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(54) TECHNIQUES FOR MODIFYING TOOL OPERATION IN A SURGICAL ROBOTIC SYSTEM BASED ON COMPARING ACTUAL AND COMMANDED STATES OF THE TOOL RELATIVE TO A SURGICAL SITE

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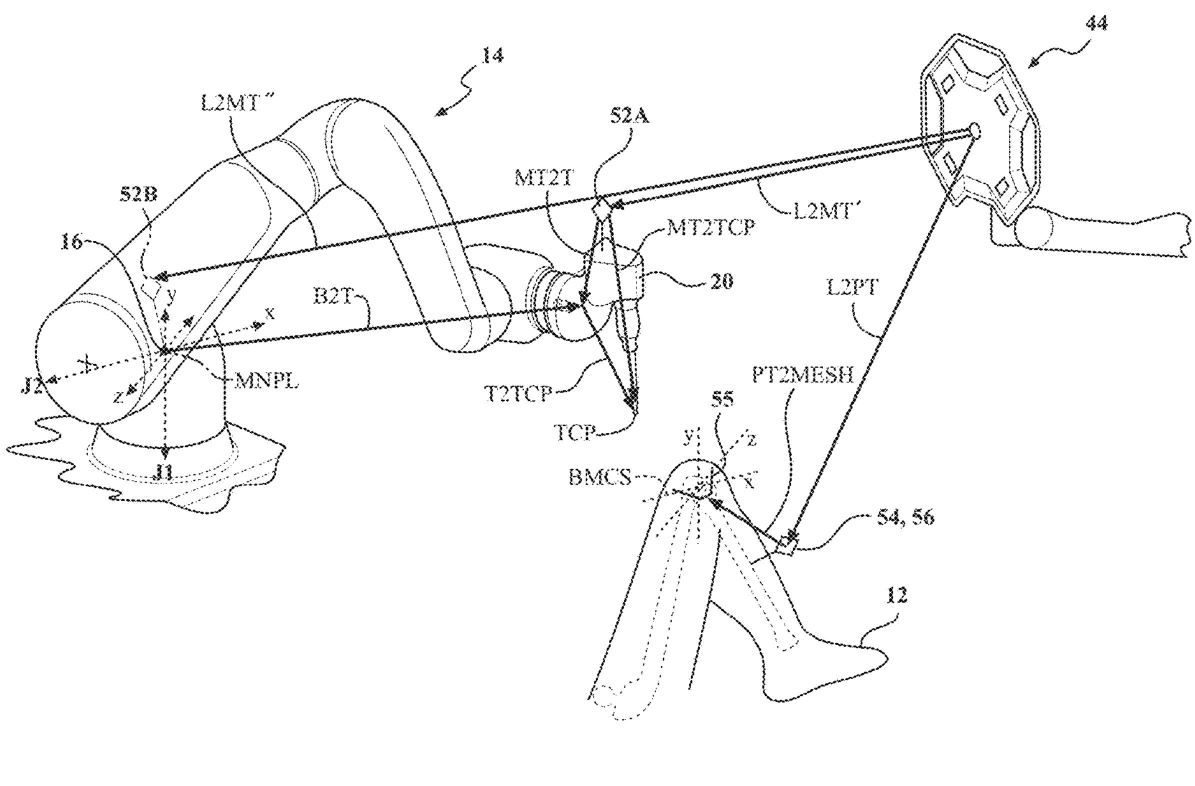
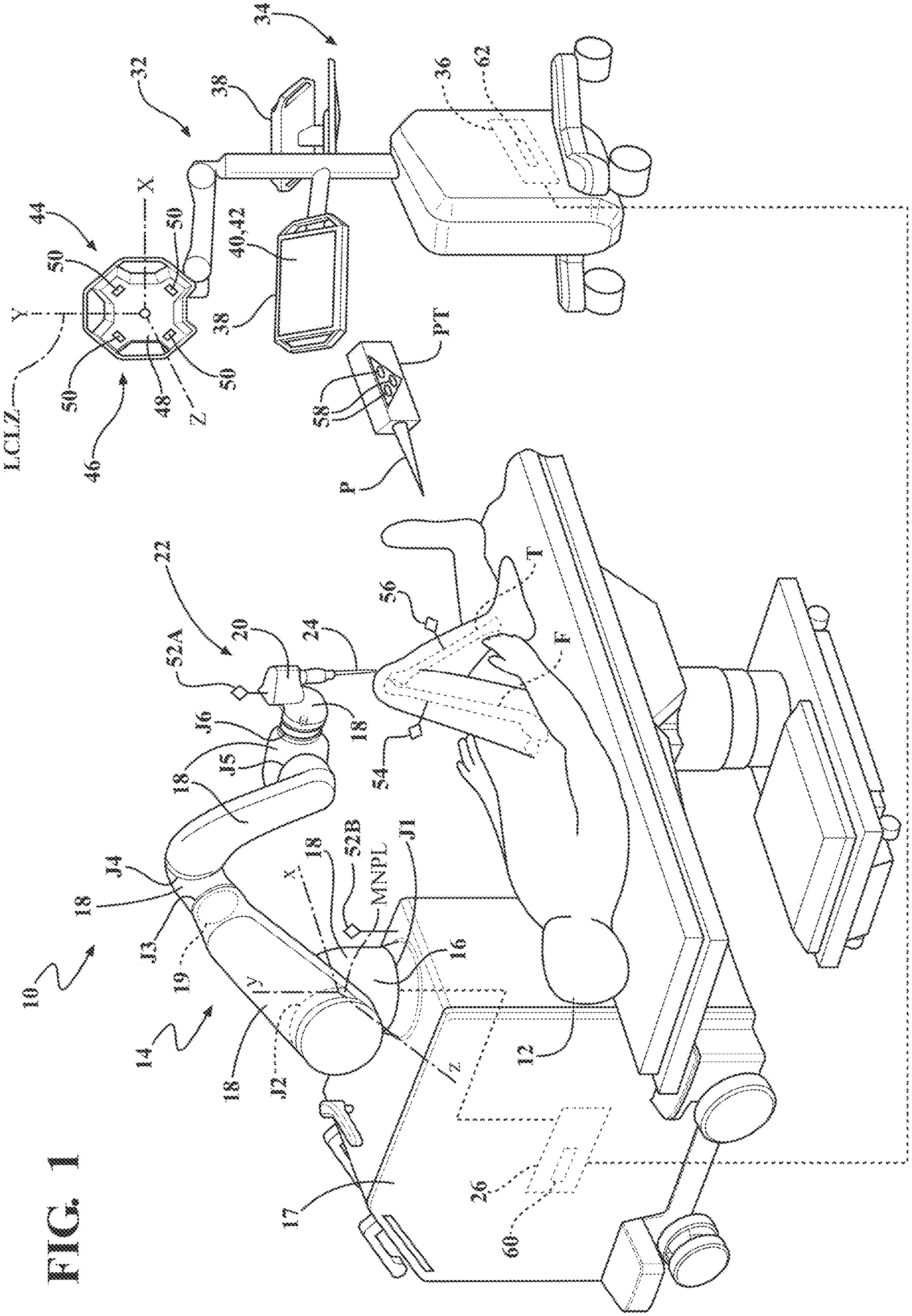
(57) **ABSTRACT**

A surgical system and method of operating the same. A manipulator supports and facilitates movement of a surgical tool along a tool path relative to a surgical site. Controller(s) determine commanded states and actual states of the surgical tool relative to the tool path for a plurality of time steps. The controller(s) detect at least one deviation between the commanded states and the actual states of the surgical tool for at least one of the plurality of time steps. The controller(s) respond to the deviation by modification of one or both of: a feed rate of the surgical tool; and the tool path.





10
14
12
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22
24
26
32
34
36
38
40,42
44
46
48
50
52A
52B
54
56
58
60
62
J1
J2
J3
J4
J5
J6
MNPL
LCLZ
PT
P
T
F
X
Y
Z


FIG. 1

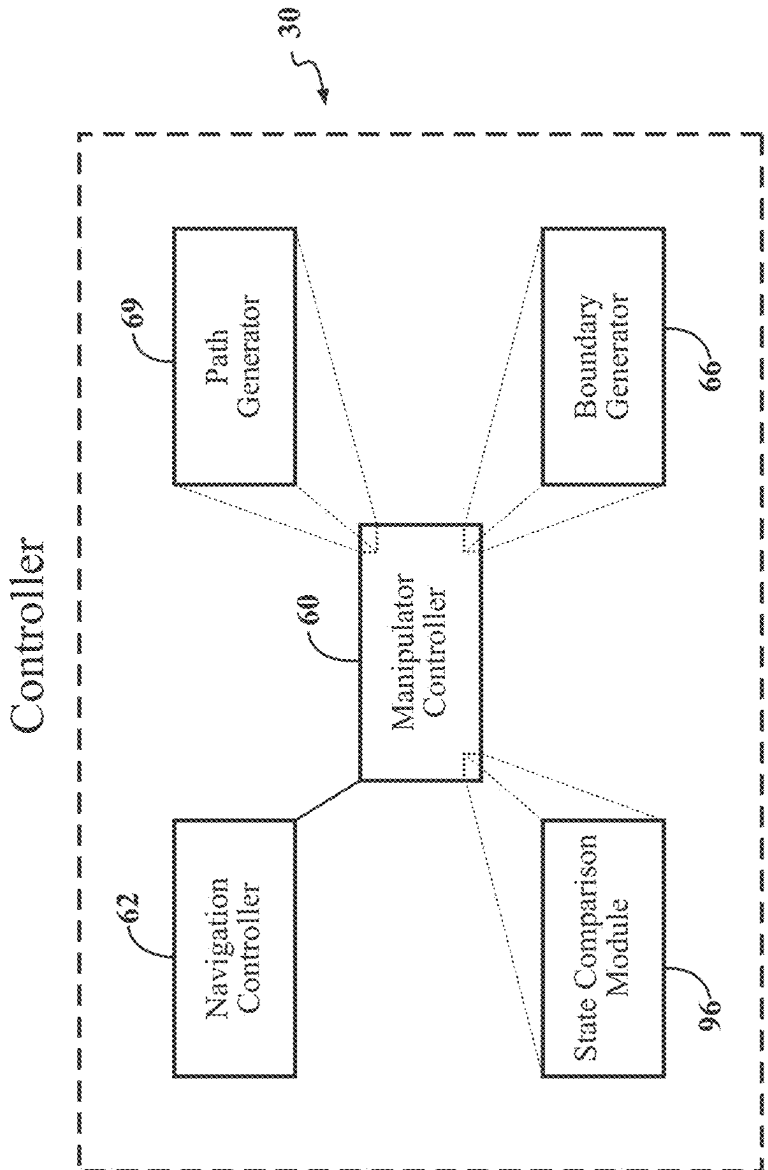

30
Controller
Path Generator
69
Boundary Generator
66
Manipulator Controller
60
Navigation Controller
62
State Comparison Module
96

FIG. 2

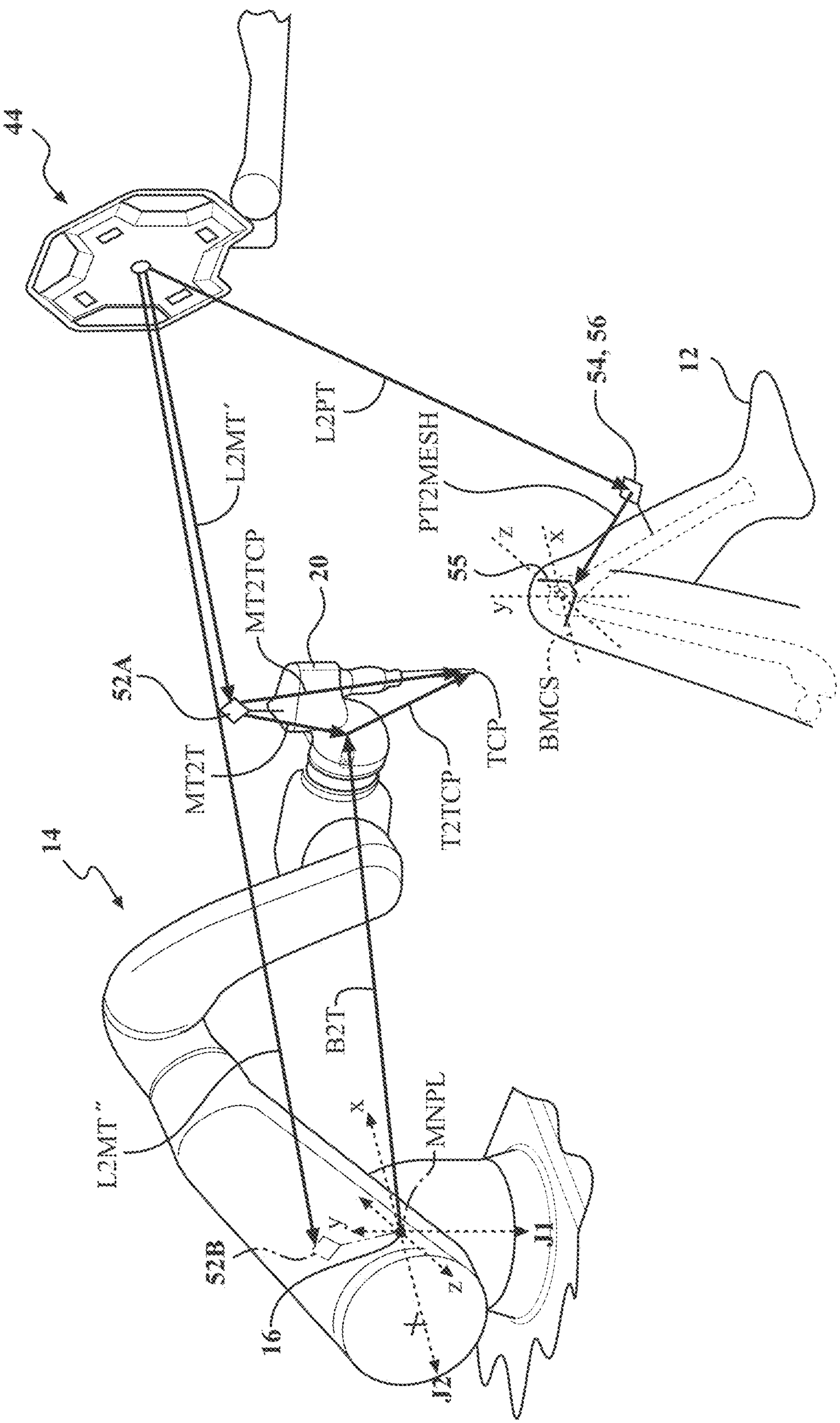

44
L2MT'
L2PT
54, 56
12
PT2MESH
55
z
x
y
BMCS
MT2TCP
20
52A
MT2T
TCP
T2TCP
14
B2T
L2MT"
MNPL
x
y
z
52B
16
J1
J2

FIG. 3

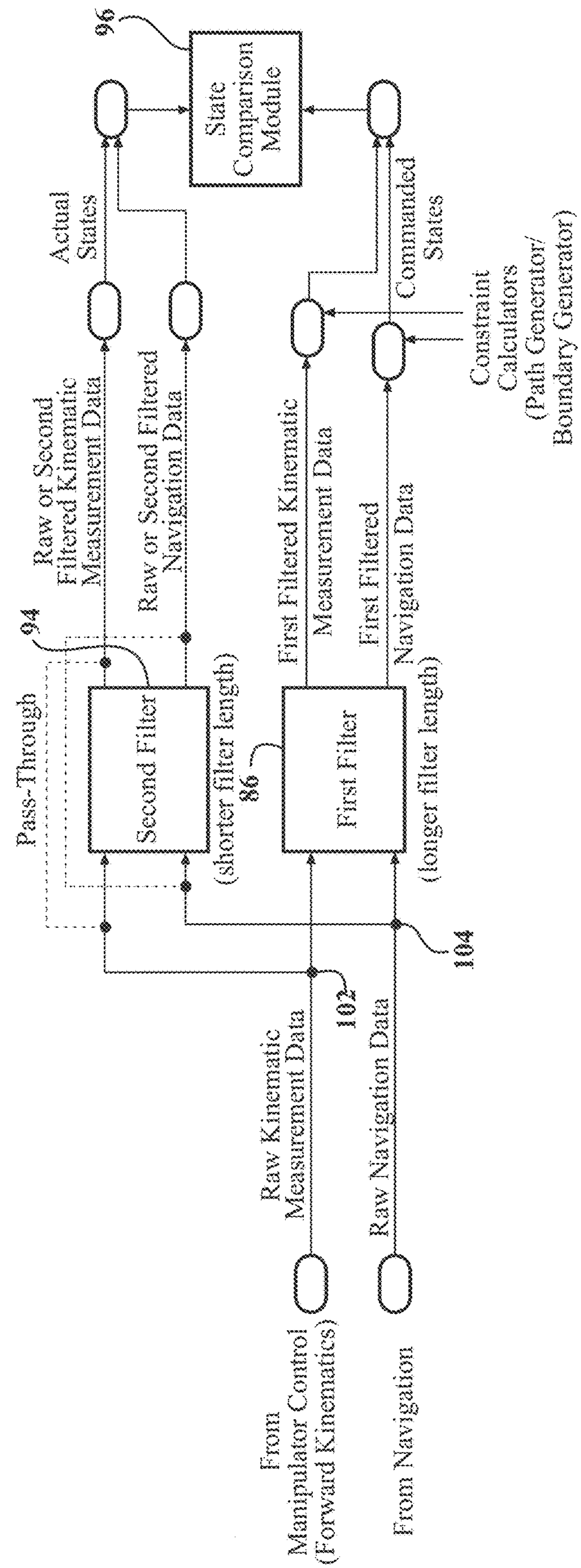
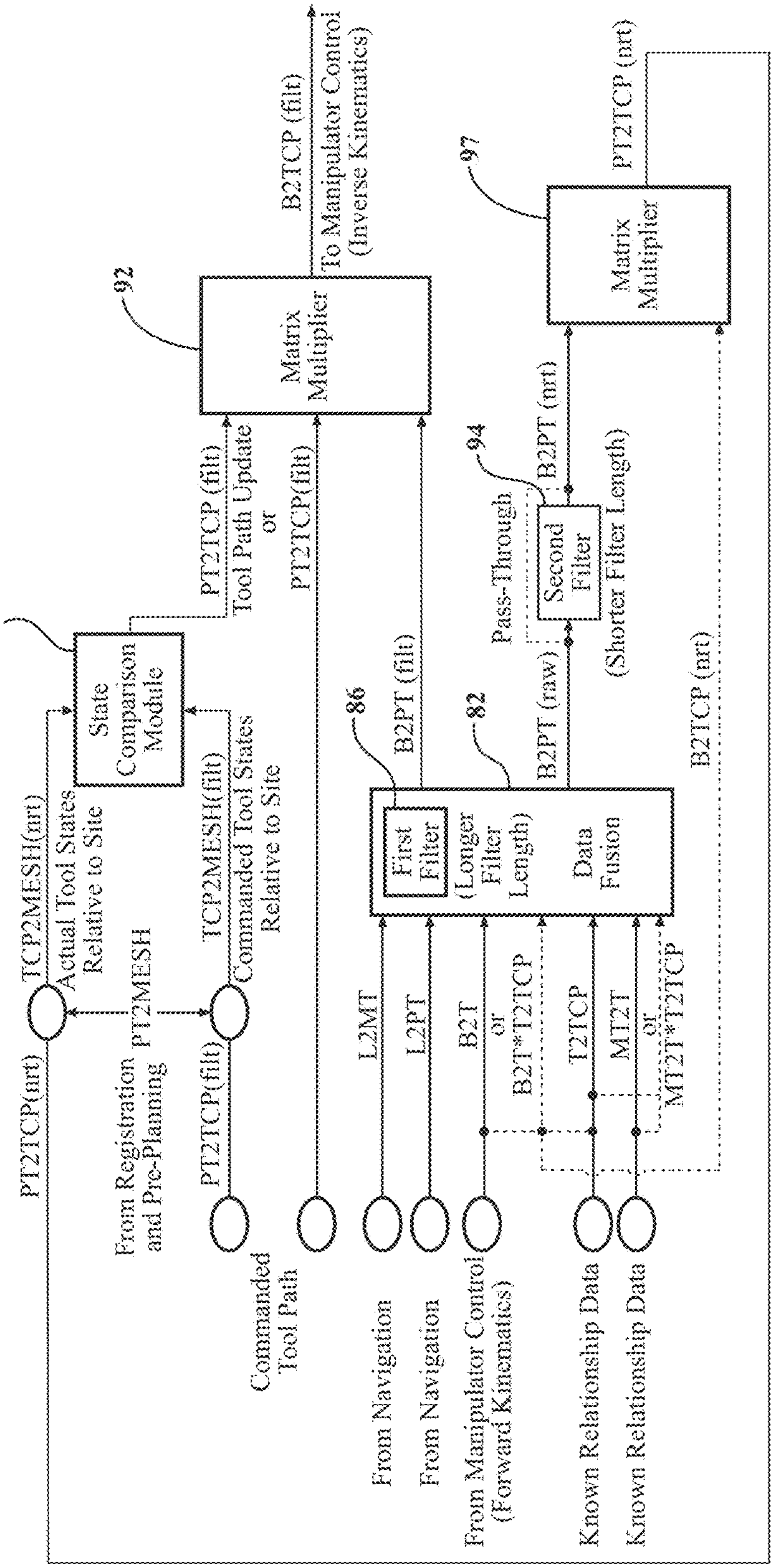

From Manipulator Control (Forward Kinematics)
From Navigation
Raw Kinematic Measurement Data
Raw Navigation Data
102
104
Pass-Through
Second Filter
(shorter filter length)
94
86
First Filter
(longer filter length)
Raw or Second Filtered Kinematic Measurement Data
Raw or Second Filtered Navigation Data
First Filtered Kinematic Measurement Data
First Filtered Navigation Data
Constraint Calculators (Path Generator/ Boundary Generator)
Actual States
Commanded States
State Comparison Module
96

FIG. 4



From Registration and Pre-Planning
PT2MESH
TCP2MESH(nrt)
Actual Tool States Relative to Site
TCP2MESH(filt)
Commanded Tool States Relative to Site
PT2TCP(nrt)
PT2TCP(filt)
Commanded Tool Path
96
State Comparison Module
PT2TCP (filt)
Tool Path Update
or
PT2TCP(filt)
92
Matrix Multiplier
B2TCP (filt)
To Manipulator Control (Inverse Kinematics)
From Navigation
L2MT
From Navigation
L2PT
From Manipulator Control (Forward Kinematics)
B2T
or
B2T*T2TCP
Known Relationship Data
T2TCP
Known Relationship Data
MT2T
or
MT2T*T2TCP
86
First Filter
(Longer Filter Length)
Data Fusion
82
B2PT (filt)
B2PT (raw)
Pass-Through
94
Second Filter
(Shorter Filter Length)
B2PT (nrt)
B2TCP (nrt)
97
Matrix Multiplier
PT2TCP (nrt)


FIG. 5

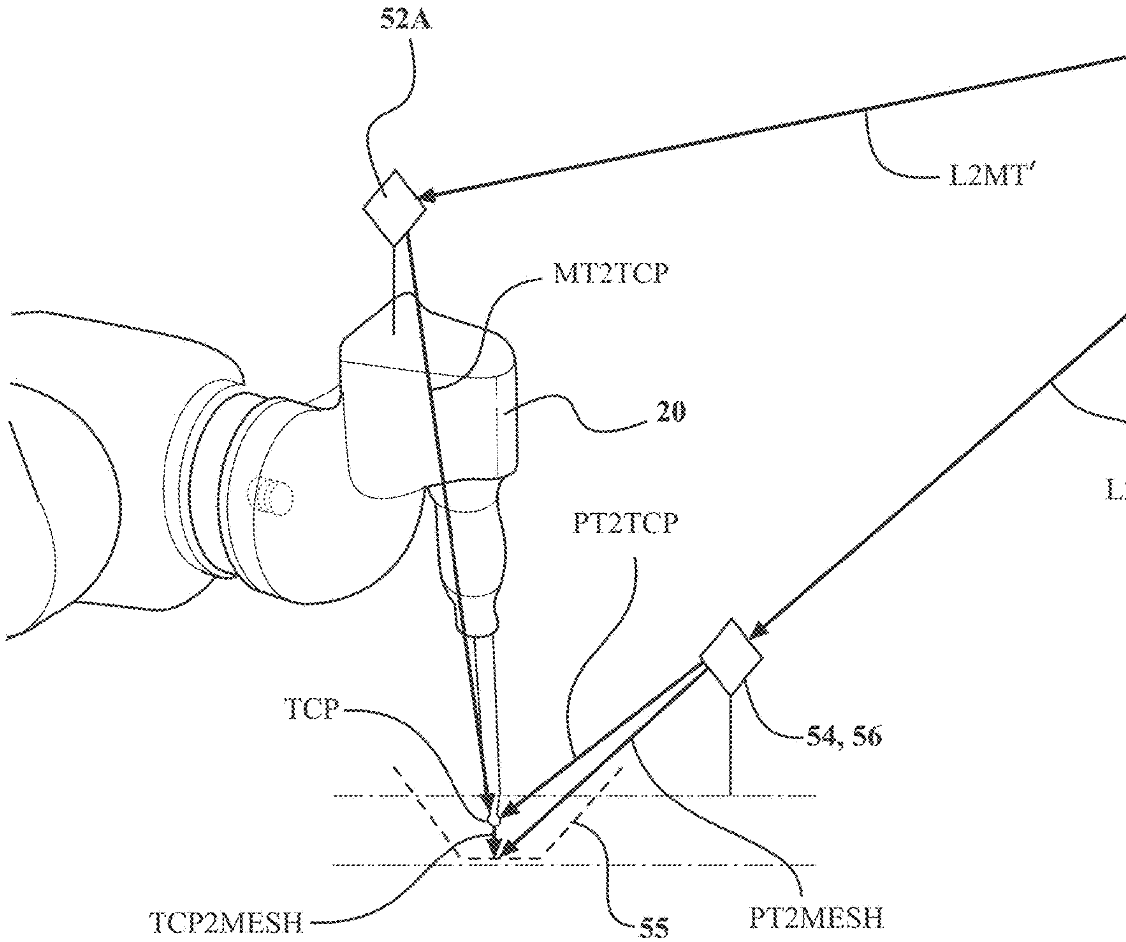



FIG. 6

FIG. 7

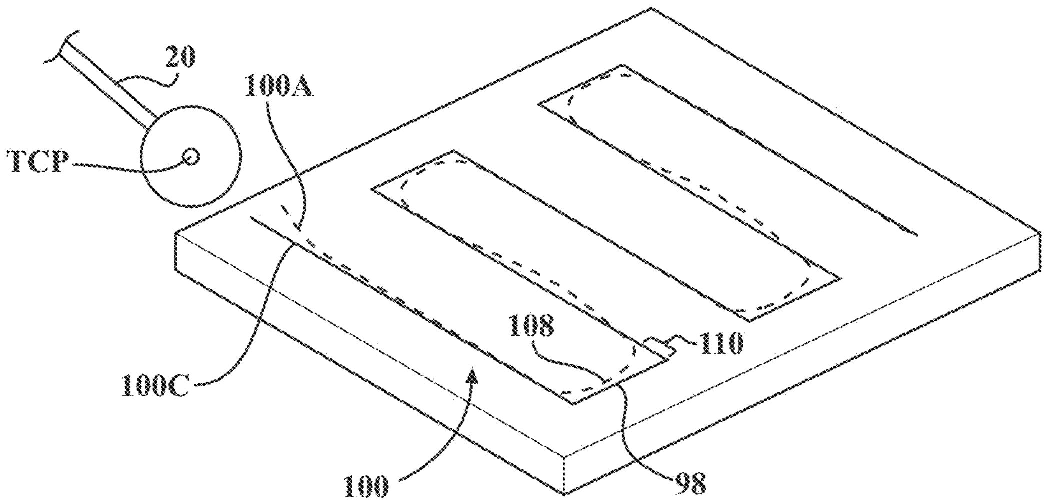
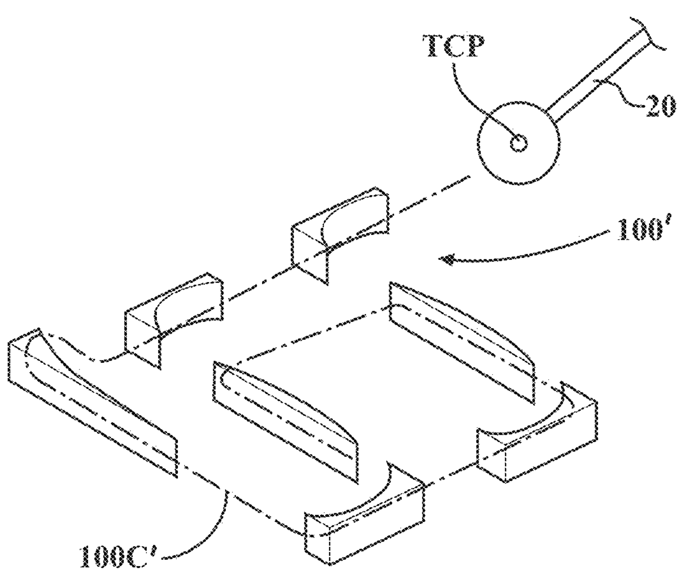



FIG. 8



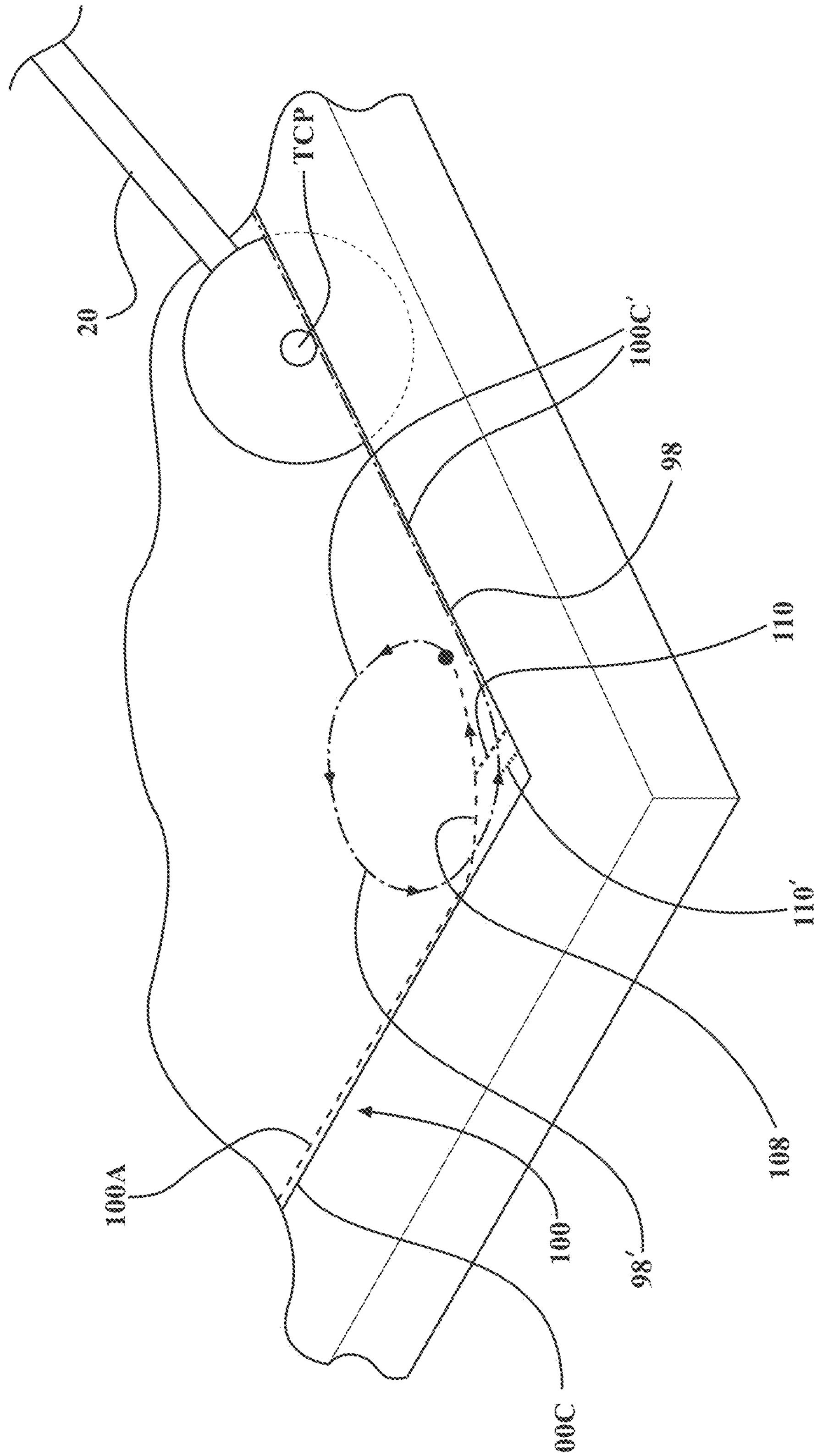
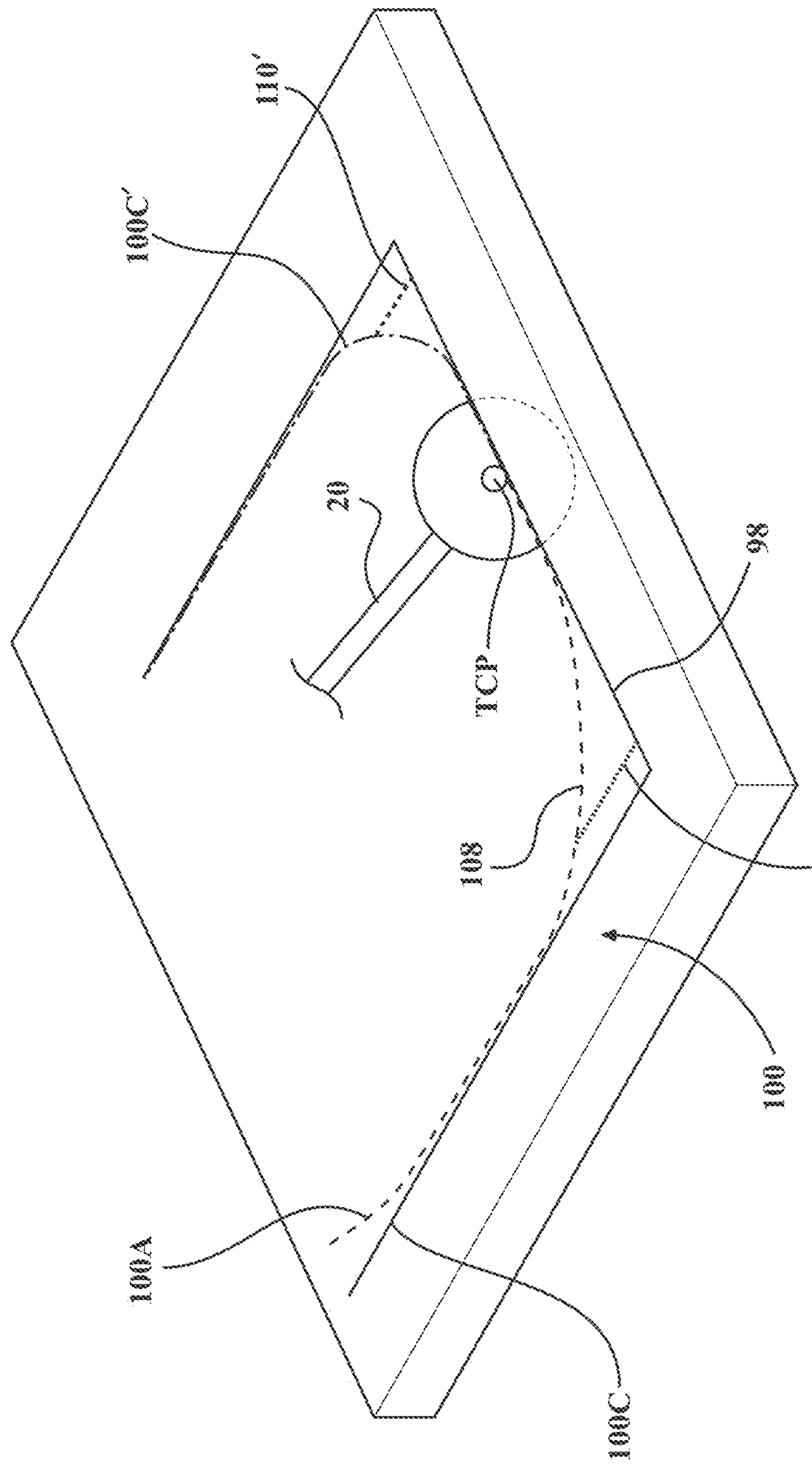



FIG. 9

FIG. 10



# TECHNIQUES FOR MODIFYING TOOL OPERATION IN A SURGICAL ROBOTIC SYSTEM BASED ON COMPARING ACTUAL AND COMMANDED STATES OF THE TOOL RELATIVE TO A SURGICAL SITE

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** The subject application is a continuation of U.S. patent application Ser. No. 18/381,658, filed Oct. 19, 2023, which is a continuation of U.S. patent application Ser. No. 17/534,499, filed Nov. 24, 2021, issued as U.S. Pat. No. 11,850,011, which is a continuation of U.S. patent application Ser. No. 15/840,278, filed Dec. 13, 2017, issued as U.S. Pat. No. 11,202,682, which claims priority to and all the benefits of U.S. Provisional Pat. App. No. 62/435,254, filed on Dec. 16, 2016, the contents of each of the aforementioned applications being hereby incorporated by reference in their entirety.

## TECHNICAL FIELD

**[0002]** The disclosure relates generally to techniques for modifying tool operation based on comparing actual and commanded states of the tool relative to a surgical site.

## BACKGROUND

**[0003]** Robotic systems are commonly used to perform surgical procedures and typically include a robot comprising a robotic arm and an end effector coupled to an end of the robotic arm. The robotic system commands the end effector along a cutting path for engaging a surgical site. Often, a supplemental tracking system, such as optical localization, is utilized to track positioning of the robot and the surgical site. Kinematic data from the robot may be aggregated with supplemental data from the tracking system to update positioning of the robot along the commanded cutting path. Such aggregation is used to provide redundancy for the critical task of positioning the end effector and to improve accuracy by accounting for kinematic errors such as residual kinematic calibration error and link deflection.

**[0004]** Tracking systems often track the robot and the anatomy at the surgical site at much higher frequencies than the closed loop bandwidth of the robot's response. Tracking systems can respond in near-real time, whereas the robot arm is limited by inertia and available power. Moreover, anatomy movement can be faster than the robot can respond. As a result, updating positioning of the robot based on data from the tracking system is a delayed process. This delay helps to avoid undesirable effects, such as positive feedback.

**[0005]** Failure to account for the lag necessary to prevent positive feedback, the near real-time actual positions of the end effector, and fast movements of the anatomy cause cutting inaccuracies at the surgical site. The issue is worsened when subsequent commanded cutting paths are generated based on previous commanded cutting paths, wherein neither the previous nor the subsequent commanded cutting path account for the near real-time, actual positions of the end effector, thereby causing regenerative cutting errors.

**[0006]** As such, there is a need in the art for systems and methods for addressing at least the aforementioned problems.

## SUMMARY

**[0007]** According to a first aspect, a surgical system is provided, which comprises: a manipulator configured to support and facilitate movement of a surgical tool along a tool path relative to a surgical site; and one or more controllers coupled to the manipulator and being configured to: determine commanded states of the surgical tool and actual states of the surgical tool relative to the tool path for a plurality of time steps; detect at least one deviation between the commanded states and the actual states of the surgical tool for at least one of the plurality of time steps; and respond to the at least one deviation by modification of one or both of: a feed rate of the surgical tool; and the tool path.

**[0008]** According to a second aspect, a method of operating a surgical system is provided, wherein the surgical system includes a manipulator to support and facilitate movement of a surgical tool along a tool path relative to a surgical site, and one or more controllers coupled to the manipulator, the method comprising the one or more controllers: determining commanded states of the surgical tool and actual states of the surgical tool relative to the tool path for a plurality of time steps; detecting at least one deviation between the commanded states and the actual states of the surgical tool for at least one of the plurality of time steps; and responding to the at least one deviation by modifying one or both of: a feed rate of the surgical tool; and the tool path.

**[0009]** The system and method determine near real-time, actual states of the surgical tool and/or tracker along the first path independent of the delay of the first filter. The system and method advantageously exploit raw or lightly (second) filtered raw kinematic measurement data and/or navigation data to modify operation of the surgical tool. Since the second filtered kinematic measurement data and/or navigation data is near instantaneous, the actual states of the surgical tool can be determined in near real time and faster than using the commanded (first filtered) states alone. The system and method acquire and utilize actual states of the surgical tool and/or tracker, which are faster than the delayed commanded states. Consequently, the actual and commanded states are compared to properly account for deviations. By doing so, the system and method increase path or cutting accuracy at the surgical site and reduce the possibility for regenerative cutting errors. The system and method may exhibit advantages other than those described herein.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** Advantages of the present invention 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 wherein:

**[0011]** FIG. **1** is a perspective view of a robotic surgical system for manipulating a target tissue of a patient with a tool, according to one embodiment.

**[0012]** FIG. **2** is a block diagram of a controller for controlling the robotic surgical system, according to one embodiment.

**[0013]** FIG. **3** is a perspective view illustrating transforms between components of a manipulator and components of a navigation system of the robotic surgical system, according to one embodiment.

**[0014]** FIG. **4** is a simplified block diagram of techniques, implemented by the controller, for filtering and fusing data from the manipulator and the navigation system, according to one embodiment.

**[0015]** FIG. **5** is a detailed block diagram of techniques, implemented by the controller, for filtering and fusing data from the manipulator and the navigation system, according to one embodiment.

**[0016]** FIG. **6** is a perspective view illustrating transforms between a localizer, patient tracker, and manipulator tracker of the navigation system, a tool center point of the tool, and a virtual mesh associated with the target tissue, according to one embodiment.

**[0017]** FIG. **7** is a diagram, according to one embodiment, illustrating sample movement of the tool along a first path for removing a portion target tissue wherein deviations between commanded and actual states of the tool are represented.

**[0018]** FIG. **8** is a diagram illustrating sample movement of the tool along a subsequent path for removing portions of the target tissue remaining from FIG. **7**.

**[0019]** FIG. **9** is a diagram illustrating sample movement of the tool along a path of movement and immediate correction of the path based on recognition of present deviations between commanded and actual states.

**[0020]** FIG. **10** is a diagram illustrating sample movement of the tool along a path of movement and proactively correction of the path based on recognition of past deviations between commanded and actual states.

## DETAILED DESCRIPTION

### I. Overview

**[0021]** Referring to the Figures, wherein like numerals indicate like or corresponding parts throughout the several views, a robotic surgical system **10** (hereinafter "system") and method for operating the system **10** are shown throughout.

**[0022]** As shown in FIG. **1**, the system **10** is a robotic surgical system for treating an anatomy (surgical site) of a patient **12**, such as bone or soft tissue. In FIG. **1**, the patient **12** is undergoing a surgical procedure. The anatomy in FIG. **1** includes a femur (F) and a tibia (T) of the patient **12**. The surgical procedure may involve tissue removal or treatment. Treatment may include cutting, coagulating, lesioning the tissue, treatment in place of tissue, or the like. In some embodiments, the surgical procedure involves partial or total knee or hip replacement surgery. In one embodiment, the system **10** is designed to cut away material to be replaced by surgical implants, such as hip and knee implants, including unicompartmental, bicompartmental, multicompartmental, or total knee implants. Some of these types of implants are shown in U.S. Patent Application Publication No. 2012/0330429, entitled, "Prosthetic Implant and Method of Implantation," the disclosure of which is hereby incorporated by reference. Those skilled in the art appreciate that the system **10** and method disclosed herein may be used to perform other procedures, surgical or non-surgical, or may be used in industrial applications or other applications where robotic systems are utilized.

**[0023]** The system **10** includes a manipulator **14**. The manipulator **14** has a base **16** and plurality of links **18**. A manipulator cart **17** supports the manipulator **14** such that the manipulator **14** is fixed to the manipulator cart **17**. The links **18** collectively form one or more arms of the manipulator **14**. The manipulator **14** may have a serial arm configuration (as shown in FIG. **1**) or a parallel arm configuration. In other embodiments, more than one manipulator **14** may be utilized in a multiple arm configuration. The manipulator **14** comprises a plurality of joints (J) and a plurality of joint encoders **19** located at the joints (J) for determining position data of the joints (J). For simplicity, only one joint encoder **19** is illustrated in FIG. **1**, although it is to be appreciated that the other joint encoders **19** may be similarly illustrated. The manipulator **14** according to one embodiment has six joints (J**1**-J**6**) implementing at least six-degrees of freedom (DOF) for the manipulator **14**. However, the manipulator **14** may have any number of degrees of freedom and may have any suitable number of joints (J) and redundant joints (J).

**[0024]** The base **16** of the manipulator **14** is generally a portion of the manipulator **14** that is stationary during usage thereby providing a fixed reference coordinate system (i.e., a virtual zero pose) for other components of the manipulator **14** or the system **10** in general. Generally, the origin of a manipulator coordinate system MNPL is defined at the fixed reference of the base **16**. The base **16** may be defined with respect to any suitable portion of the manipulator **14**, such as one or more of the links **18**. Alternatively, or additionally, the base **16** may be defined with respect to the manipulator cart **17**, such as where the manipulator **14** is physically attached to the cart **17**. In a preferred embodiment, the base **16** is defined at an intersection of the axes of joints J**1** and J**2** (see FIG. **3**). Thus, although joints J**1** and J**2** are moving components in reality, the intersection of the axes of joints J**1** and J**2** is nevertheless a virtual fixed reference point, which does not move in the manipulator coordinate system MNPL. The manipulator **14** and/or manipulator cart **17** house a manipulator computer **26**, or other type of control unit.

**[0025]** A surgical tool **20** (hereinafter "tool") couples to the manipulator **14** and is movable relative to the base **16** to interact with the anatomy in certain modes. The tool **20** is or forms part of an end effector **22** in certain modes. The tool **20** may be grasped by the operator. One exemplary arrangement of the manipulator **14** and the tool **20** is described in U.S. Pat. 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. The manipulator **14** and the tool **20** may be arranged in alternative configurations. The tool **20** can be like that shown in U.S. Patent Application Publication No. 2014/0276949, filed on Mar. 15, 2014, entitled, "End Effector of a Surgical Robotic Manipulator," hereby incorporated by reference.

**[0026]** The tool **20** includes an energy applicator **24** designed to contact the tissue of the patient **12** at the surgical site. The energy applicator **24** may be a drill, a saw blade, a bur, an ultrasonic vibrating tip, or the like. The tool **20** comprises a TCP, which in one embodiment, is a predetermined reference point defined at the energy applicator **24**. The TCP has known position in its own coordinate system. In one embodiment, the TCP is assumed to be located at the center of a spherical of the tool **20** such that only one point is tracked. The TCP may relate to a bur having a specified diameter. The TCP may be defined according to various manners depending on the configuration of the energy applicator **24**.

**[0027]** Referring to FIG. **2**, the system **10** includes a controller **30**. The controller **30** includes software and/or hardware for controlling the manipulator **14**. The controller **30** directs the motion of the manipulator **14** and controls a state (position and/or orientation) of the tool **20** with respect to a coordinate system. In one embodiment, the coordinate system is the manipulator coordinate system MNPL, as shown in FIG. **1**. The manipulator coordinate system MNPL has an origin located at any suitable pose with respect to the manipulator **14**. Axes of the manipulator coordinate system MNPL may be arbitrarily chosen as well. Generally, the origin of the manipulator coordinate system MNPL is defined at the fixed reference point of the base **16**. One example of the manipulator coordinate system MNPL is described in U.S. Pat. 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.

**[0028]** As shown in FIG. **1**, the system **10** further includes a navigation system **32**. One example of the navigation system **32** is described in U.S. Pat. No. 9,008,757, filed on Sep. 24, 2013, entitled, "Navigation System Including Optical and Non-Optical Sensors," hereby incorporated by reference. The navigation system **32** is configured to track movement of various objects. Such objects include, for example, the manipulator **14**, the tool **20** and the anatomy, e.g., femur F and tibia T. The navigation system **32** tracks these objects to gather state information of each object with respect to a (navigation) localizer coordinate system LCLZ. Coordinates in the localizer coordinate system LCLZ may be transformed to the manipulator coordinate system MNPL, and/or vice-versa, using transformation techniques described herein.

**[0029]** The navigation system **32** includes a cart assembly **34** that houses a navigation computer **36**, and/or other types of control units. A navigation interface is in operative communication with the navigation computer **36**. The navigation interface includes one or more displays **38**. The navigation system **32** is capable of displaying a graphical representation of the relative states of the tracked objects to the operator using the one or more displays **38**. First and second input devices **40**, **42** may be used to input information into the navigation computer **36** or otherwise to select/control certain aspects of the navigation computer **36**. As shown in FIG. **1**, such input devices **40**, **42** include interactive touchscreen displays. However, the input devices **40**, **42** may include any one or more of a keyboard, a mouse, a microphone (voice-activation), gesture control devices, and the like. The controller **30** may be implemented on any suitable device or devices in the system **10**, including, but not limited to, the manipulator computer **26**, the navigation computer **36**, and any combination thereof.

**[0030]** The navigation system **32** also includes a navigation localizer **44** (hereinafter "localizer") coupled to the navigation computer **36**. In one embodiment, 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**.

**[0031]** The navigation system **32** includes one or more trackers. In one embodiment, the trackers include a pointer tracker PT, one or more manipulator trackers **52**, a first patient tracker **54**, and a second patient tracker **56**. In the illustrated embodiment of FIG. **1**, the manipulator tracker **52** is firmly attached to the tool **20** (i.e., tracker **52**A), 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 embodiment, the patient trackers **54**, **56** are firmly affixed to sections of bone. The pointer tracker PT is firmly affixed to a pointer P used for registering the anatomy to the localizer coordinate system LCLZ. The manipulator tracker **52** may be affixed to any suitable component of the manipulator **14**, in addition to, or other than the tool **20**, such as the base **16** (i.e., tracker **52**B), or any one or more links **18** of the manipulator **14**. Those skilled in the art appreciate that the trackers **52**, **54**, **56**, PT may be fixed to their respective components in any suitable manner.

**[0032]** Any one or more of the trackers may include active markers **58**. The active markers **58** may include light emitting diodes (LEDs). Alternatively, the trackers **52**, **54**, **56** may have passive markers, such as reflectors, which reflect light emitted from the camera unit **46**. Other suitable markers not specifically described herein may be utilized.

**[0033]** The localizer **44** tracks the trackers **52**, **54**, **56** to determine a state of each of the trackers **52**, **54**, **56**, which correspond respectively to the state of the object respectively attached thereto. The localizer **44** provides the state of the trackers **52**, **54**, **56** to the navigation computer **36**. In one embodiment, the navigation computer **36** determines and communicates the state the trackers **52**, **54**, **56** to the manipulator computer **26**. 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 or equivalents/derivatives of the position and/or orientation. For example, the state may be a pose of the object, and may include linear data, and/or angular velocity data, and the like.

**[0034]** Although one embodiment of the navigation system **32** is shown in the Figures, the navigation system **32** may have any other suitable configuration for tracking the manipulator **14** and the patient **12**. In one embodiment, 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 computer **36**. The ultrasound imaging device images any of the aforementioned objects, e.g., the manipulator **14** and the patient **12**, and generates state signals to the controller **30** based on the ultrasound images. The ultrasound images may be 2-D, 3-D, or a combination of both. The navigation computer **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 FIG. **1**.

**[0035]** In another embodiment, 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 computer **36**. The manipulator **14** and 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 controller **30** based on RF signals received from the RF emitters. The navigation computer **36** and/or the controller **30** 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** as shown in FIG. **1**.

**[0036]** In yet another embodiment, the navigation system **32** and/or localizer **44** arc electromagnetically based. For example, the navigation system **32** may comprise an EM transceiver coupled to the navigation computer **36**. The manipulator **14** and 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 controller **30** based upon EM signals received from the trackers. The navigation computer **36** and/or the controller **30** may analyze the received EM signals to associate relative states thereto. Again, such navigation system **32** embodiments may have structural configurations that are different than the navigation system **32** configuration as shown throughout the Figures.

**[0037]** Those skilled in the art appreciate that the navigation system **32** and/or localizer **44** 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 camera-based navigation system **32** shown throughout the Figures may be implemented or provided for any of the other embodiments of the navigation system **32** described herein. For example, the navigation system **32** may utilize solely inertial tracking or any combination of tracking techniques.

**[0038]** As shown in FIG. **2**, the controller **30** further includes software modules. The software modules may be part of a computer program or programs that operate on the manipulator computer **26**, navigation computer **36**, or a combination thereof, to process data to assist with control of the system **10**. The software modules include instructions stored in memory on the manipulator computer **26**, navigation computer **36**, or a combination thereof, to be executed by one or more processors of the computers **26**, **36**. Additionally, software modules for prompting and/or communicating with the operator may form part of the program or programs and may include instructions stored in memory on the manipulator computer **26**, navigation computer **36**, or a combination thereof. The operator interacts with the first and second input devices **40**, **42** and the one or more displays **38** to communicate with the software modules. The user interface software may run on a separate device from the manipulator computer **26** and navigation computer **36**.

**[0039]** The controller **30** includes a manipulator controller **60** for processing data to direct motion of the manipulator **14**. In one embodiment, as shown in FIG. **1**, the manipulator controller is implemented on the manipulator computer **26**. The manipulator controller **60** may receive and process data from a single source or multiple sources. The controller **30** further includes a navigation controller **62** for communicating the state data relating to the femur F, tibia T, and manipulator **14** to the manipulator controller **60**. The manipulator controller **60** receives and processes the state data provided by the navigation controller **62** to direct movement of the manipulator **14**. In one embodiment, as shown in FIG. **1**, the navigation controller **62** is implemented on the navigation computer **36**. The manipulator controller **60** or navigation controller **62** may also communicate states of the patient **12** and manipulator **14** to the operator by displaying an image of the femur F and/or tibia T and the manipulator **14** on the one or more displays **38**. The manipulator computer **26** or navigation computer **36** may also command display of instructions or request information using the display **38** to interact with the operator and for directing the manipulator **14**.

**[0040]** As shown in FIG. **2**, the controller **30** includes a boundary generator **66**. The boundary generator **66** is a software module that may be implemented on the manipulator controller **60**. Alternatively, the boundary generator **66** may be implemented on other components, such as the navigation controller **62**. The boundary generator **66** generates virtual boundaries **55** for constraining the tool **20**, as shown in FIG. **3**. Such virtual boundaries **55** may also be referred to as virtual meshes, virtual constraints, or the like. The virtual boundaries **55** may be defined with respect to a **3**-D bone model registered to the one or more patient trackers **54**, **56** such that the virtual boundaries **55** are fixed relative to the bone model. The state of the tool **20** is tracked relative to the virtual boundaries **55**. In one embodiment, the state of the TCP is measured relative to the virtual boundaries **55** for purposes of determining when and where haptic feedback force is applied to the manipulator **14**, or more specifically, the tool **20**.

**[0041]** A tool path generator **68** is another software module run by the controller **30**, and more specifically, the manipulator controller **60**. The tool path generator **68** generates a path **100** for the tool **20** to traverse, such as for removing sections of the anatomy to receive an implant. One exemplary system and method for generating the tool path **100** is explained in U.S. Pat. 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 embodiments, the virtual boundaries **55** and/or tool paths **100** may be generated offline rather than on the manipulator computer **26** or navigation computer **36**. Thereafter, the virtual boundaries **55** and/or tool paths **100** may be utilized at runtime by the manipulator controller **60**. Yet another software module in FIG. **2** is a state comparison module **96**, the details of which are described below.

## II. Data Fusion and Filtering for Determining Commanded States of the Tool Relative to the Surgical Site

**[0042]** As described above, the manipulator **14** and the navigation system **32** operate with respect to different coordinate systems, i.e., the manipulator coordinate system MNPL and the localizer coordinate system LCLZ, respectively. As such, in some embodiments, the controller **30** fuses data from the manipulator **14** and the navigation system **32** for controlling the manipulator **14** using the navigation system **32**. To do so, the controller **30** utilizes data fusion techniques as described herein.

**[0043]** In general, the controller **30** acquires raw data of various transforms between components of the system **10**. As used herein, the term "raw" is used to describe data representing an actual or true state of one or more components of the system **10** (e.g., base **16**, tool **20**, localizer **44**, trackers **52**, **54**, **56**) relative to at least another component(s) of the system **10**, whereby the raw data is obtained near instantaneously (in near real time) from its respective source such that the raw data is unfiltered. The raw data is an unaltered or minimally processed measurement.

**[0044]** As used herein, the term “filtered” is used to describe raw data that is filtered according to a filter length and that represents a filtered state of one or more components of the system **10** relative to at least another component (s) of the system **10**. The filtered data is delayed with respect to the near instantaneously obtained raw data due to application of the filter length in the filter. As will be described below, the raw data is ultimately filtered to control the manipulator **14**. Additional details related to filtering are described below.

**[0045]** Each tracked component has its own coordinate system separate from the manipulator coordinate system MNPL and localizer coordinate system LCLZ. The state of each component is defined by its own coordinate system with respect to MNPL and/or LCLZ. Each of these coordinate systems has an origin that may be identified as a point relative to the origin of the manipulator coordinate system MNPL and/or the localizer coordinate system LCLZ. A vector defines the position of the origin of each of these coordinate systems relative to another one of the other coordinate systems. The location of a coordinate system is thus understood to be the location of the origin of the coordinate system. Each of these coordinate systems also has an orientation that, more often than not, is different from the coordinate systems of the other components. The orientation of a coordinate system may be considered as the relationship of the X, Y and Z-axes of the coordinate system relative to the corresponding axes of another coordinate system, such as MNPL and/or LCLZ.

**[0046]** Referring to FIGS. **3** and **6**, the state of one component of the system **10** relative to the state of another component is represented as a transform (shown in the figures using arrows). In one embodiment, each transform is specified as a transformation matrix, such as a 4×4 homogenous transformation matrix. The transformation matrix, for example, includes three unit vectors representing orientation, specifying the axes (X, Y, Z) from the first coordinate system expressed in coordinates of the second coordinate system (forming a rotation matrix), and one vector (position vector) representing position using the origin from the first coordinate system expressed in coordinates of the second coordinate system.

**[0047]** The transform, when calculated, gives the state (position and/or orientation) of the component from the first coordinate system given with respect to a second coordinate system. The controller **30** calculates/obtains and combines a plurality of transforms e.g., from the various components of the system **10** to control the manipulator **14**, as described below.

**[0048]** As shown in FIG. **3**, the transforms include the following: transform (B**2**T) between the base **16** and the tool **20**, transform (MT**2**T) between the manipulator tracker **52** and the tool **20**, transform (L**2**MT') between the localizer **44** and the manipulator tracker **52** on the tool **20**, transform (L**2**MT") between the localizer **44** and the manipulator tracker **52** at the base **16**, transform (L**2**PT) between the localizer **44** and one or more of the patient trackers **54**, **56**, transform (MT**2**TCP) between the manipulator tracker **52** and the TCP, and transform (T**2**TCP) between the tool **20** and the TCP.

**[0049]** Referring to FIG. **6**, additional transforms include transform (PT**2**TCP) between the one or more patient trackers **54**, **56** and the TCP, transform (TCP**2**MESH) between the TCP and the virtual boundary **55**, and transform (PT**2**MESH) between the one or more patient trackers **54**, **56** and the virtual boundary **55**.

**[0050]** One exemplary system and method for obtaining the transforms of the various components of the system is explained in U.S. Pat. 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.

**[0051]** The output (e.g., values) of the transforms are regarded as raw data when obtained instantaneously (in near real time) and when unfiltered. Such raw data may be understood as being derived from a near transform, i.e., a near instantaneous determination of the state of one component of the system **10** relative to the state of another component. On the other hand, the output values of such transforms are regarded as filtered data when the values are filtered, such as for reasons described below.

**[0052]** The transforms are now described in detail. The controller **30** acquires raw kinematic measurement data relating to a state of the tool **20**. The state of the tool **20** may be determined relative to the manipulator coordinate system MNPL. In some instances, the raw kinematic measurement data may relate to the state of the tool **20** relative to the base **16**. The raw kinematic measurement data may be obtained from the manipulator controller **60**. Specifically, as shown in FIG. **3**, the controller **30** is configured to acquire the raw kinematic measurement data by acquiring one or more values of transform (B**2**T) between a state of the base **16** and the state of the tool **20**. Here, the raw kinematic measurement data may be obtained from kinematic data of the manipulator **14**. In particular, the controller **30** may acquire one or more values of the first transform (B**2**T) by applying a forward kinematic calculation to values acquired from the joint encoders **19**. Thus, the state of the tool **20** can be determined relative to the manipulator coordinate system MNPL without intervention from the navigation system **32**. In other words, the first transform (B**2**T) may be obtained irrespective of any measurements from the navigation system **32**.

**[0053]** In FIG. **3**, transform (B**2**T) is indicated by an arrow having an origin at the base **16** and extending to and having an arrowhead pointing to the tool **20**. In one exemplary convention used throughout FIG. **3**, the arrowhead points to the component having its state derived or specified relative to the component at the origin. Transform (B**2**T) may be determined using any suitable reference frames (coordinate systems) on the base **16** and the tool **20**.

**[0054]** The controller **30** may further acquire known relationship data relating to the state of the manipulator tracker **52** relative to the tool **20**. In general, the known relationship data may be derived from any known relationship between the manipulator tracker **52** and the tool **20**. In other words, the manipulator tracker **52** and the tool **20** have a relationship that is known or calculatable using any suitable method. The manipulator tracker **52** and the tool **20** may be fixed or moving relative to each other. For example, the manipulator tracker **52** may be attached directly to the tool **20**, as shown in FIG. **3**. Alternatively, the manipulator tracker **52** may be attached to one of the links **18**, which move relative to the tool **20**. In general, the manipulator tracker **52** and the tool **20** are tracked by different techniques, i.e., by navigation data and kinematic measurement data, respectively. The known relationship data assists to bridge the kinematic measurement data and the navigation data by aligning the manipulator tracker **52** and the tool **20** to a common coordinate system.

**[0055]** The known relationship data may be fixed (constant or static) or variable. In embodiments where the known relationship data is fixed, the known relationship data may be derived from calibration information relating to the manipulator tracker **52** and/or the tool **20**. For example, the calibration information may be obtained at a manufacturing/assembly stage, e.g., using coordinate measuring machine (CMM) measurements, etc. The known relationship data may be obtained using any suitable method, such as reading the known relationship data from a computer-readable medium, an RFID tag, a barcode scanner, or the like. The known relationship data may be imported into system **10** at any suitable moment such that the known relationship data is readily accessible by the controller **30**. In embodiments where the known relationship data is variable, the known relationship data may be measured or computed using any ancillary measurement system or components, such as additional sensors, trackers, encoders, or the like. The known relationship data may also be acquired after mounting the manipulator tracker **52** to the tool **20** in preparation for a procedure by using any suitable technique or calibration method.

**[0056]** Whether static or variable, the known relationship data may or may not be regarded as raw data, as described herein, depending on the desired technique for obtaining the same. In one embodiment, the controller **30** may acquire the known relationship data by acquiring one or more values of transform (MT**2**T) between the state of the manipulator tracker **52**A and the state of the tool **20**. Transform (MT**2**T) may be determined with respect to any suitable coordinate system or frame on the manipulator tracker **52** and the tool **20**.

**[0057]** In other embodiments, the controller **30** may determine transform (MT**2**T) using any one or more of kinematic measurement data from the manipulator **14** and navigation data from the navigation system **32** such that known relationship data is not utilized. For example, transform (MT**2**T) may be calculated using one or more of raw kinematic measurement data relating to the state of the tool **20** relative to the manipulator coordinate system MNPL from the manipulator **14** and raw navigation data relating to the state of the tracker **52** relative to the localizer **44** from the navigation system **32**. For example, the tool **20** may be rotated about its wrist to create a circular or spherical fit of the tool **20** relative to the manipulator tracker **52**.

**[0058]** In some embodiments, it may be desirable to determine the state of the TCP relative to the manipulator coordinate system MNPL and/or localizer coordinate system LCLZ. For example, the controller **30** may further acquire known relationship data relating to the state of the tool **20** relative to the TCP by acquiring one or more values of transform (T**2**TCP), as shown in FIG. **3**. Additionally, or alternatively, the controller **30** may acquire known relationship data relating to the state of the manipulator tracker **52**A relative to the TCP by acquiring one or more values of transform (MT**2**TCP), as shown in FIG. **3**. Transforms (T**2**TCP) and (MT**2**TCP) may be acquired using any of the aforementioned techniques described with respect to transform (MT**2**T). Transforms (T**2**TCP) and (MT**2**TCP) may be utilized to determine commanded states **98** of the TCP relative to the surgical site, as well as actual states **108** of the same, as described in the subsequent section.

**[0059]** The controller **30** is further configured to acquire, from the navigation system **32**, raw navigation data relating to the state of the manipulator tracker **52** relative to the localizer **44**. The controller **30** may do so by acquiring one or more values of transform (L**2**MT') between the manipulator tracker **52**A on the tool **20** and the localizer **44** and/or transform (L**2**MT") between the manipulator tracker **52**B at the base **16** and the localizer **44**. Transforms (L**2**MT' or L**2**MT") can be calculated using navigation data alone, irrespective of kinematic measurement data from the manipulator **14**.

**[0060]** The transform (L**2**PT) between the localizer **44** and one or more of the patient trackers **54**, **56** may be determined by the controller **30** by similar techniques and assumptions as described above with respect to transforms (L**2**MT' or L**2**MT"). Specifically, the localizer **44** is configured to monitor the state of one or more of the patient trackers **54**, **56** and the controller **30** is configured to acquire, from the navigation system **32**, raw navigation data relating to the state of the one or more of the patient trackers **54**, **56** relative to the localizer **44**.

**[0061]** Referring to FIG. **6**, transform (PT**2**MESH) may be calculated between one or more of the patient trackers **54**, **56** and the virtual boundary **55** associated with the anatomy of the patient **12** using registration techniques involving the navigation system **32** and the pointer (P). In one embodiment, the pointer (P) is tracked by the navigation system **32** via the pointer tracker (PT) and is touched to various points on a surface of the anatomy. The navigation system **32**, knowing the state of the pointer (P), registers the state of the anatomy with respect to one or more of the patient trackers **54**, **56**. Alternatively, (PT**2**MESH) may be broken up into additional (intermediate) transforms that are combined to result in (PT**2**MESH). For example, transform (IMAGE**2**MESH) may correspond to implant placement (e.g., from surgical planning) relative to a pre-op image, acquired using techniques such as CT, MRI, etc., and transform (PT**2**IMAGE) may correspond to location of the one or more patient trackers **54**, **56** relative to that same pre-op image (e.g., from registration). These intermediate transforms may be combined to obtain transform (PT**2**MESH). One exemplary system and method for registering the anatomy is explained in U.S. Pat. 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.

**[0062]** In FIG. **6**, two additional transforms are shown which relate to the TCP. Specifically, these transforms include transform (PT**2**TCP) between the one or more patient trackers **54**, **56** and the TCP and transform (TCP**2**MESH) between the TCP and the virtual boundary **55**. As will be described below, these transforms are utilized to determine actual and commanded states **98** of the tool **20** relative to the surgical site. Transforms (PT**2**TCP) and (TCP**2**MESH) may be determined using navigation data alone, or navigation data in combination with kinematic measurement data. Those skilled in the art appreciate that given the various components of the system **10**, other transforms other than those described above may be utilized in the techniques described herein.

**[0063]** With the transforms identified, one simplified embodiment of the data fusion and filtering techniques is illustrated in FIG. **4**. As shown, the controller **30** acquires the raw kinematic measurement data, which in this embodiment, relates to kinematically derived states of the manipulator **14**. In one example, the raw kinematic measurement data may relate to the state of the tool **20** relative to the base **16** or manipulator coordinate system MNPL, i.e., (B2T)) Additionally or alternatively, the raw kinematic measurement data may relate to a state of one or more of the links **18** relative to the base **16**, a state of the tool **20** relative to one or more of the links **18**, a state of one or more of the joints (**J1**-**J6**) relative to the base **16**, a state of the tool **20** relative to one or more of the joints (**J1**-**J6**), a state of the TCP relative to any of the aforementioned components, or the like. The controller **30** may acquire this raw kinematic measurement data using forward kinematic calculations, and by using any suitable transform depending on which components of the manipulator **14** have states that are being tracked.

**[0064]** The controller **30** is also configured to acquire, from the navigation system **32**, raw navigation data. The raw navigation data may relate to the state of the manipulator tracker **52** relative to the localizer **44** (L2MT', L2MT") and/or data relating to the state of the one or more patient trackers **54**, **56** relative to the localizer **44** (L2PT).

**[0065]** In FIG. **4**, the raw kinematic measurement data and raw navigation data (i.e., raw data) is passed to a first filter **86**. The first filter **86** applies a first filter length, to produce first filtered kinematic measurement data and first filtered navigation data, respectively. The first filtered measurement and navigation data are utilized to determine commanded states **98** of the tool **20** while commanding the tool **20** to move relative to the surgical site, e.g., along a tool path **100**.

**[0066]** The first filter **86** is a digital temporal filter that filters the raw data. This filtering may occur in the time-domain. Filtering may be understood as performing a type of averaging over a time history of data. Filtering does not affect the update or measurement rate but rather the frequency of content of the output signal (e.g., how quickly or smoothly the output changes), yet still providing a new output for each sample. In general, the greater the filter length for the filter, the greater the filter latency (delay) and averaging. In other words, a greater filter length provides more time to take into account (or average) determinations of the raw data over time. Thus, the greater the filter length, the smoother the raw data is over time. As will be described below, this first filtered data is involved in the calculation of constraints and downstream control commands, ultimately used to control the manipulator **14**. The first filter **86** may consequently result in spatial filtering by ultimately causing the manipulator **14** to lag (as compared with the second filtered data, described below) in the spatial domain.

**[0067]** The first filter **86** may be one or more of various types of filters. In one embodiment, the first filter **86** may be understood as averaging inputted data, or averaging a time history of data. For example, the first filter **86** may be an infinite impulse response (IIR) filter, a finite impulse response filter (FIR), a "boxcar" filter, or the like. In addition, the filter order and length or filter length maybe chosen to meet requirements of the application. Generally, the filtering described herein applies to low pass-type filtering, however, other filter-types, such as band pass, high pass, or notch filtering may be utilized. The filter length takes into account the time history of the filter. Examples of a filter length include a "time constant" for IIR filters, number of taps or coefficients (i.e., memory depth) for a FIR (finite impulse response) filter, or any parameter of a filter relating to the amount of depth of data that is processed or averaged. In addition, the filter order and length maybe chosen to meet requirements of the application. Generally, the filtering described herein applies to low pass-type filtering, however, other filter-types, such as band pass, high pass, or notch filtering may be utilized.

**[0068]** The filter length of the first filter **86** may be expressed as a unit of time. For example, the filter length may be represented in milliseconds (ms) or seconds(s). In one embodiment, the first filter length is greater than or equal to 100 ms and less than or equal to 1000 ms. For example, the first filter length may be 1000 ms. In this example, for any given time step, the filtered relationship is based on the raw relationship determinations averaged over the previous 1000 ms relative to the given time step.

**[0069]** Filtering by the first filter **86** is performed on the raw data for two primary purposes, i.e., reducing noise and increasing system stability. If it were possible, using the raw data alone to control the system **10** is would be preferred since doing so would give the fastest and most accurate response. However, filtering is needed because of practical limitations on the system **10**. Such practical limitations include noise reduction and stability improvements by removal of positive feedback. The localizer **44** is capable of operating at a much higher bandwidth as compared to the manipulator **14**. That is, the localizer **44** tracks poses of the trackers **52**, **54**, **56** faster than the manipulator **14** can respond. Controlling off the raw data alone causes instability of system **10** because the manipulator **14** must react to commanded movements including those arising from random signal variation (i.e., noise), which are provided at the rate of the localizer **44**. For example, the manipulator **14** would have to respond to every variation in the raw data. Commanded movement occurring at a rate higher than the manipulator **14** can respond results in heat, audible noise, mechanical wear, and potentially resonance, which can cause system instability. Because the localization data feedback represents an outer positioning loop, it is important not to close this outer loop at a higher bandwidth than the manipulator **14** can respond, to avoid instability.

**[0070]** Filtering with the first filter **86** reduces the bandwidth of the outer positioning loop thereby accommodating the bandwidth limitations of the inner positioning loop of the manipulator **14**. Through such filtering, noise is reduced and stability is improved by removal or reduction in positive feedback. The manipulator **14** is prevented from reacting to every minor change in the raw data. Otherwise, if the manipulator **14** had react to noisy data, the manipulator **14** may be susceptible to spatial overshoot of tool **20** along the tool path **100** (such as when turning corners). Such spatial overshoot may cause the tool **20** to overcut the anatomy contrary to best design practices of favoring undercutting rather than overcutting. Instead, filtering of the raw data causes the manipulator **14** to behave more smoothly and run more efficiently. Further, noise may be introduced into the system **10** through measurement error in the sensors (e.g., encoders, localization feedback data, etc.). Filtering limits overall noise to a threshold tolerable by the system **10**.

**[0071]** FIG. **5** is a block diagram illustrating, in part, aspects of the data fusion techniques implemented by the controller **30** and as described herein. In this section, only those portions of FIG. **5** relating to generating commanded states **98** of the tool **20** relative to the surgical site are described. As shown, the transforms (L**2**MT, L**2**PT) are provided from navigation data, transform (B**2**T) is provided from kinematic measurement data, and transforms (T**2**TCP, MT**2**T) are provided from known relationship data, as described above. As shown, transforms (B**2**T) and (T**2**TCP) may be combined from kinematic measurement data and known relationship data to form transform (BT**2**TCP) between the base **16** and the TCP. Similarly, transforms (MT**2**T) and (T**2**TCP) may be combined from known relationship data to form transform (MT**2**TCP) between the manipulator tracker **52** and the TCP.

**[0072]** The controller **30** combines any combination of these transforms from different sources at data fusion block **82**. The controller **30** may apply any suitable matrix multiplier at data fusion block **82**. The output of the data fusion block **82** is transform (B**2**PT) between the base **16** and one or more of the patient trackers **54**, **56**. However, transform (B**2**PT) is filtered by the first filter **86**, and hence is identified in FIG. **5** using the abbreviation "filt" representing a filtered version of this transform. Filtered transform (B**2**PT) may be understood as representing first filtered states of the one or more patient trackers **54**, **56** relative to the base **16**. The first filter **86** is shown within the data fusion block **82** in FIG. **5**. However, the first filter **86** may be applied at the output of the data fusion block **82** instead. Filtered transform (B**2**PT), which is based on pose data, is primarily or entirely a spatial relationship. However, the sequences of such pose data may also signify one or more relationships that are derived from spatial parameters, such as relationships with respect to velocity and/or acceleration of the respective components of the transform.

**[0073]** In one embodiment, transform (B**2**PT) is formed by combining transforms (B**2**T), (MT**2**T), (L**2**MT'; localizer **44** to tool tracker **52**A) and (L**2**PT). Transforms (MT**2**T) and (L**2**MT') may be inverted to enable proper combination these transforms. In another embodiment, transform (B**2**PT) is formed by combining transforms (L**2**MT"; localizer **44** to base tracker **52**B) and (L**2**PT). Those skilled in the art appreciate that transform (B**2**PT) may be formed using any other suitable combination of transforms from kinematic measurement, navigation, and/or known relationship data.

**[0074]** The one or more patient trackers **54**, **56** are assumed to move during operation of the system **10**. Movement of the patient trackers **54**, **56** may result from movement of a table on which the patient **12** rests, movement of the patient **12** generally, and/or local movement of the anatomy subject to the procedure. Movement may also occur from anatomy holder dynamics, cut forces affecting movement of the anatomy, and/or physical force applied to the anatomy by an external source, i.e., another person, or a collision with an object. As such, it is desirable to provide the first filter **86** or a different filter to transform (L**2**PT) to enable the manipulator **14** to track/respond to motion within practical limits needed for stability. Such filtering is utilized for many of the same reasons described above with respect to the first filter **86**, i.e., signal noise reduction and increasing system stability.

**[0075]** As shown in FIG. **5**, the controller **30** combines filtered transform (B**2**PT) and the filtered version of transform (PT**2**TCP) to produce filtered transform (B**2**TCP) between the base **16** and the TCP. The controller **30** produces this transform by utilizing matrix multiplier at block **92**. The controller **30** utilizes filtered transform (B**2**TCP) for controlling the manipulator **14** using inverse kinematic calculations wherein the path generator **69** generates the tool path **100** based on the filtered transform (B**2**TCP) and such that the boundary generator **66** assesses the filtered transform (B**2**TCP) with respect to the virtual boundaries **55**. Mainly, filtered transform (B**2**PT) may be combined with filtered transform (B**2**TCP) to produce filtered transform (PT**2**TCP) between the one or more patient trackers **54**, **56** and the TCP. As shown in FIG. **5**, filtered transform (PT**2**TCP) may be combined with transform (PT**2**MESH) from registration and pre-planning to produce filtered transform (TCP**2**MESH). Ultimately, filtered transform (TCP**2**MESH) represents command states of the tool **20**, and more specifically the TCP, relative to the surgical site.

## III. Techniques for Determining Actual States of the Tool Relative to the Surgical Site and Comparing Actual States to Commanded States

**[0076]** In the embodiments of the techniques described above, the raw kinematic measurement and/or raw navigation data are filtered individually, or in combination, for determining commanded states **98** of the tool **20**. Notably, the raw kinematic measurement and raw navigation data remain available prior to being filtered in FIG. **4**. This raw data is exploited for techniques for modifying operation of the tool **20**, as described in detail below.

**[0077]** In FIG. **4**, the raw data remain available and are duplicated or accessed and passed to the branch including the second filter **94**, leaving the first filtered measurement and/or navigation data in tact for control purposes downstream. The second filter **94** applies a second filter length that is shorter than the first filter length, to produce raw or second filtered kinematic measurement data and raw or second filtered navigation data, respectively. The raw or second filtered measurement and navigation data are utilized to determine actual states **108** of the tool **20** relative to the surgical site. The state comparison module **96** compares the actual states **108** and commanded states **98**. The second filtered data is produced specifically for comparison to the first filtered data to determine how to modify operation of the tool **20** based on the outcome of the comparison.

**[0078]** Utilizing the raw kinematic measurement and navigation data before filtering by the first filter **86** enables the controller **30** to record to memory a log of actual states **108** of the tool **20**. The controller **30** is configured to determine actual states **108** of the tool **20** while commanding the tool **20** to move relative to the surgical site, e.g., along the tool path **100**. As will be described below, the actual states **108** are determined using one or more of second filtered (or unfiltered) kinematic measurement data and second filtered (or unfiltered) navigation data. For any given time step during movement of the tool **20**, each commanded state **98** has a corresponding actual state **108**. As described above, the first filter **86** generally has a longer filter length to accommodate stability requirements of the outer position loop. Thus, these actual states **108** are in contrast to the commanded states **98**, which are otherwise delayed by filtering by the longer filter length of the first filter **84**. Accordingly, the term 'actual' as used herein is not intended to be limited solely to instantaneous states of the tool **108**. Said differently, the raw kinematic measurement data and/or raw navigation data is lightly filtered relative to the filtering of the first filtered measurement and/or navigation data. The actual states **108** may be purely instantaneous (unfiltered) or more instantaneous (less filtered) than the commanded states **98**.

**[0079]** In one embodiment, the controller **30** is configured to utilize the raw kinematic measurement and/or navigation data (instead of the second filtered measurement and/or navigation data), e.g., from any one or more of the transforms, to determine the actual states **108**. The raw kinematic measurement and/or navigation data, in this embodiment, are filtered by the second filter **94** having a filter length of zero. If filtered by the filter length of zero, the raw kinematic measurement and/or navigation data "passes through" the second filter **94**, as shown in FIGS. **4** and **5**.

**[0080]** The raw data are filtered by the second filter **94** to remove high frequency noise or high frequency jitter from the raw signal. The amount of filtering (filter length) applied by the second filter **94** may be chosen such that it is long enough to remove the aforementioned high frequency noise/jitter in the raw signal, but short enough to represent the near real time states of the tool **20** to the extent practical. When filtered, it is generally understood that the filter length is greater than zero. In one example, the filter length of the second filter **94** is greater than 0 ms and less than or equal to 50 ms, as compared to, for example, the filter length of 1000 ms for the first filter **86**. The second filter **94** may have any configuration and may be any type of filter as those described above with respect to the first filter **86**.

**[0081]** The controller **30** is configured to filter any of the raw data with the second filter **94** (e.g., from any one or more of the transforms of FIGS. **3** and **6**) to arrive at the actual states **108**. However, in one specific embodiment, as shown in FIG. **5**, the actual states **108** are derived using the following technique. Any suitable combination of the transforms of FIG. **5** are combined in the data fusion block **82**. Another output of the data fusion block **82** is transform (B**2**PT) between the base **16** and one or more of the patient trackers **54**, **56**. However, transform (B**2**PT) is raw, and hence is identified in FIG. **5** using "raw" representing a raw version of this transform. Raw transform (B**2**PT) may be understood as representing raw states of the one or more patient trackers **54**, **56** relative to the base **16**. The raw transform (B**2**PT) then passes to the second filter **94**, which applies the shorter filter length of 0 (pass-through) or for example, between 0-50 ms (i.e., lightly filtered). Assuming the filter length is greater than 0, a near real time (i.e., "nrt") transform (B**2**PT) is produced.

**[0082]** As shown in FIG. **5**, the controller **30** combines near real time transform (B**2**PT) and a near real time version of transform (BT**2**TCP), which is extracted from the transforms before input into the data fusion block **82**. The combination of these transforms produces a near real time transform (PT**2**TCP) between the one or more patient trackers **54**, **56** and the TCP. The controller **30** produces near real time transform (PT**2**TCP) by utilizing matrix multiplier at block **97**. Near real time transform (PT**2**TCP) may be combined with transform (PT**2**MESH) from registration and pre-planning to produce near real time transform (TCP**2**MESH). Ultimately, near real time transform (TCP**2**MESH) represents actual states **108** of the tool **20**, and more specifically the TCP, relative to the surgical site.

**[0083]** Those skilled in the art appreciate that various other combinations of transforms, other than those described herein may be utilized to determine actual states **108** of the tool **20**, and/or TCP relative to the surgical site, and that such various combinations may depend on any factors, such as the location of the object being tracked, the desired coordinate system, or the like.

**[0084]** As described in the previous section, filtered transform (PT**2**TCP) is produced and represents commanded states **98** of the tool **20**, and more specifically the TCP, relative to the surgical site. The values from the near real time and filtered transform (TCP**2**MESH) are inputted into the comparison module **96**. The state comparison module **96** determines deviations **110** between the commanded states **98** and the actual states **108**. Consequently, the commanded states **98** are compared to the actual states **108** to properly account for actual states that may be different than commanded states of the tool **20** or TCP. For example, as described in the next section, the controller **30** determines tool path **100** or feed rate updates/modifications for the tool **20** based on an outcome of this comparison.

**[0085]** The deviations **110** may be represented with respect to any components of the pose of the tool **20**. In one sense, the deviations **110** may be understood by a difference (subtraction) between the commanded and actual states **98**, **108**. These deviations **110** can be identified by the state comparison module **96**, which compares the underlying data respectively corresponding to the commanded and actual states **98**, **108**.

**[0086]** Deviations **110** between the commanded and actual states **98**, **108** may not always occur. For example, there may be situations where the state of the tool **20** or TCP is constant, enabling temporary alignment between the commanded and actual states **98**, **108**. However, more likely than not, such deviations **110** occur because of sudden or abrupt changes in movement of the tool **20** or TCP. In general, the more abrupt the change in movement of the tool **20** or TCP for any given time step, the greater the deviation **110** will be between the commanded and actual states **98**, **108**. Of course, the commanded and actual states **98**, **108** may have any relationship with respect to each other and may deviate according to any manner depending on factors such as the type of data being compared (e.g., measurement or navigation data) and the respective filter lengths of the first filter **86** and the second filter **94**, and the like.

**[0087]** Comparison between the commanded and actual states **98**, **108** over time may be executed according to various implementations. In one example, the deviations **110** are converted into respective positional and angular components. The state comparison module **96** may perform this conversion to analyze each of the components individually.

**[0088]** In some embodiments, the deviations **110**, or components thereof, may be taken "as-is" such that the state comparison module **96** accounts for an entirety of such deviations **110**. Alternatively, the controller **30** is configured to compare the deviations **110** to one or more predetermined thresholds. For example, the positional and angular components of the deviations **110** are compared to one or more thresholds. If the deviation **110** exceeds the threshold, the deviation **110** is accounted for by the controller **30** for purposes of modifying operation of the tool **20**.

**[0089]** In some instances, it may be undesirable to account for an entirety of the deviation **110** for any one or more of the positional and angular components. For example, the sensitivity of the threshold should be set such that only noticeable and/or meaningful deviations **110** exceed the threshold. In one example, the threshold should be greater than zero such that minor or negligible deviations **110** are disregarded. The threshold for the positional and/or angular components may be chosen based on cutting guidelines for the system **10**. For example, the threshold may be set according to a predetermined distance or range (e.g., 1 mm) such that there is some safety margin to prevent over cutting of the target tissue, but sensitive enough to detect meaningful deviations **110** between the commanded **98** and actual states **108**. The threshold may be an upper threshold or a lower threshold and may have any suitable limit, minimum, maximum, range, standard deviation from profile, or other configuration.

**[0090]** The state comparison module **96** may be implemented by the manipulator controller **60**, as shown in FIG. **2**. The state comparison module **96** may comprise any suitable computer-executable instructions, algorithms, and/or logic for comparing the raw/second filtered data to the first filtered data.

## IV. Techniques for Modifying Tool Operation Based on Comparing Actual and Commanded States of the Surgical Tool Relative to the Surgical Site

**[0091]** Based on an outcome or result of comparing commanded and actual states **98**, **108** relative to the surgical site, the controller **30** dynamically modifies operation of the tool **20** relative to the surgical site. Such modification of tool **20** operation may be performed according to various techniques, but generally are focused on modifying the path of movement and/or the feed rate of the tool **20**.

**[0092]** Although the tool **20** is subject to many of the techniques described herein, and it should be understood that because the TCP derived from the tool **20**, the TCP similarly may be subject of these techniques, even when not explicitly stated.

**[0093]** Generally, the commanded states **98** are utilized to move the tool **20** relative to the surgical site. As shown in FIGS. **7-10**, for example, such movement of the tool **20** may be along a commanded first path **100**C.

**[0094]** To implement such modification, in one embodiment, the controller **30** determines a subsequent (follow-up) path **100'** for the tool **20** to account for the deviations **110** between the commanded and actual states **98**, **108**. That is, the controller **30** provides a subsequent correction of the first path **100**.

**[0095]** FIG. **7** is a diagram illustrating one example of the commanded and actual states **98**, **108** of the tool **20** along the first path **100** with respect to time. In this example, the first path **100** is a cutting path for manipulating a target tissue at the surgical site. The tool **20** is commanded to move along the first path **100** for removing a first section of the target tissue. As shown, the tool **20** is commanded to move along the commanded first path **100**C according to the commanded states **98**. The commanded first path **100**C is defined by a combination of all commanded states **98** with respect to time. However, because the commanded states **98** are derived from first filtered data, the tool **20** does not completely follow the commanded first path **100**C. Instead, the tool **20** follows the actual states **108** as shown in FIG. **7**, which are determined based on raw or second filtered data. In doing so, the tool **20** slightly deviates from the commanded first path **100**C and follows an actual first path **100**A, which is defined by a combination of all actual states **108** with respect to time. Here, the deviations **110** between the commanded and actual states **98**, **108** over time are represented in FIG. **7** by a variable gap between the commanded and actual first paths **100**C, **100**A.

**[0096]** In FIG. **7**, it has been demonstrated that the tool **20** follows the actual first path **100**A instead of the commanded first path **100**C. As a result, the tool **20** removes the first section of the target tissue as defined by the actual first path **100**A rather than by the commanded first path **100**C. If the system **10** proceeded on the basis that the tool **20** followed the commanded first path **100**C alone, then the system **10** may falsely assume that the tool **20** removed the first section of tissue as commanded and as desired. However, FIG. **7** demonstrates that this is not the case. Specifically, certain peaks or uncut portions of the first section may remain because of the deviations **110**. For simplicity, these peaks or uncut portions left over from the first section are referred to as the second section, which are illustrated in FIG. **8**. In this specific example, the commanded first path **100**C alone may be suitable for removing a "bulk" portion of the target tissue. However, in this example, the commanded first path **100**C alone may be inadequate for "fine" removal of the residual target tissue.

**[0097]** As such, as shown in FIG. **8**, the controller **30** generates the second path **100'** as a follow-up path to account for the deviations **110** between the commanded and actual states **98**, **108**. In other words, the second path **100'** is designed for more accurately or "finely" removing the target tissue, and more specifically, the second section left behind after commanding the tool **20** to move along the commanded first path **100**C.

**[0098]** In one example, the second path **100'** may be generated similarly to the first path **100** in that the controller **30** may determine (second) commanded states **98'** for moving the tool **20** along a second commanded path **100**C'. As such, any of the details described above with respect to generating of the first path **100** may apply to the second path **100'**. However, even if commanded, the commanded second path **100**C' is different than the commanded first path **100**C in that the commanded second path **100**C' accounts for the deviations **110** between the commanded and actual states **98**, **108**, whereas the commanded first path **100**C does not. For this reason, the commanded second path **100**C' in FIG. **8** follows a different route than the commanded first path **100**C in FIG. **7**.

**[0099]** The second path **100'** may also be generated when the TCP is tracked to determine the deviations **110**. In this example, a solid body model of the tissue, which is removed based on data from the actual states **108**, may be utilized to determine what needs to be removed in second path **100'**. The diameter of the TCP may be taken into account to determine what was actually removed from the surgical site. In one embodiment, if there are any deviations **110** between the commanded and actual states **98**, **108** of the TCP, but the commanded and actual states **98**, **108** overlap in a way that the TCP removes all the tissue from its actual states **108**, such deviations **110** from the commanded states **98** may be disregarded to increase efficiency of the second path **100'** and to avoid cutting when the tissue has already been removed.

**[0100]** The techniques described above for comparing the commanded and actual states **98**, **108** from the first path **100** may be similarly applied to the commanded and actual states **98'**, **108'** from the second path **100'** to generate yet another path, e.g., a third path. Through this iterative process, any number of paths may be generated, thereby gradually removing the target tissue until a suitable state of the target tissue is achieved. In one example, this iterative process may be understood in that each currently generated path is designed to remove target tissue according to a level of accuracy that is greater than a preceding generated path. Said differently, the deviations **110** between commanded and actual states **98**, **108** for any current path should have magnitudes being less than the deviations **110** between commanded and actual states **98**, **108** for the preceding path.

**[0101]** Hence, in this "follow-up" or "clean-up" path embodiment, the error, i.e., the deviations between the commanded and actual bone surfaces (derived from transform between near real time capture of TCP path and commanded TCP path) are detected and under-cut errors (predominant) are corrected with the subsequent tool path **100'** pass or passes until the residual error is within a pre-determined tolerance.

**[0102]** Although the technique of this embodiment has specific benefits, there may be drawbacks. For example, it will be apparent to the user that deviations **110** are occurring and corrections of such deviations **100** take time. Further, since most deviations **110** are likely to occur in corners or over disparate places on the cut surface, there is wasted time as the tool **20** "air cuts" from undercut area to undercut area. Additionally, if the second path **100'** is not performed until the end of machining, early undercut errors may be amplified due to "regenerative cutting error" since undercut areas will impose greater tool forces than in non-undercut areas, thereby causing a greater undercut on the next pass, i.e., positive feedback. The next embodiment addresses some of these setbacks.

**[0103]** In another embodiment as shown in FIG. **9**, the controller **30**, based on the outcome of comparing the commanded and actual states **98**, **108**, immediately modifies operation of the tool **20** along the path **100** to account for the deviations **110**. This may be done, for example, by immediately altering the path **100**. Alternatively, or additionally, the controller **30** may immediately alter a feed rate of the tool **20**, as described below.

**[0104]** In the example of FIG. **9**, a single tool path **100** is shown and as compared with FIG. **8**, there is no subsequent tool path **100'**. Here, the tool **20** follows the commanded path **100**C, and actual states **108** of the tool **20** deviate from the commanded states **108** near a corner thereby causing deviations **110**, which produce an undercut. Upon immediately recognizing these deviations **110**, the controller **30** generates an updated commanded tool path **100**C' with updated commanded states **98'**. This immediate updating occurs at a point in time represented by a dot on the commanded tool path **100**C. The updated commanded tool path **100**C' loops back around with a localized clean up pass, thereby minimizing deviations **110'**. In FIG. **9**, the updated commanded tool path **100**C' may continue along the originally commanded path **100**C or any other suitable updated commanded tool path **100**C'.

**[0105]** Using such "immediate" correction, the undercut is corrected before the remainder of the tool path **100** is executed. Due to the need for the first filter **86** to prevent positive feedback in the machining control loops, actions to address the undercut deviations **110** must occur, at a minimum, after the filter length of the first filter **86**. One exception to this is to slow down the feed rate of the tool **20** along the tool path **100**, which may be done in near real time (within the acceleration limits of the manipulator **14**). As soon as the undercut deviation **110** is recognized, the commanded speed can be reduced. This action alone will often largely mitigate undercut deviation **110** because such errors are often caused by increases in machining force due to bone density increases or movement of the bone away from the tool **20**. Any undercut occurring during the transient will be minimized. When the deviation **110** falls below a tolerance threshold, the initial undercut error is then corrected with the localized cleanup pass, thereby removing the potential for regenerative cutting error development.

**[0106]** One method of addressing the initial undercut deviation **110** is to reverse the direction of feed and iteratively traverse a location of the undercut deviation **110** until the undercut is removed. This may be done with or without the aforementioned immediate feed rate slowdown, such as when the undercut deviation **110** is reduced below the tolerance threshold. That is, the undercut is sensed, but not acted upon until after the situation causing the undercut has ended. For example, large actuator accelerations commanded when turning a sharp corner at a high feed rate may not be achievable by the system **10**, resulting in an undercut. Upon stabilizing on a subsequent low radius or straight area, the system **10** would sense that undercutting has stopped. The direction of feed would then reverse to go back along the tool path **100** to address the undercut, most likely at a lower feed rate. Feed rate may be ramped down and/or the re-transited path iterated until the undercut deviation **110** is reduced to the tolerance threshold.

**[0107]** In a situation where the tool path **100** is creating a pocket several times greater than the TCP diameter, a more sophisticated method of addressing the undercut deviation **110** would be to circle back to the undercut location using a circle having a radius, which the system **10** can follow with low error given its feed rate. In some instances, however, the circular/helical path milling may only be used to address undercut deviation **110**, and then the original tool path **100** would be resumed until the next undercut deviation **110** is sensed.

**[0108]** In a third embodiment, as shown in FIG. **10**, the controller **30**, based on the outcome of comparing the commanded and actual states **98**, **108**, proactively modifies operation of the tool **20** along the path **100** to account for the deviations **110**. This may be done, for example, by proactively altering the path **100**. Alternatively, or additionally, the controller **30** may proactively alter the feed rate of the tool **20**, as described below.

**[0109]** Once again, in the example of FIG. **10**, a single tool path **100** is shown and as compared with FIG. **8**, there is no subsequent tool path **100'**. Here, the tool **20** follows the commanded path **100**C, and actual states **108** of the tool **20** deviate from the commanded states **108** near a first corner thereby causing deviations **110**, which produce the undercut. Upon immediately recognizing these deviations **110**, the controller **30** proactively generates the commanded tool path **100**C'. This proactive updating occurs at a point in time represented by the present location of the TCP in FIG. **10**. The proactively generated and updated commanded tool path **100**C' is configured to minimize deviations **110'** at a second corner (as compared to the deviations **110** from the first corner). Thus, the controller **30**, in a sense, predicts future undercuts and modifies operation of the tool **20** accordingly. In FIG. **10**, the proactively updated commanded tool path **100**C' may continue along the originally commanded path **100**C or any other suitable updated commanded tool path **100**C'.

**[0110]** In proactive correction, the system **10** learns from the prior undercut deviations **110** and adjusts the feed rate and/or tool path accordingly before similar deviations **110** can occur, thereby avoiding the need for subsequent correction. Due to the high variation in bone density, the preferred implementation of proactive correction is reduction in feed rate. Tool path corrections would need to be approached conservatively to avoid potential overcorrection or overcut "correction" error.

**[0111]** In this embodiment, the threshold value to proactively correct deviations **110** may be variable. For example, the threshold value may be dependent on whether the machining is a roughing pass or finishing pass. Alternatively, or additionally, the threshold value may be dependent on the function and criticality of the feature being machined. For example, lower undercut errors would likely be tolerable in the middle 2/3rds of a surface intended for a press fit interface. This is since undercuts in this region would result in rocking of the implant, which could lead to poor fixation and/or alignment. Larger undercuts would be allowable in the outer portion since bone is not strictly rigid and, within localized areas, highpoints can compress and adapt to the implant upon impaction.

**[0112]** The controller **30** may use any of the above described techniques individually, or in combination to modify operation of the tool **20** to account for deviations **110** between the commanded and actual states **20**.

**[0113]** Additionally, it may be desirable to associate any of the aforementioned first and second paths **100**, **100'** to certain modes of operation for the system **10**. For example, the system **10** may enable the manipulator **14** to interact with the site using manual and semi- autonomous modes of operation. An example of the semi-autonomous mode is described in U.S. Pat. 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 the semi-autonomous mode, the manipulator **14** directs movement of the tool **20** and, in turn, the energy applicator **24** at the surgical site. In one embodiment, the controller **30** models the tool **20** and/or energy applicator **24** as a virtual rigid body and determines forces and torques to apply to the virtual rigid body to advance and constrain the tool **20** and/or energy applicator **24** along any of the first and second paths **100**, **100'** in the semi-autonomous mode. Movement of the tool **20** in the semi-autonomous mode is constrained in relation to the virtual constraints generated by the boundary generator **66** and/or path generator **69**.

**[0114]** In the semi-autonomous mode, the manipulator **14** is capable of moving the tool **20** free of operator assistance. Free of operator assistance may mean that an operator does not physically contact the tool **20** to apply force to move the tool **20**. Instead, the operator may use some form of control to remotely manage starting and stopping of movement. For example, the operator may hold down a button of a remote control to start movement of the tool **20** and release the button to stop movement of the tool **20**. Alternatively, the operator may press a button to start movement of the tool **20** and press a button to stop movement of the tool **20**.

**[0115]** Alternatively, the system **10** may be operated in the manual mode. Here, in one embodiment, the operator manually directs, and the manipulator **14** controls, movement of the tool **20** and, in turn, the energy applicator **24** at the surgical site. The operator physically contacts the tool **20** to cause movement of the tool **20**. The manipulator **14** monitors the forces and torques placed on the tool **20** by the operator in order to position the tool **20**. A sensor that is part of the manipulator **14**, such as a force-torque transducer, measures these forces and torques. In response to the applied forces and torques, the manipulator **14** mechanically moves the tool **20** in a manner that emulates the movement that would have occurred based on the forces and torques applied by the operator. Movement of the tool **20** in the manual mode is also constrained in relation to the virtual constraints generated by the boundary generator **66** and/or path generator **69**.

**[0116]** For the "subsequent path" technique of FIGS. **7** and **8**, the controller **30**, in one example, commands movement of the tool **20** along the first path **100** according to the manual mode and commands movement of the tool **20** along the second path **100'** according to the semi-autonomous mode. For example, it may be desirable to use the manual mode to control the tool **20** along the first path **100** for rough or bulk manipulation of the target tissue. In other words, the desire may be to quickly, but less accurately, remove large sections of the target tissue in the manual mode. Such bulk manipulation may result in relatively large deviations **110** between the commanded and actual states **98**, **108**. Accordingly, the semi-autonomous mode may be utilized to account for deviations **110** resulting from manual manipulation by commanding the tool **20** along the second path **100'**. This scenario provides an automated and highly accurate follow-up or clean-up after manual manipulation.

**[0117]** For the "subsequent path" technique, the controller **30** may alternatively command movement of the tool **20** along both the first and second paths **100**, **100'** according to the semi-autonomous mode. For example, it may be desirable to use the semi-autonomous mode to control the tool **20** along the first path **100** for rough or bulk manipulation of the target tissue. In other words, the desire may be to quickly, but less accurately remove large sections of the target tissue. In one example, rough-cut paths may be designed for the most efficient bulk removal of material given the capability and workspace stability of the manipulator **14**, without particular regard for accuracy. Thereafter, the semi-autonomous mode may again be utilized to account for deviations **110** from the first iteration of semi-autonomous manipulation by commanding the tool **20** along the second path **100'**. Using the semi-autonomous mode in this fashion provides an iterative process for removing the target tissue, as described above. That is, any number of follow-up paths may be generated, thereby gradually removing the target tissue and gradually reducing the deviations **110** between commanded and actual states **98**, **108** until a suitable state or threshold for the target tissue is achieved.

**[0118]** In other embodiments of this technique, the controller **30** is configured to command movement of the tool **20** along both the first and second paths **100**, **100'** according to the manual mode, in accordance with the techniques described above. Those skilled in the art appreciate that the controller **30** may command movement of the tool **20** along the first and second paths **100**, **100'** according to any other modes of operation and for other reasons not specifically recited herein

**[0119]** For any of the embodiments shown in FIGS. **7-10**, the system **10** may enable switching between the manual mode and the semi-autonomous mode at any time, and for any tool path. In one embodiment, such switching occurs in response to manual input. For example, the operator may use any suitable form of control to manage, e.g., remotely, which mode should be active. Alternatively, switching may be implemented autonomously in response to certain events or conditions. For example, the controller **30** may determine that the requisite amount of tissue has been removed in the manual mode and switch to the semi- autonomous mode in response. The controller **30** may further enable switching for the second tool path **100'**, to immediately correct the original tool path **100** or in anticipation of proactive correction of the original tool path **100**. Furthermore, switching may occur based on analysis of the deviations **110** with respect to the threshold tolerance. Those skilled in the art appreciate that switching between manual and semi-autonomous modes may be performed according to other methods not explicitly described herein.

**[0120]** Several embodiments have been described in the foregoing description. However, the embodiments discussed herein are not intended to be exhaustive or limit the invention 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 invention may be practiced otherwise than as specifically described.

**[0121]** The many features and advantages of the invention are apparent from the detailed specification, and thus, it is intended by the appended claims to cover all such features and advantages of the invention which fall within the true spirit and scope of the invention. Further, since numerous modifications and variations will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

What is claimed is:

**1**. A surgical system comprising:

a manipulator configured to support and facilitate movement of a surgical tool along a tool path relative to a surgical site; and

one or more controllers coupled to the manipulator and being configured to:

determine commanded states of the surgical tool and actual states of the surgical tool relative to the tool path for a plurality of time steps;

detect at least one deviation between the commanded states and the actual states of the surgical tool for at least one of the plurality of time steps; and

respond to the at least one deviation by modification of one or both of: a feed rate of the surgical tool; and the tool path.

**2**. The surgical system of claim **1**, wherein the one or more controllers to:

compare the at least one deviation to a threshold, wherein the threshold is at least one of:

a minimum, a maximum, a range, or a standard deviation;

determine that the at least one deviation exceeds the threshold; and

respond to the at least one deviation in response to determining that the at least one deviation exceeds the threshold.

**3**. The surgical system of claim **1**, wherein the one or more controllers respond to the at least one deviation by immediate modification of one or both of: the feed rate of the surgical tool; and the tool path.

**4**. The surgical system of claim **1**, wherein the one or more controllers respond to the at least one deviation by reduction of the feed rate of the surgical tool.

**5**. The surgical system of claim **1**, wherein the one or more controllers respond to the at least one deviation by modification of the tool path to include a follow-up tool path that returns relative to the at least one deviation to address the at least one deviation.

**6**. The surgical system of claim **1**, wherein the one or more controllers respond to the at least one deviation by reversal of a direction of the feed rate to enable the surgical tool to go back along the tool path.

**7**. The surgical system of claim **1**, wherein the one or more controllers further respond to the at least one deviation by being configured to generate a new tool path for the surgical tool.

**8**. The surgical system of claim **1**, wherein the one or more controllers are further configured to predict, based on the at least one deviation, at least one future deviation between future commanded states and future actual states of the surgical tool.

**9**. The surgical system of claim **8**, wherein the one or more controllers are configured to proactively modify the tool path to account for the future deviation.

**10**. The surgical system of claim **8**, wherein the one or more controllers are configured to proactively modify the feed rate of the surgical tool to account for the future deviation.

**11**. The surgical system of claim **1**, wherein the one or more controllers are configured to respond to the at least one deviation by automatic modification of one or both of: the feed rate of the surgical tool; and the tool path.

**12**. The surgical system of claim **1**, wherein the one or more controllers are configured to utilize data from the manipulator to determine the commanded states of the surgical tool and the actual states of the surgical tool.

**13**. The surgical system of claim **12**, wherein the one or more controllers are configured to:

filter the data from the manipulator according to a first filter length; and

determine the commanded states of the surgical tool using the data filtered according to the first filter length.

**14**. The surgical system of claim **13**, wherein the one or more controllers are further configured to:

filter the data from the manipulator according to a second filter length being shorter than the first filter length; and

determine the actual states of the surgical tool using the data filtered according to the second filter length.

**15**. The surgical system of claim **13**, wherein the one or more controllers are further configured to:

obtain the data from the manipulator, wherein the data is unfiltered; and

determine the actual states of the surgical tool using the data that is unfiltered.

**16**. The surgical system of claim **1**, wherein:

the surgical site is a bone;

the tool path is defined relative to the bone; and

the surgical tool is a cutting bur configured to remove material from the bone.

**17**. The surgical system of claim **1**, wherein the one or more controllers are configured to:

facilitate movement of the surgical tool along the tool path in a semi-autonomous mode, and in the semi-autonomous mode, the manipulator directs movement of the surgical tool along the tool path free of operator assistance, wherein the tool path is predefined; and

respond to the at least one deviation in the semi-autonomous mode.

**18**. The surgical system of claim **1**, wherein the one or more controllers are configured to:

facilitate movement of the surgical tool along the tool path in a manual mode, and in the manual mode, a user manually directs, and the manipulator controls, movement of the surgical tool along the tool path, wherein the tool path is defined by the user; and

respond to the at least one deviation in the manual mode.

**19**. A method of operating a surgical system, the surgical system including a manipulator to support and facilitate movement of a surgical tool along a tool path relative to a surgical site, and one or more controllers coupled to the manipulator, the method comprising the one or more controllers:

determining commanded states of the surgical tool and actual states of the surgical tool relative to the tool path for a plurality of time steps;

detecting at least one deviation between the commanded states and the actual states of the surgical tool for at least one of the plurality of time steps; and

responding to the at least one deviation by modifying one or both of: a feed rate of the surgical tool; and the tool path.

**20**. The method of claim **19**, comprising the one or more controllers:

comparing the at least one deviation to a threshold, wherein the threshold is at least one of: a minimum, a maximum, a range, or a standard deviation;

determining that the at least one deviation exceeds the threshold; and

responding to the at least one deviation in response to determining that the at least one deviation exceeds the threshold.

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