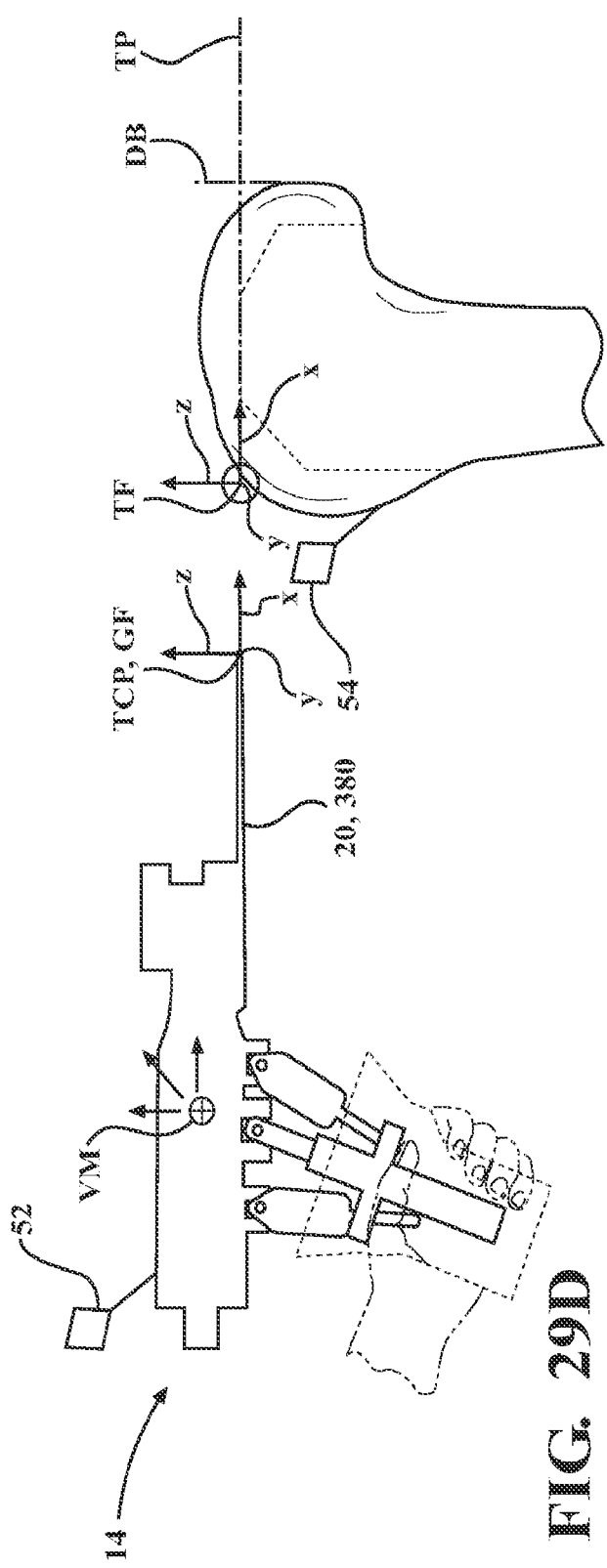


FIG. 29B





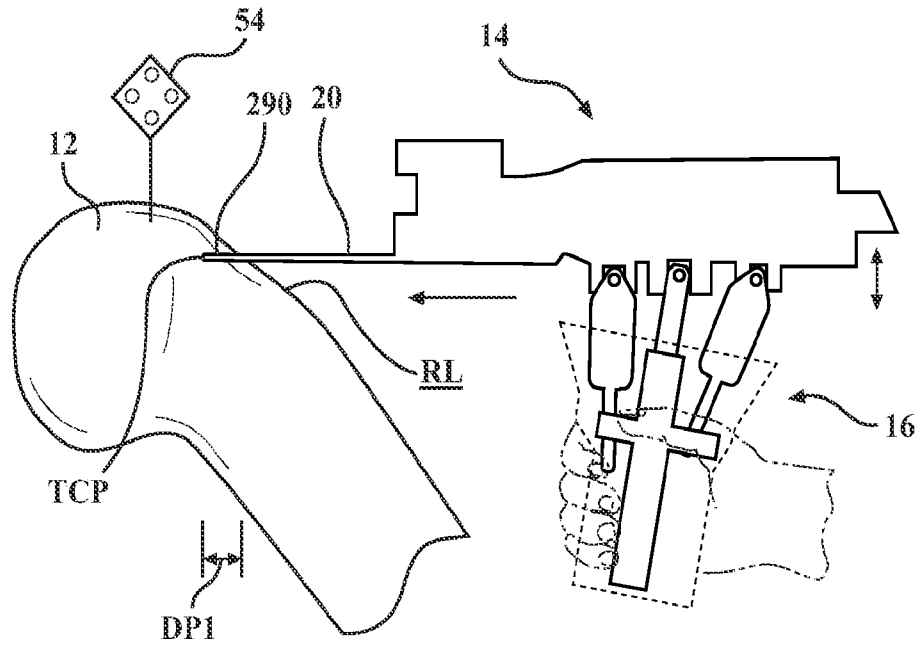


FIG. 30A

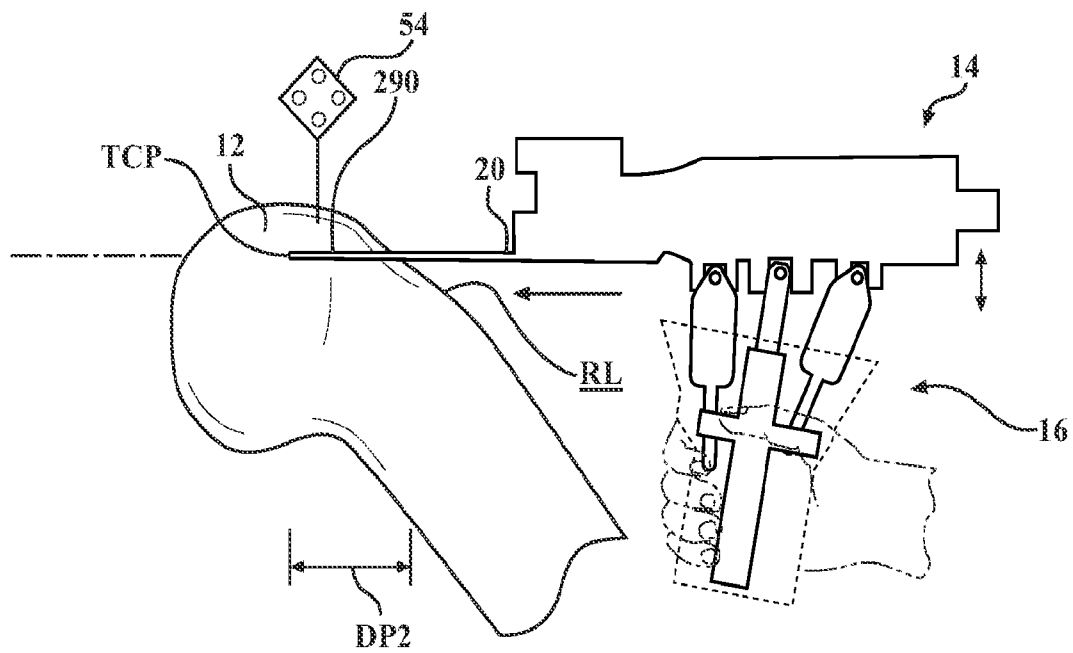


FIG. 30B

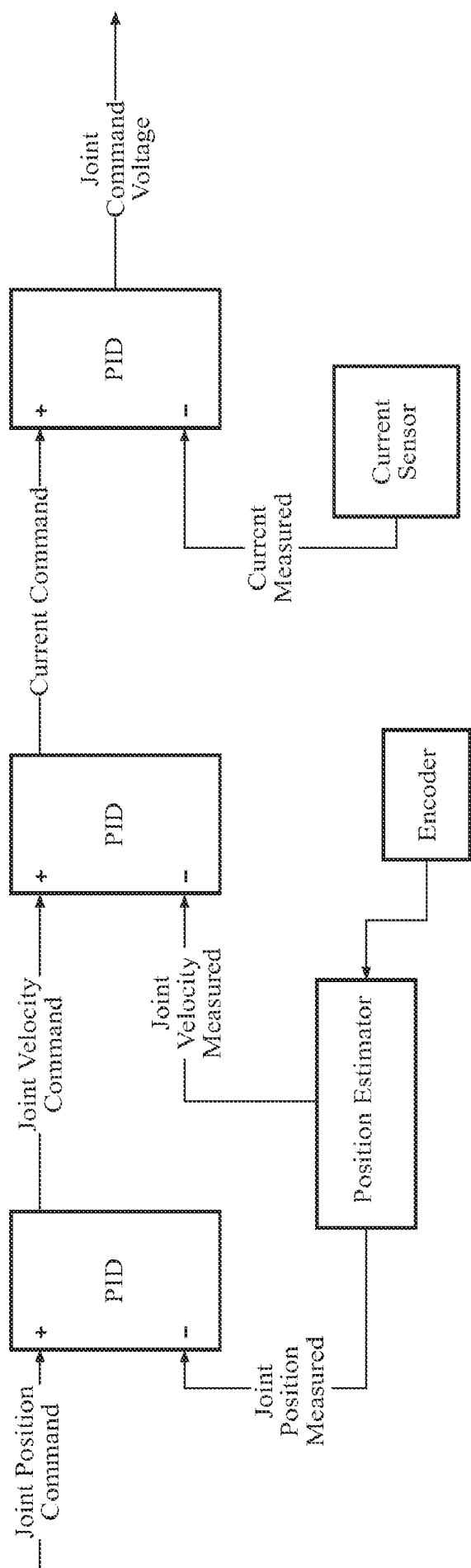
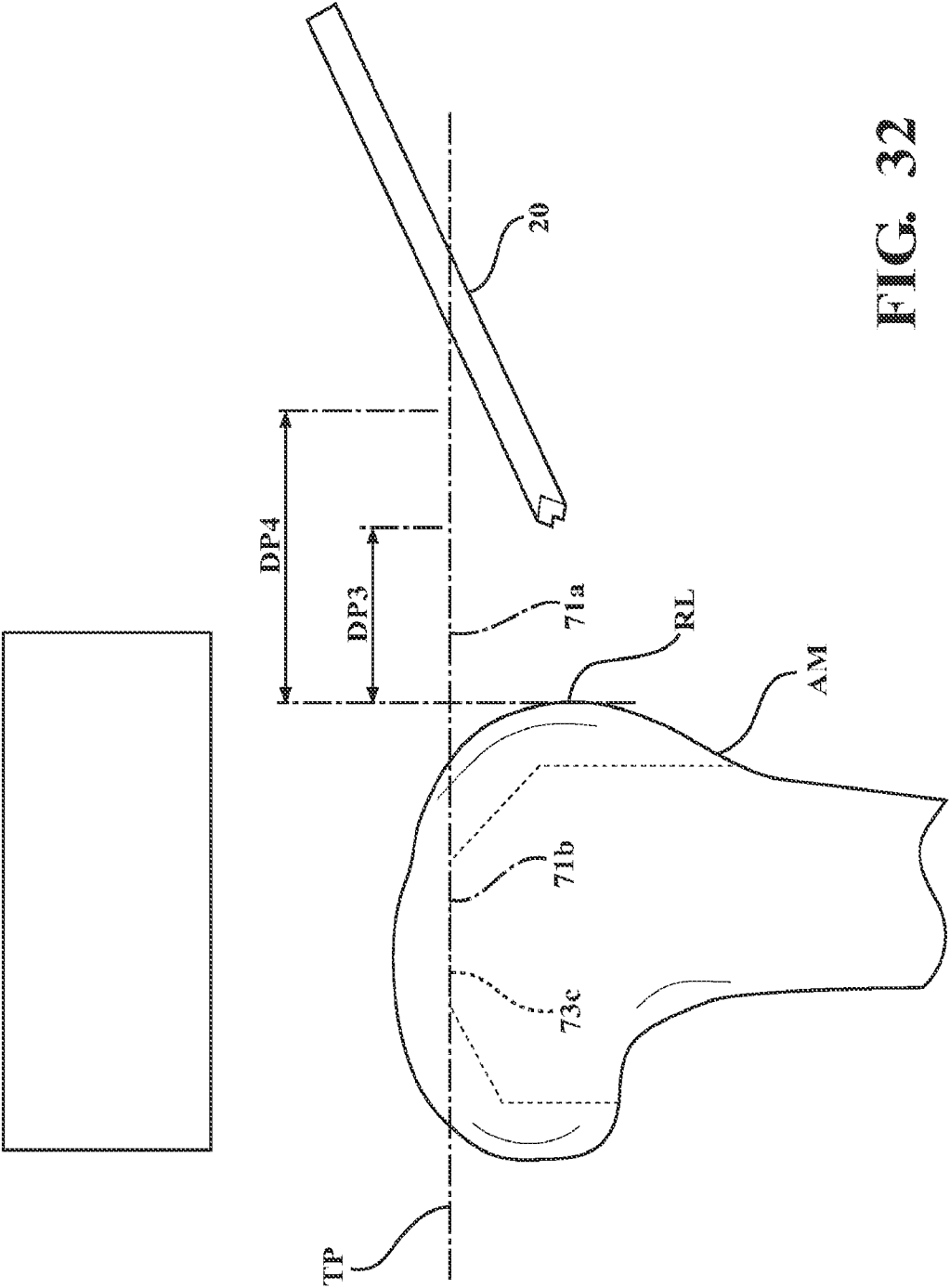


FIG. 31



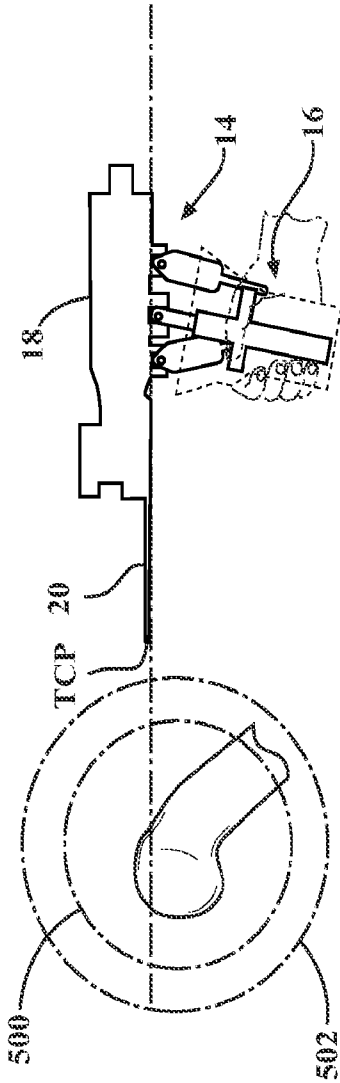


FIG. 33A

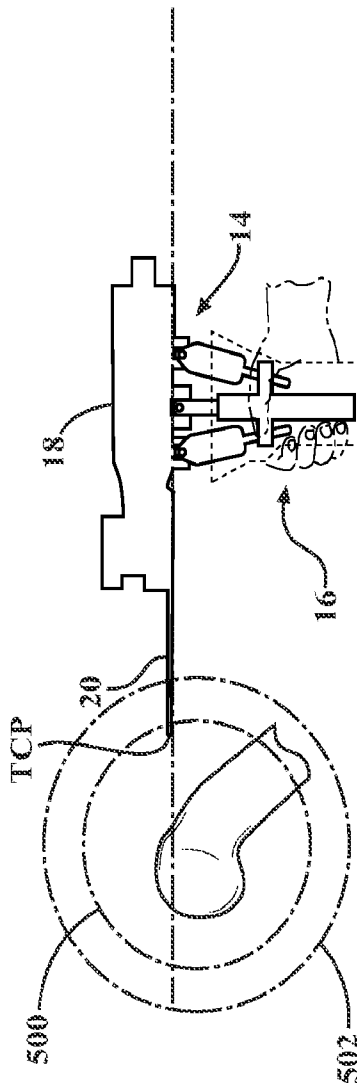


FIG. 33B

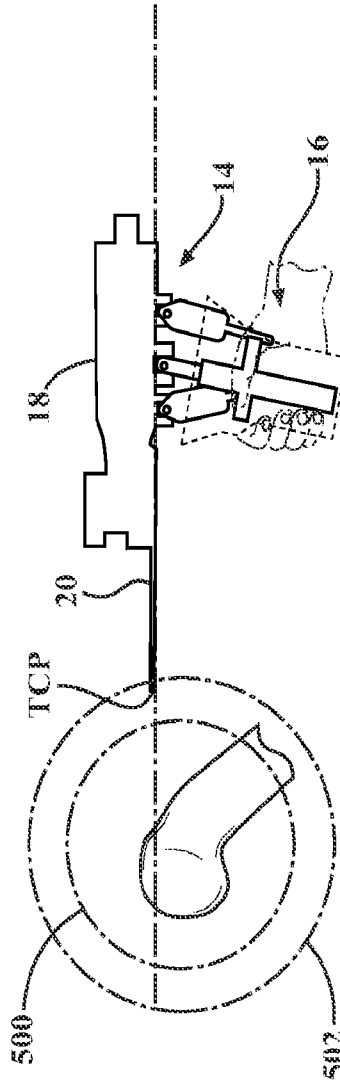


FIG. 33C

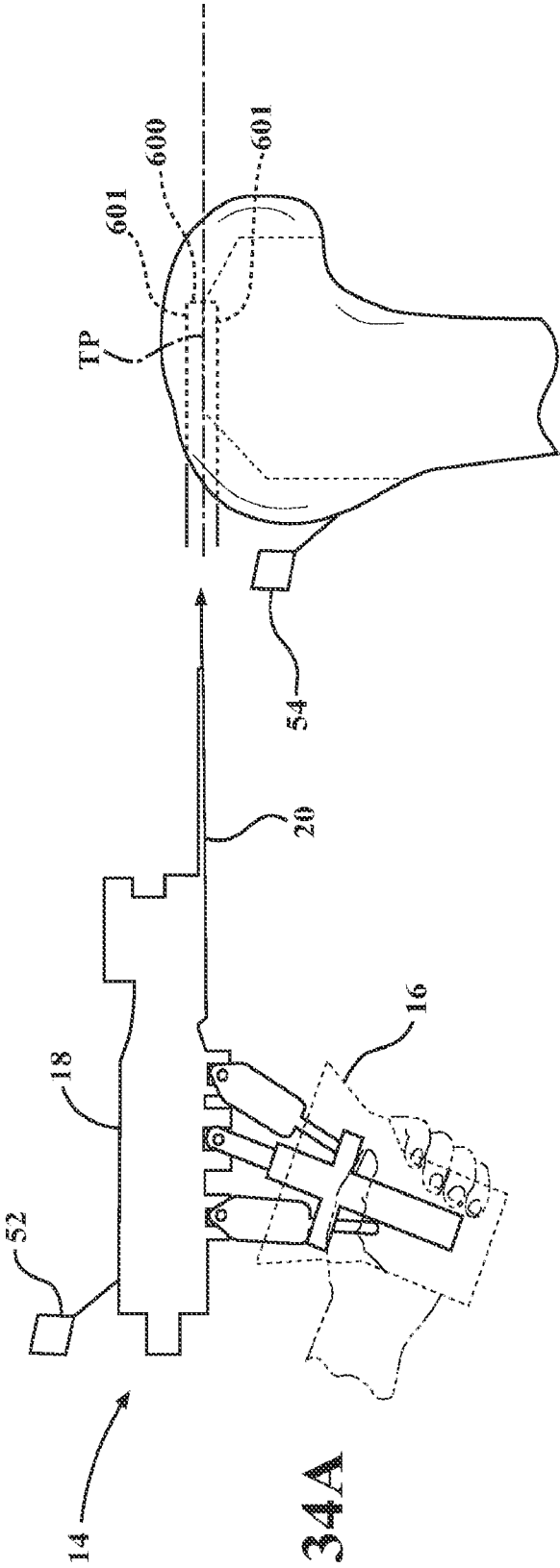


FIG. 34A

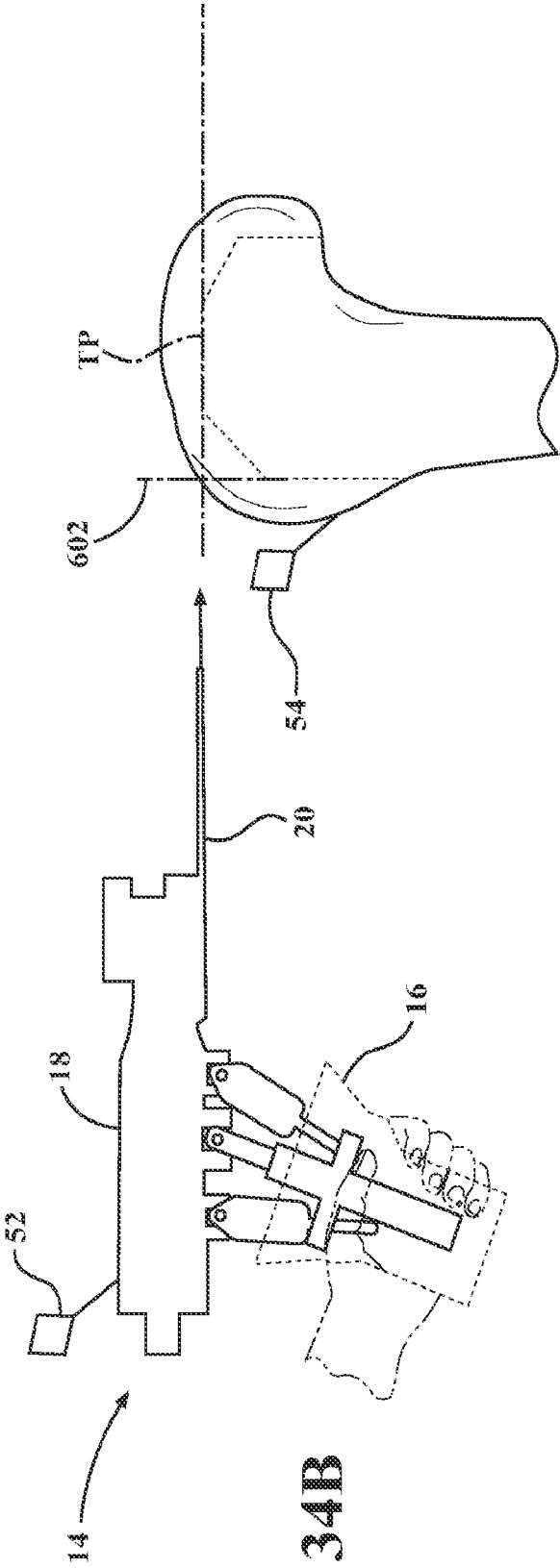
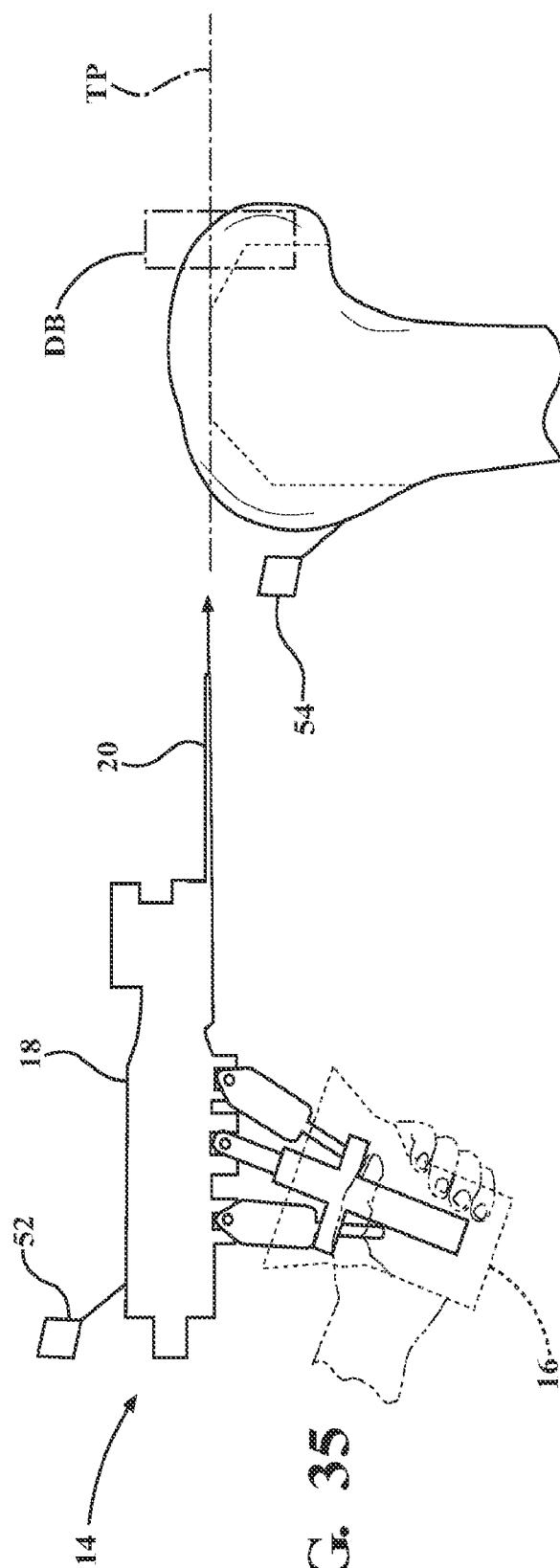


FIG. 34B



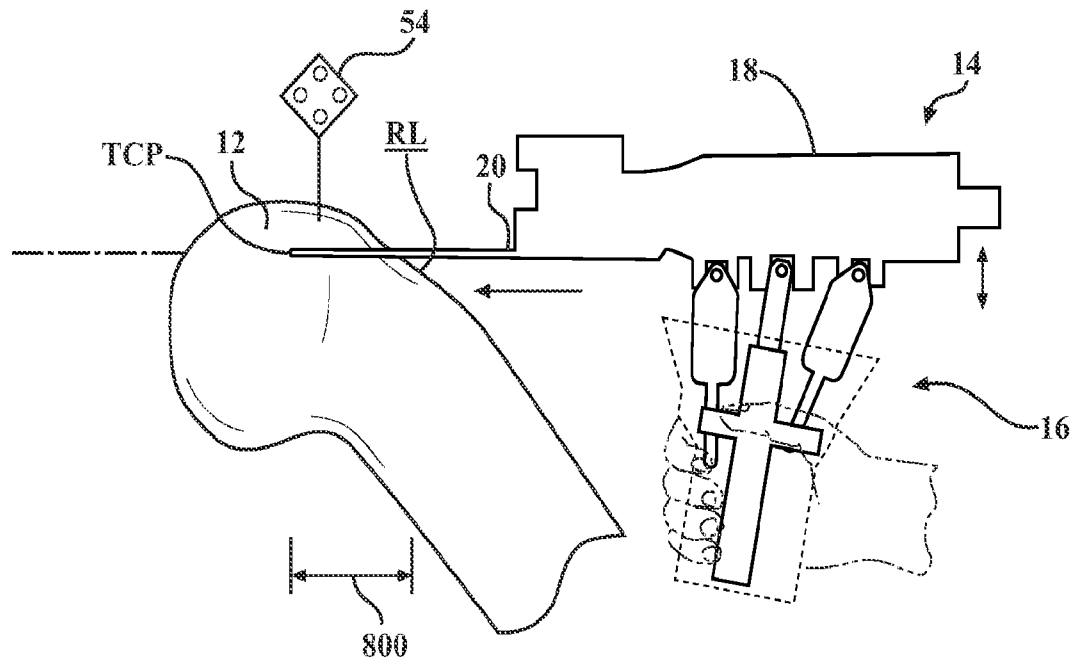


FIG. 36A

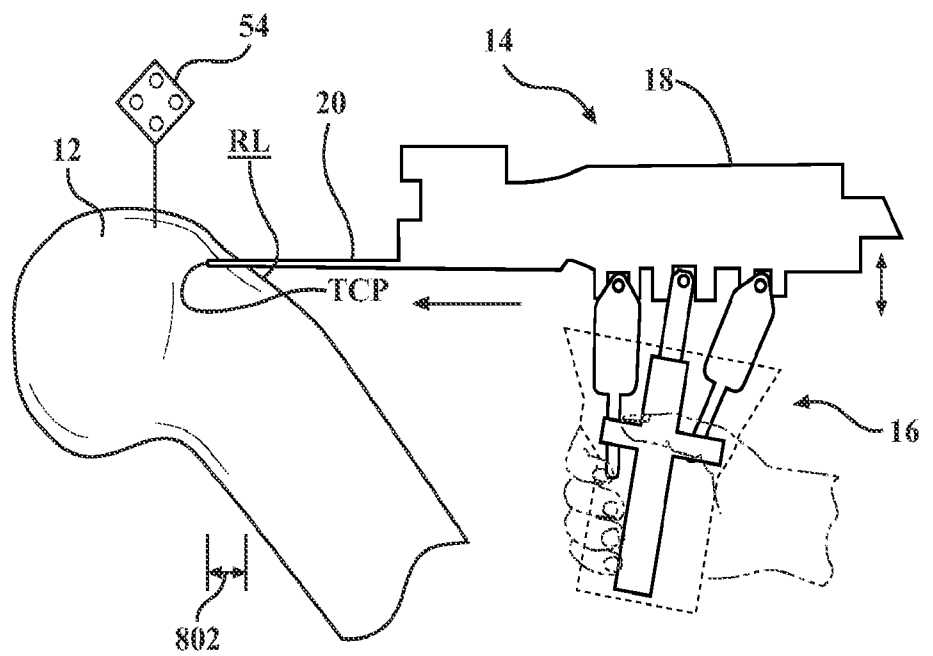


FIG. 36B

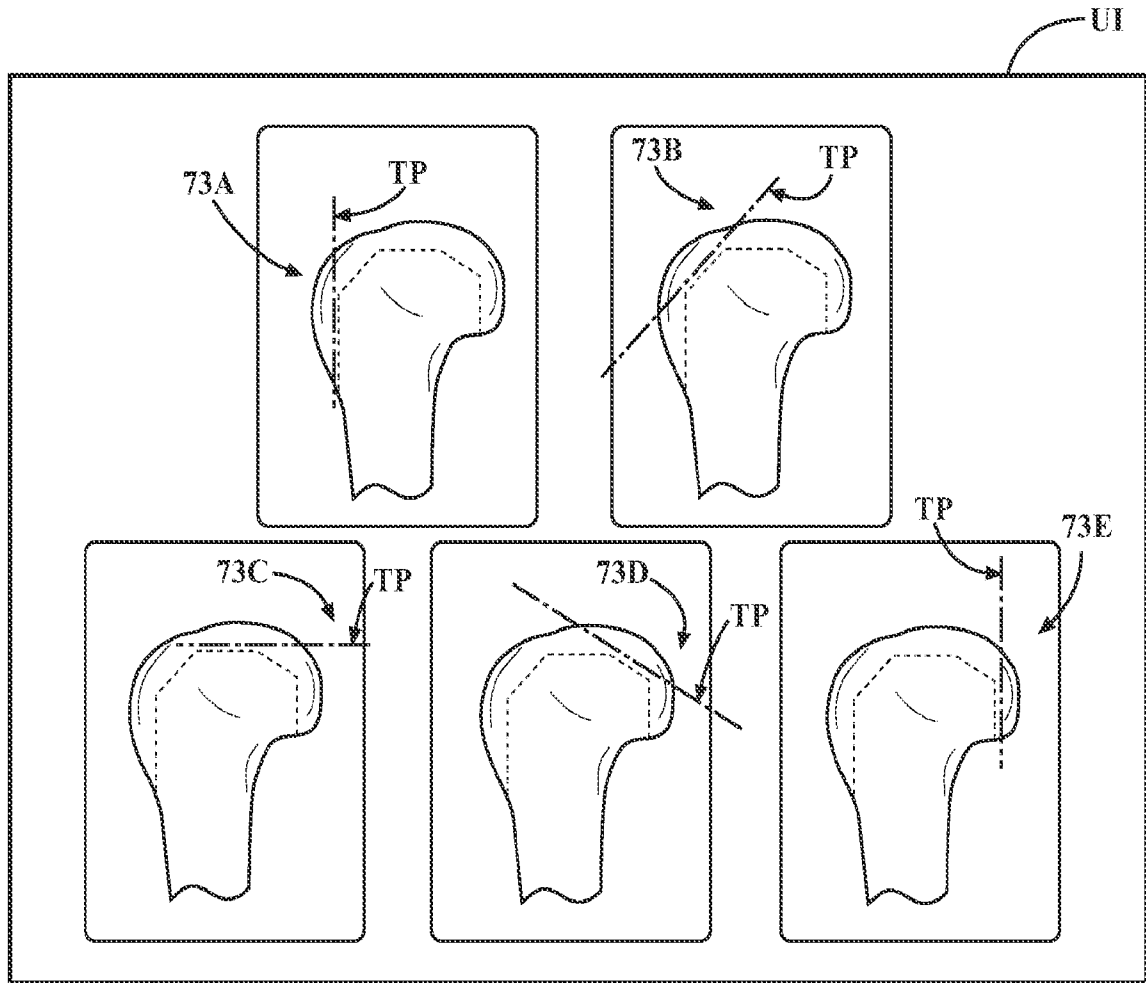


FIG. 37

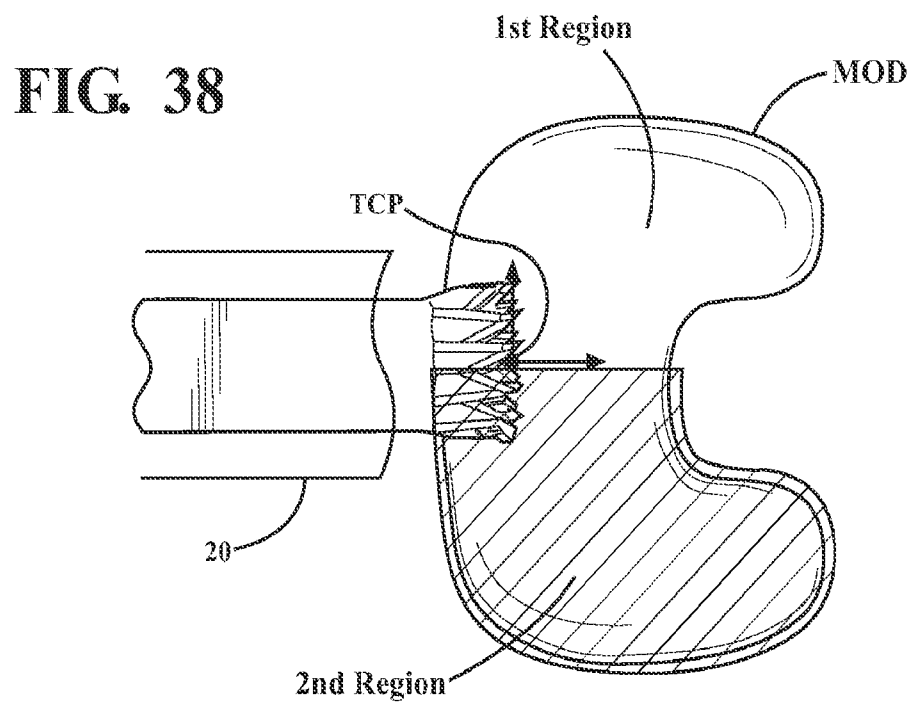


FIG. 38

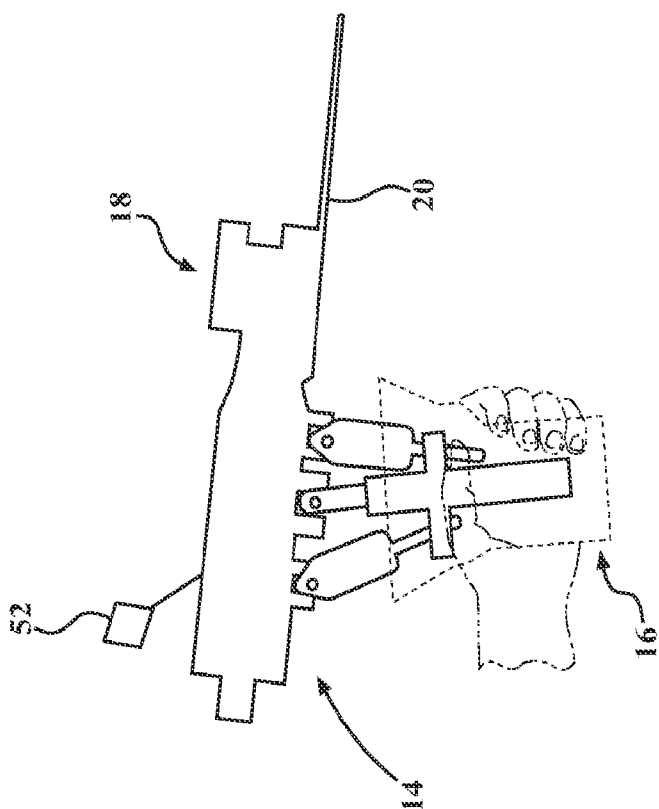


FIG. 39A

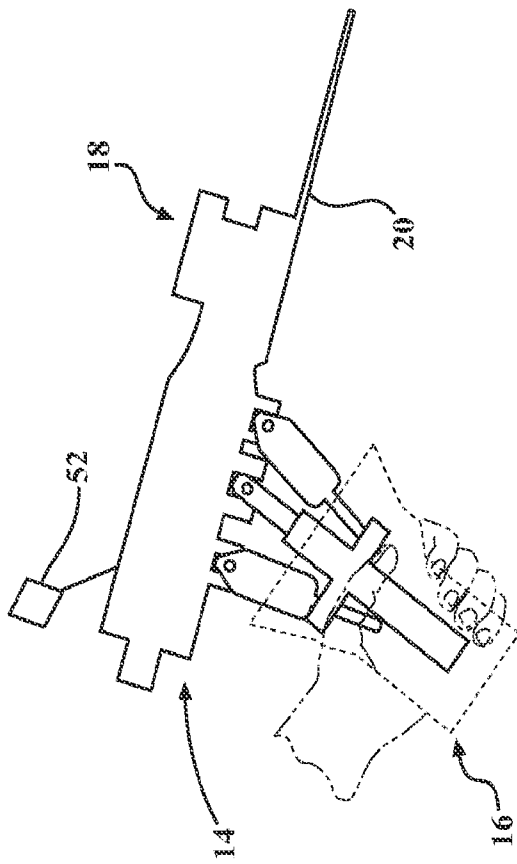


FIG. 39B

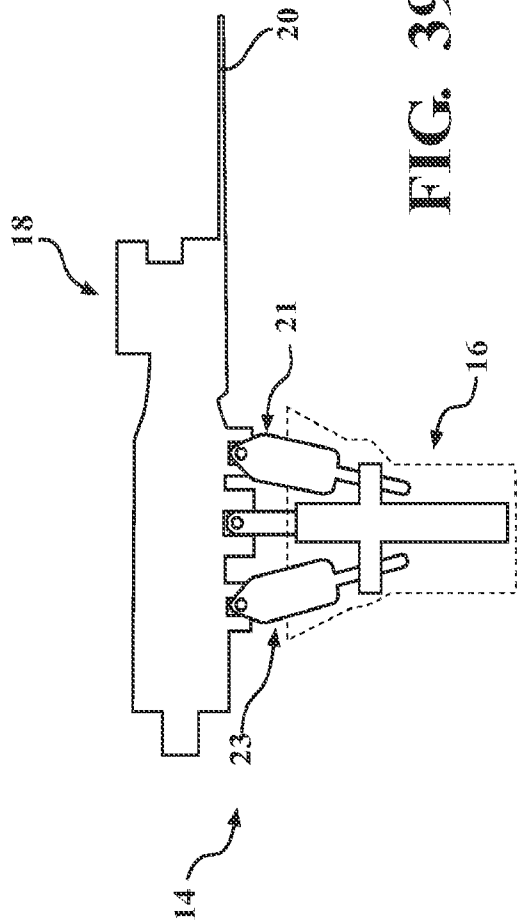


FIG. 39C

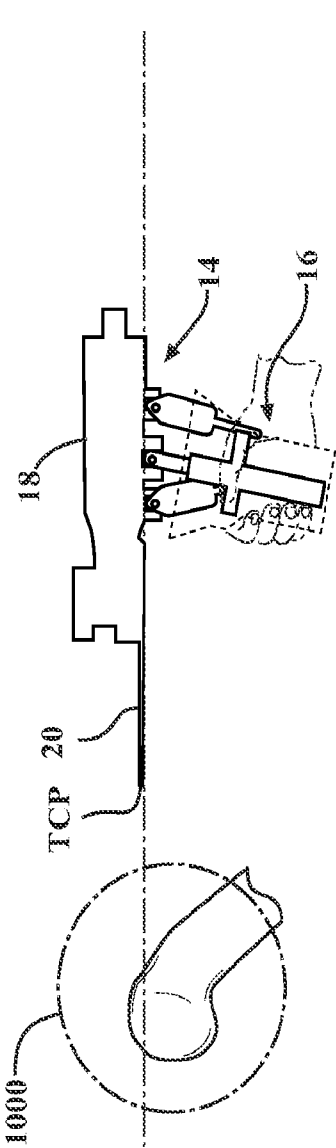


FIG. 40

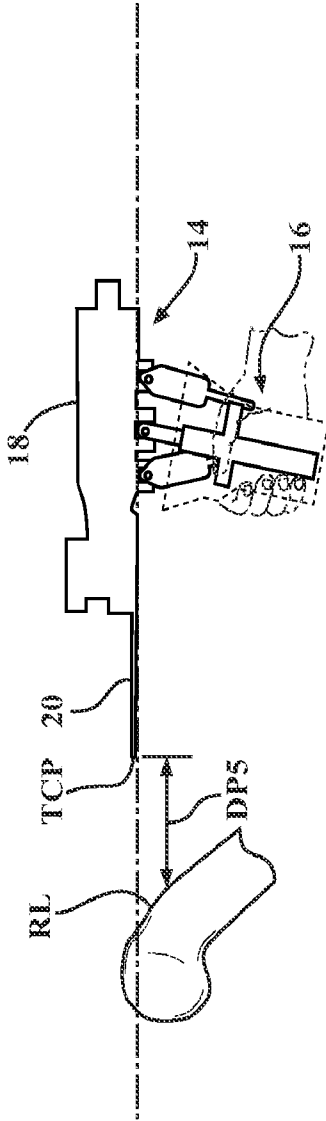


FIG. 41

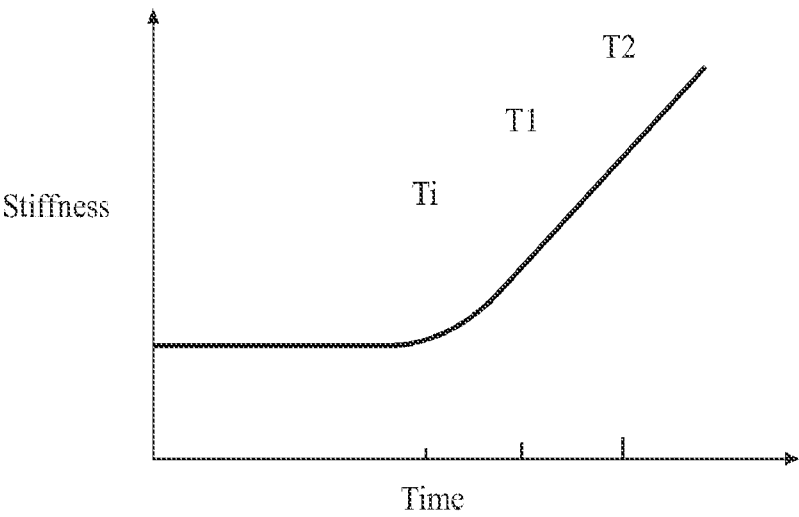


FIG. 42

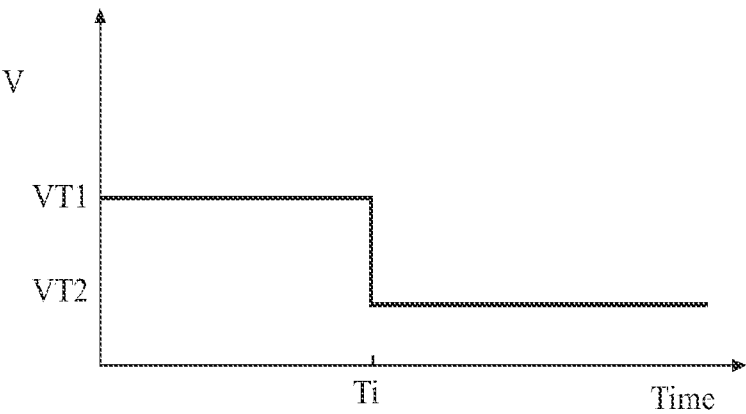


FIG. 43

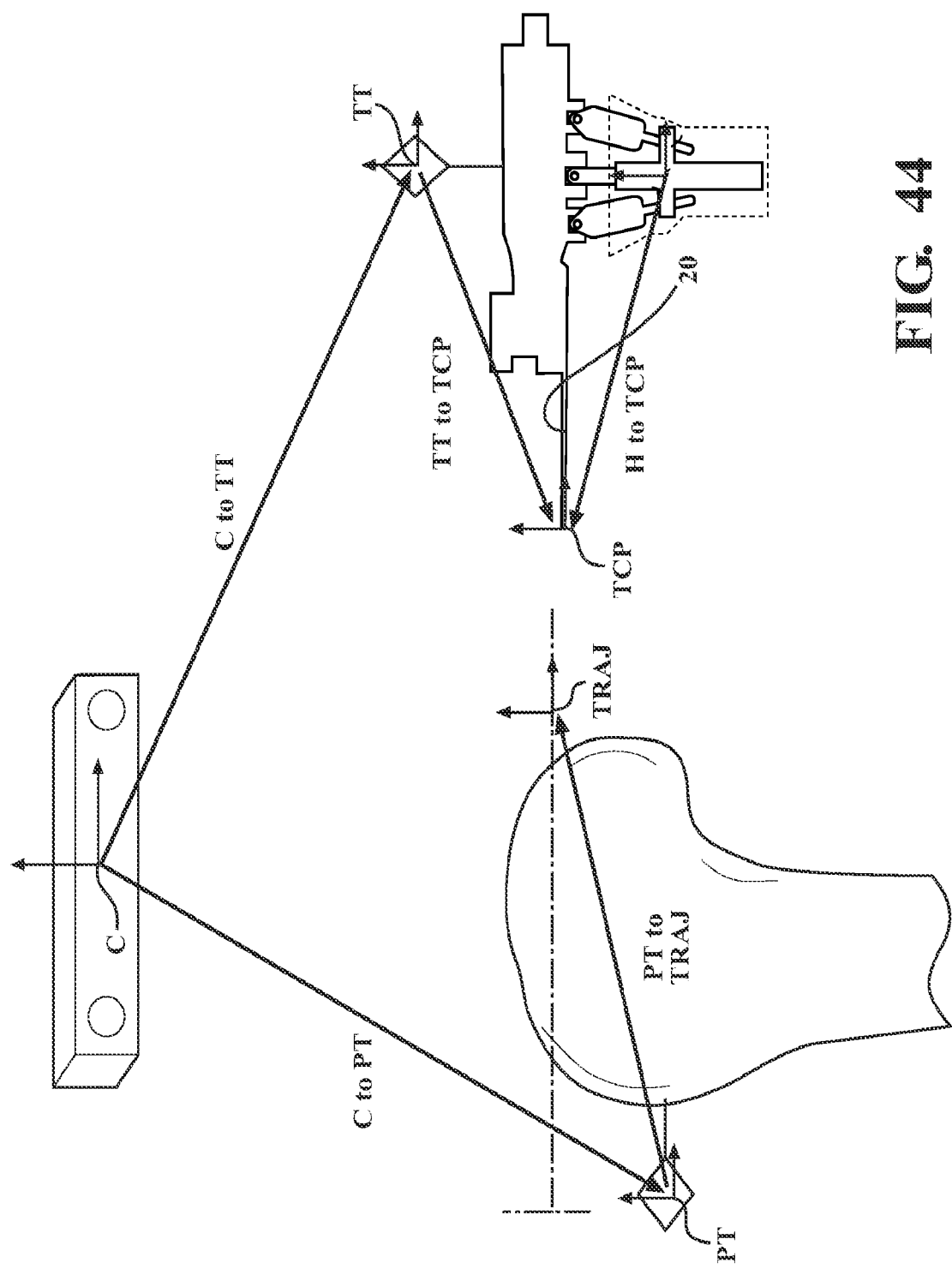
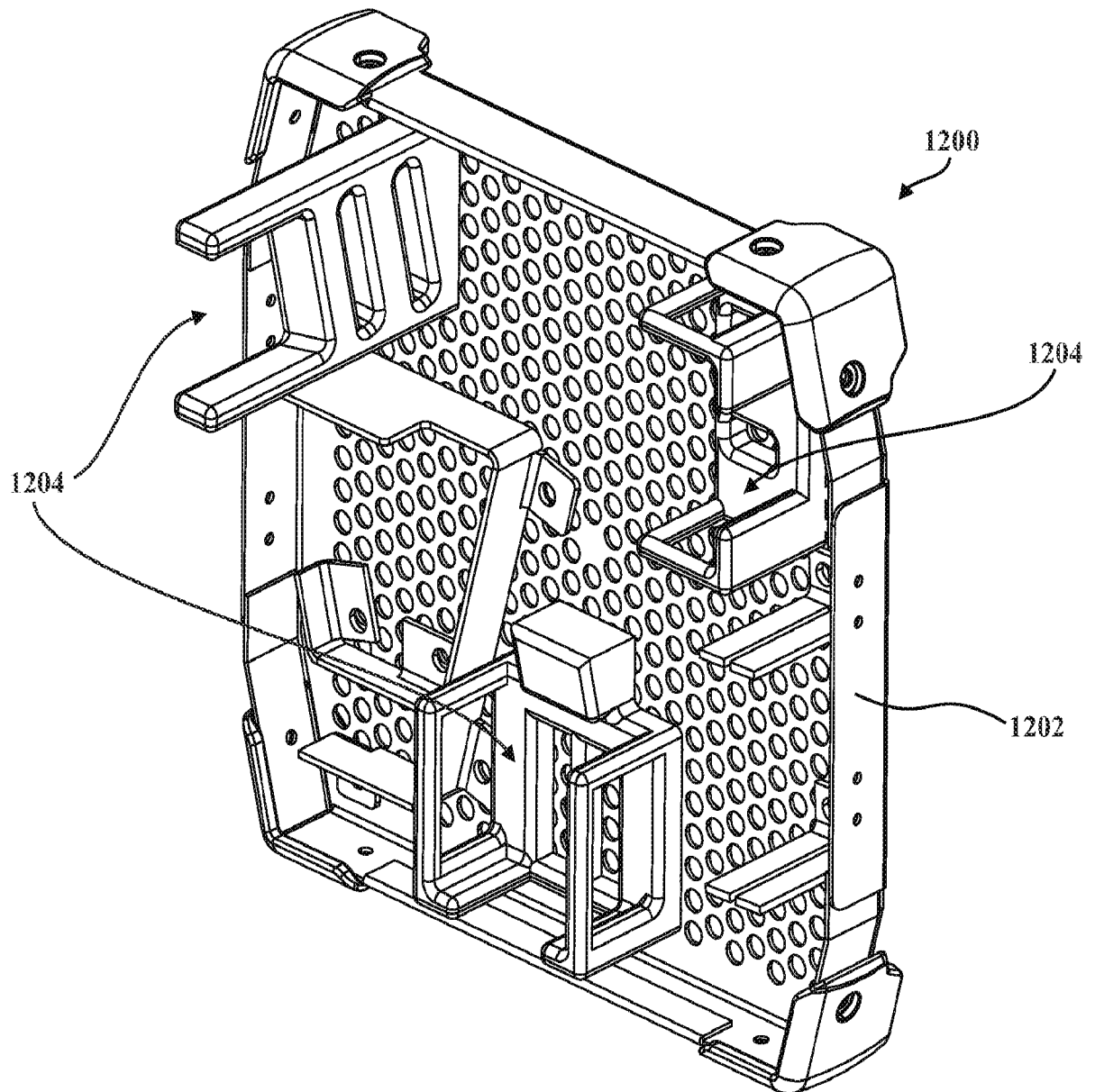


FIG. 44

**FIG. 45**

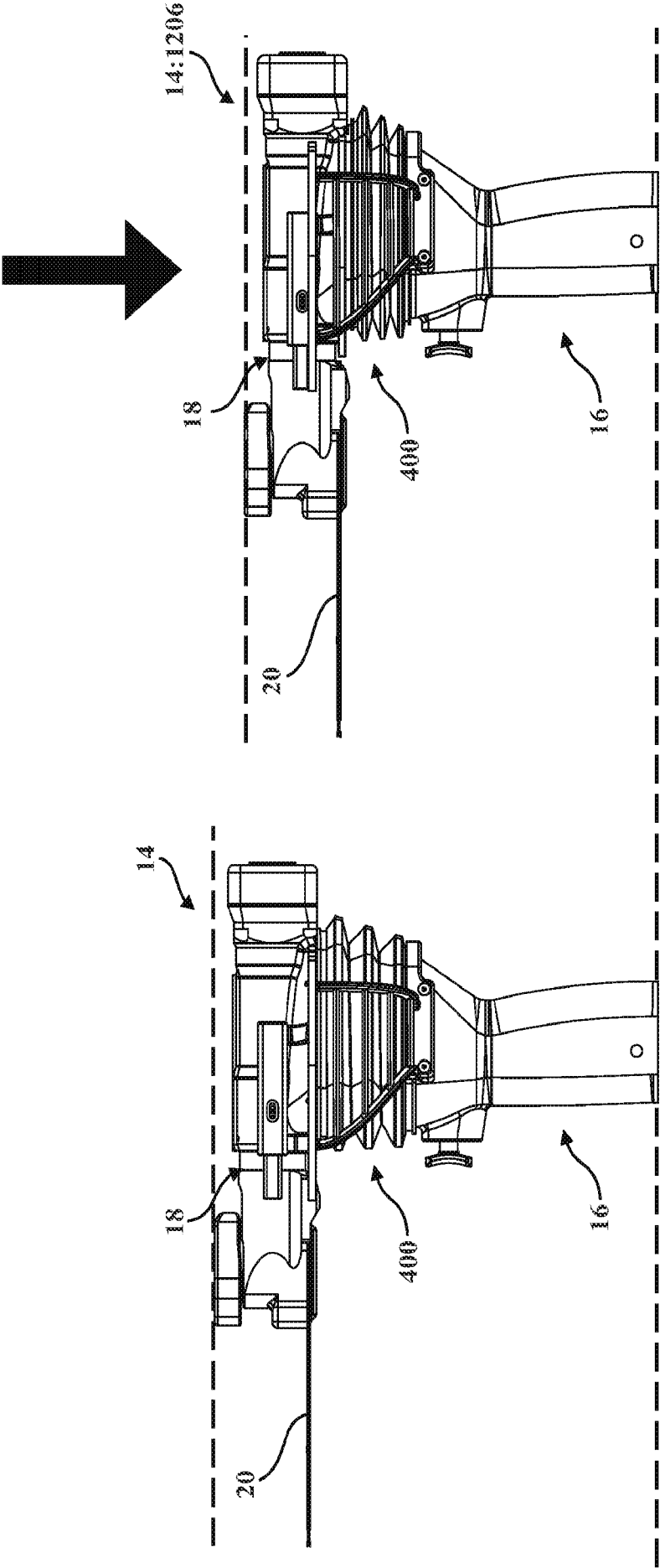
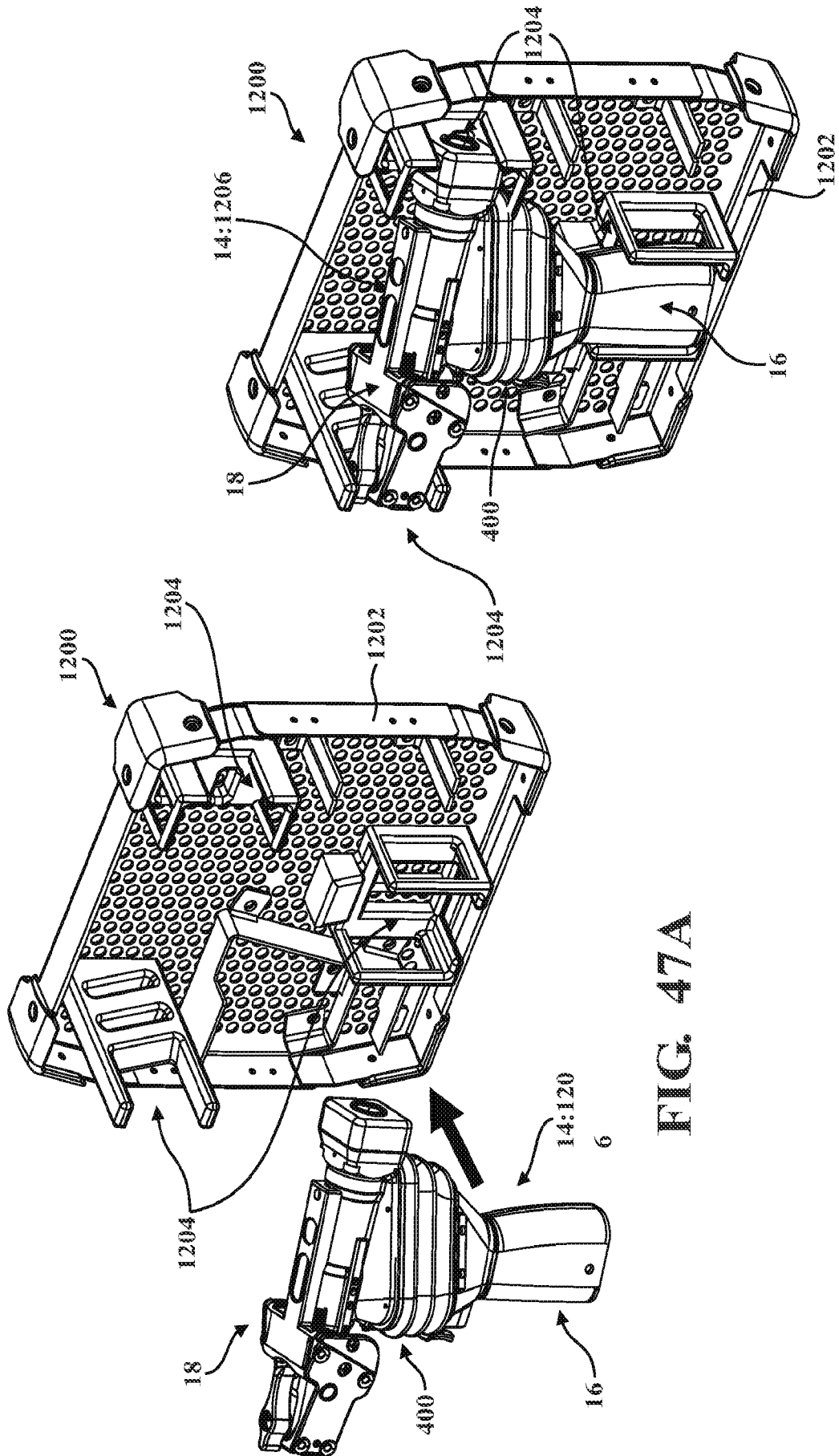


FIG. 46B

FIG. 46A



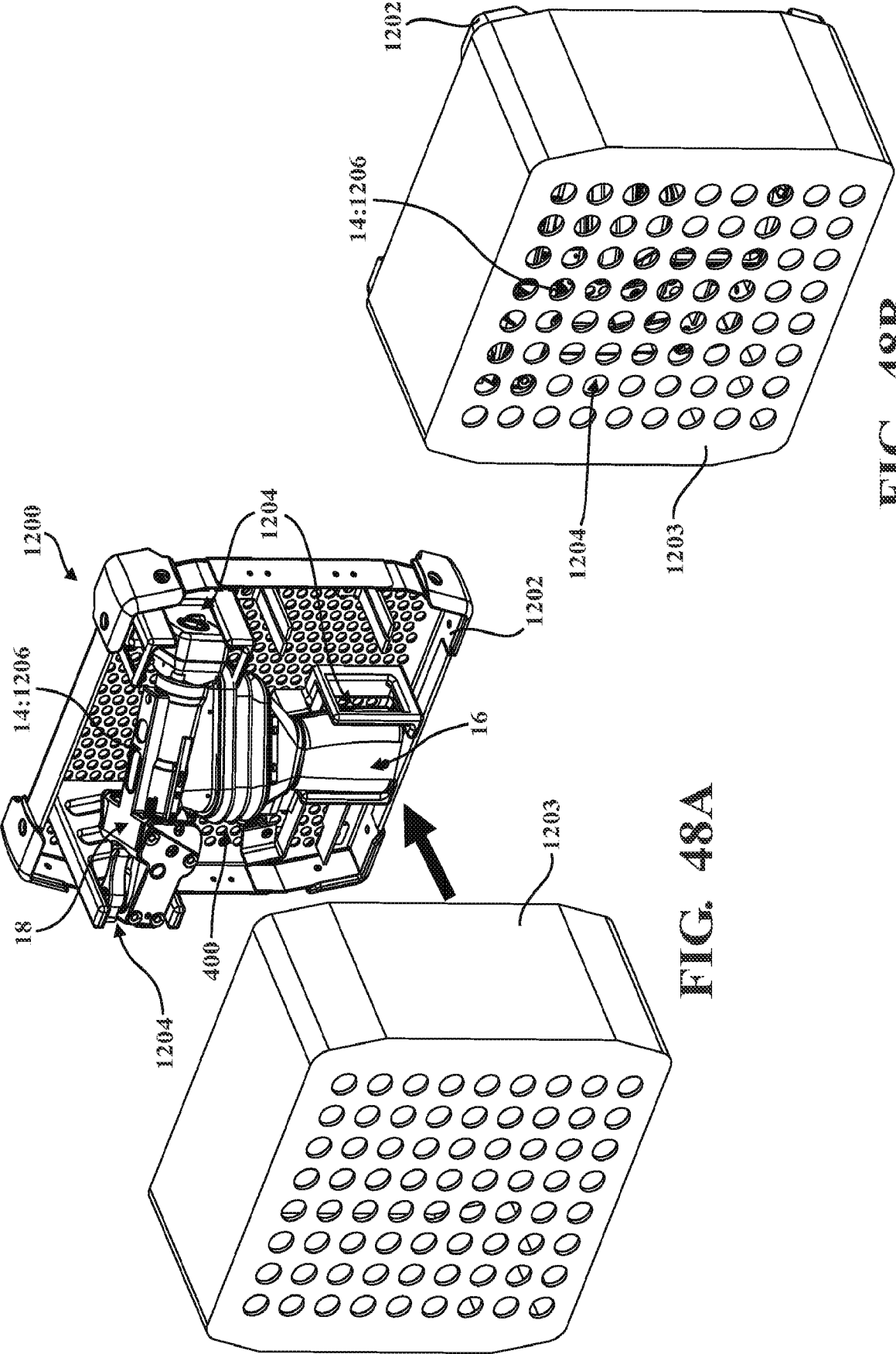


FIG. 48B

FIG. 48A

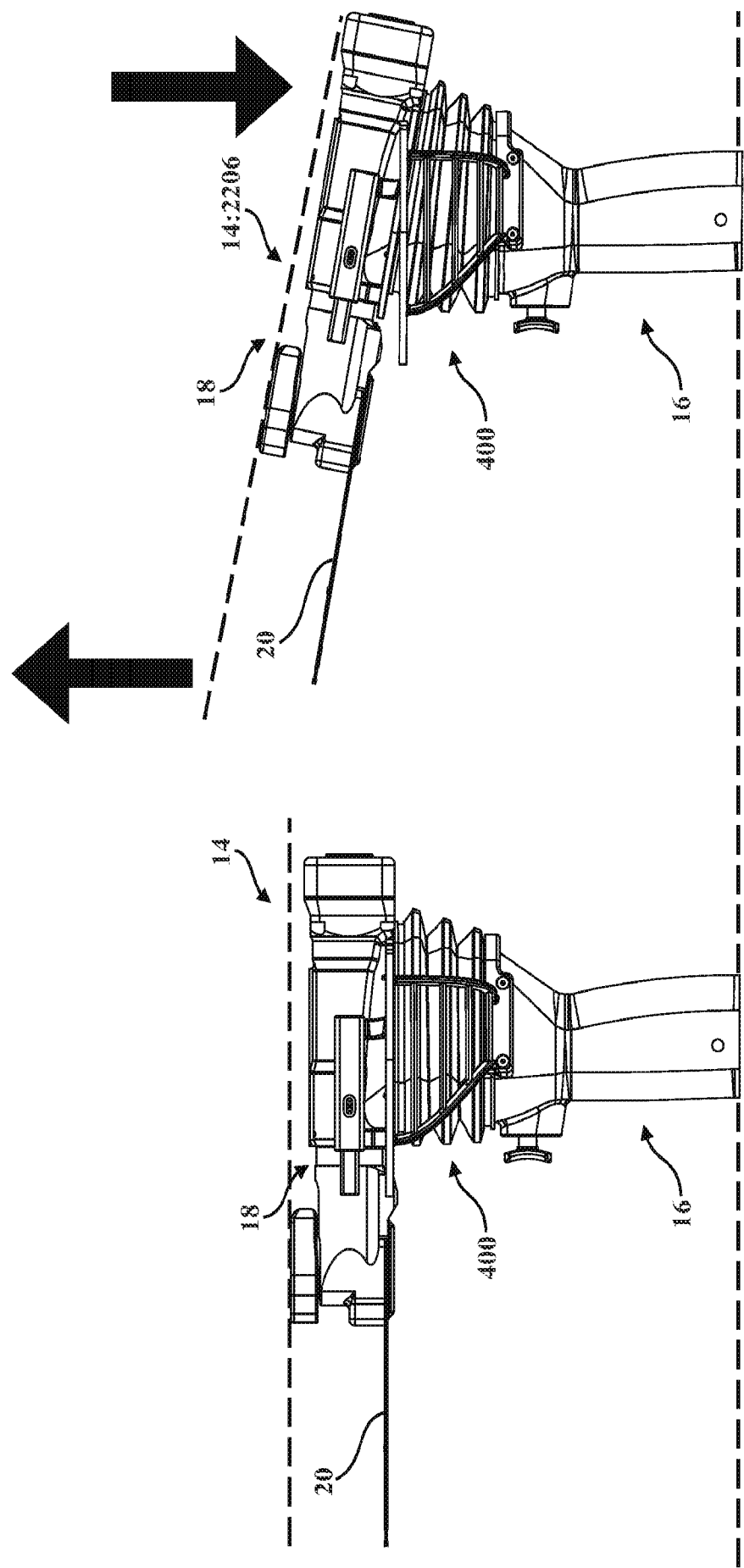


FIG. 49B

FIG. 49A

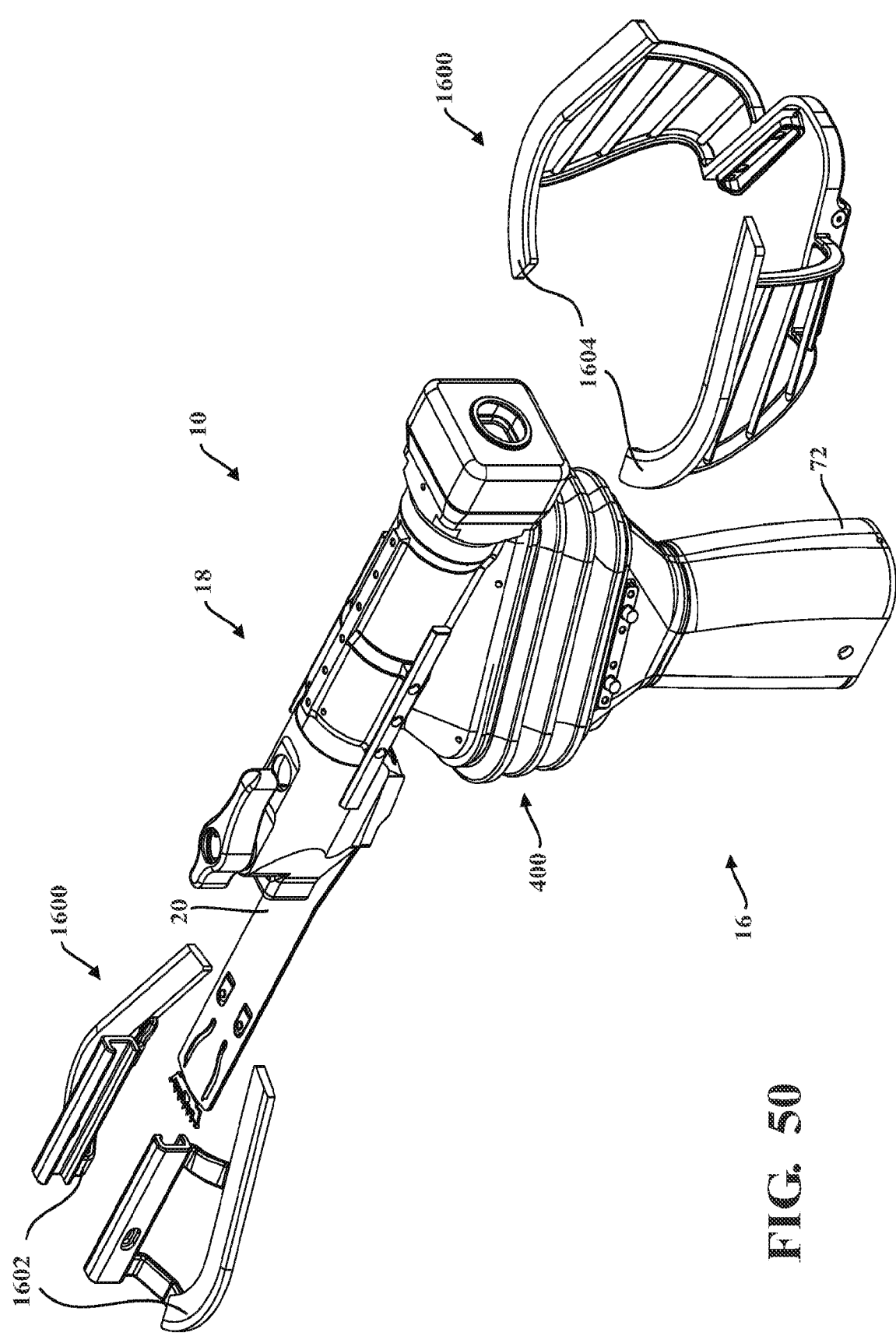


FIG. 50

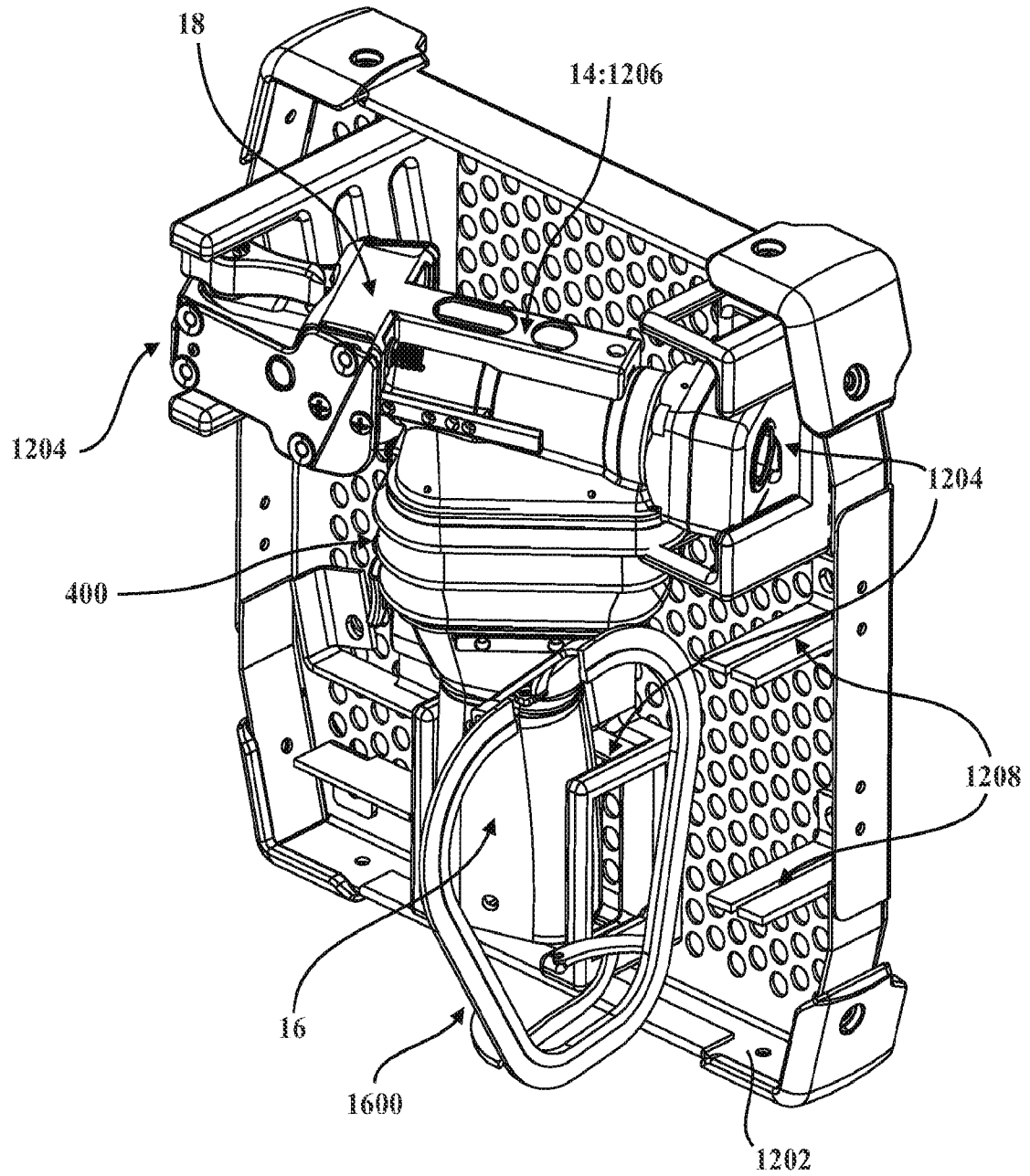


FIG. 51

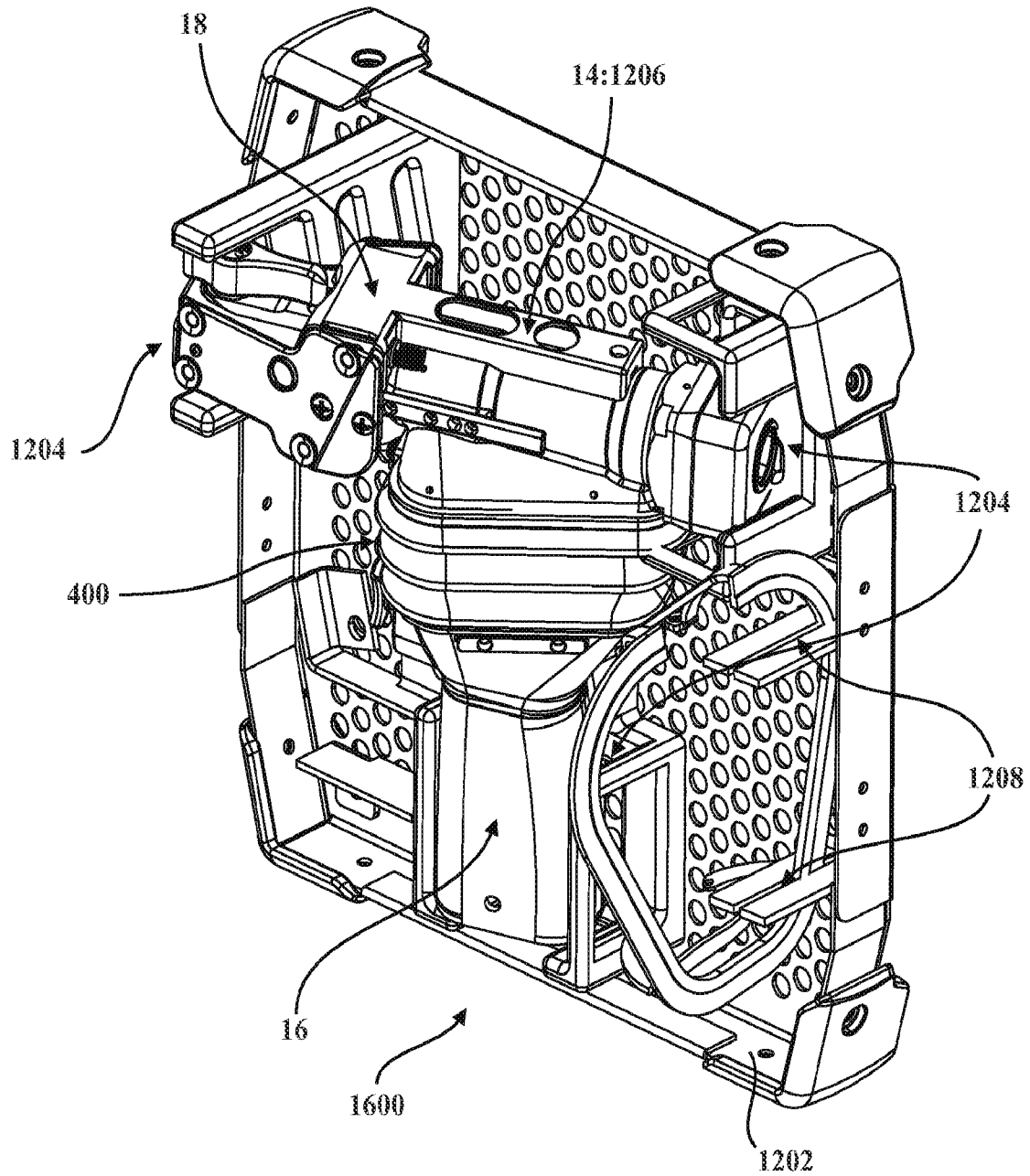


FIG. 52

FIG. 53

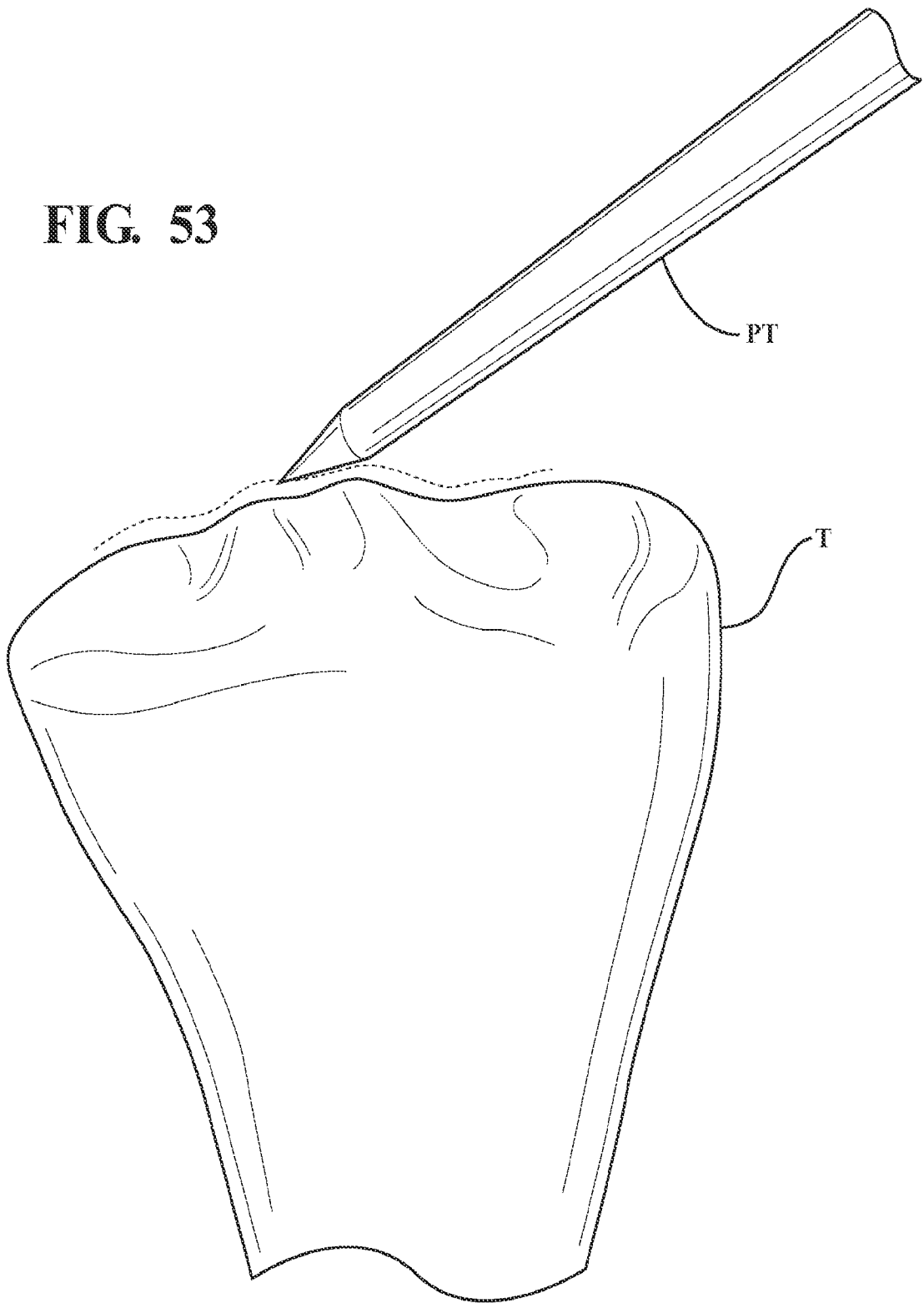


FIG. 54

