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(54) **RATCHETING FOR MASTER ALIGNMENT OF A TELEOPERATED MINIMALLY INVASIVE SURGICAL INSTRUMENT**

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This patent is subject to a terminal disclaimer.

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(51) **Int. Cl.**

B25J 9/16	(2006.01)
A61B 34/00	(2016.01)

(Continued)

(52) **U.S. Cl.**

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(Continued)

(58) **Field of Classification Search**

USPC 606/1, 130; 318/568.11–568.22, 572; 700/245–264

See application file for complete search history.

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(57) **ABSTRACT**

Techniques for ratcheting an alignment between an input means and an instrument include a teleoperated system comprising a robotic means configured to support an instrument, an input means configured to be manipulated by an operator to command motion of the instrument, and a ratcheting means. The ratcheting means is configured to determine first rotation values describing an orientation of the input means; determine second rotation values describ-

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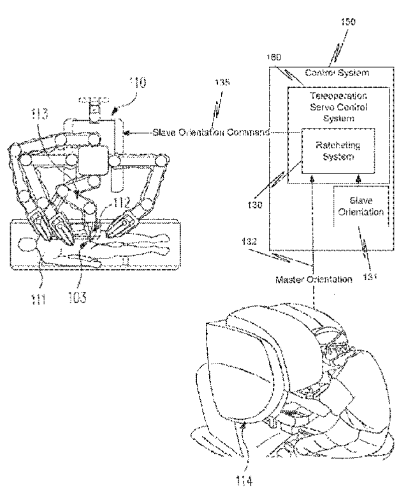

ing an orientation of the instrument; determine, based on the first rotation values and the second rotation values, an orientation error between the orientation of the input means and the orientation of the instrument; generate, based on the orientation error, a motion command for the instrument to reduce the orientation error by increasing an alignment between the input means and the instrument; and command the robotic means to move in accordance with the motion command.

20 Claims, 10 Drawing Sheets

Related U.S. Application Data

continuation of application No. 17/107,862, filed on Nov. 30, 2020, now Pat. No. 11,672,619, which is a continuation of application No. 16/862,412, filed on Apr. 29, 2020, now Pat. No. 10,881,473, which is a continuation of application No. 16/353,932, filed on Mar. 14, 2019, now Pat. No. 10,675,109, which is a continuation of application No. 15/706,883, filed on Sep. 18, 2017, now Pat. No. 10,278,783, which is a continuation of application No. 15/399,600, filed on Jan. 5, 2017, now Pat. No. 9,814,537, which is a continuation of application No. 14/996,073, filed on Jan. 14, 2016, now Pat. No. 9,579,164, which is a continuation of application No. 14/534,526, filed on Nov. 6, 2014, now Pat. No. 9,265,584, which is a continuation of application No. 13/839,438, filed on Mar. 15, 2013, now Pat. No. 8,903,549, which is a continuation of application No. 12/495,213, filed on Jun. 30, 2009, now Pat. No. 8,423,186.

(51) **Int. Cl.**
A61B 34/30 (2016.01)
A61B 34/35 (2016.01)
A61B 34/37 (2016.01)
A61B 90/10 (2016.01)
B25J 3/00 (2006.01)
A61B 17/00 (2006.01)

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CPC ***A61B 90/10*** (2016.02); ***B25J 3/00*** (2013.01); ***B25J 9/1669*** (2013.01); ***B25J 9/1689*** (2013.01); *A61B 2017/00725* (2013.01); *A61B 2034/305* (2016.02); *G05B 2219/45117* (2013.01); *Y10S 901/27* (2013.01); *Y10S 901/41* (2013.01)

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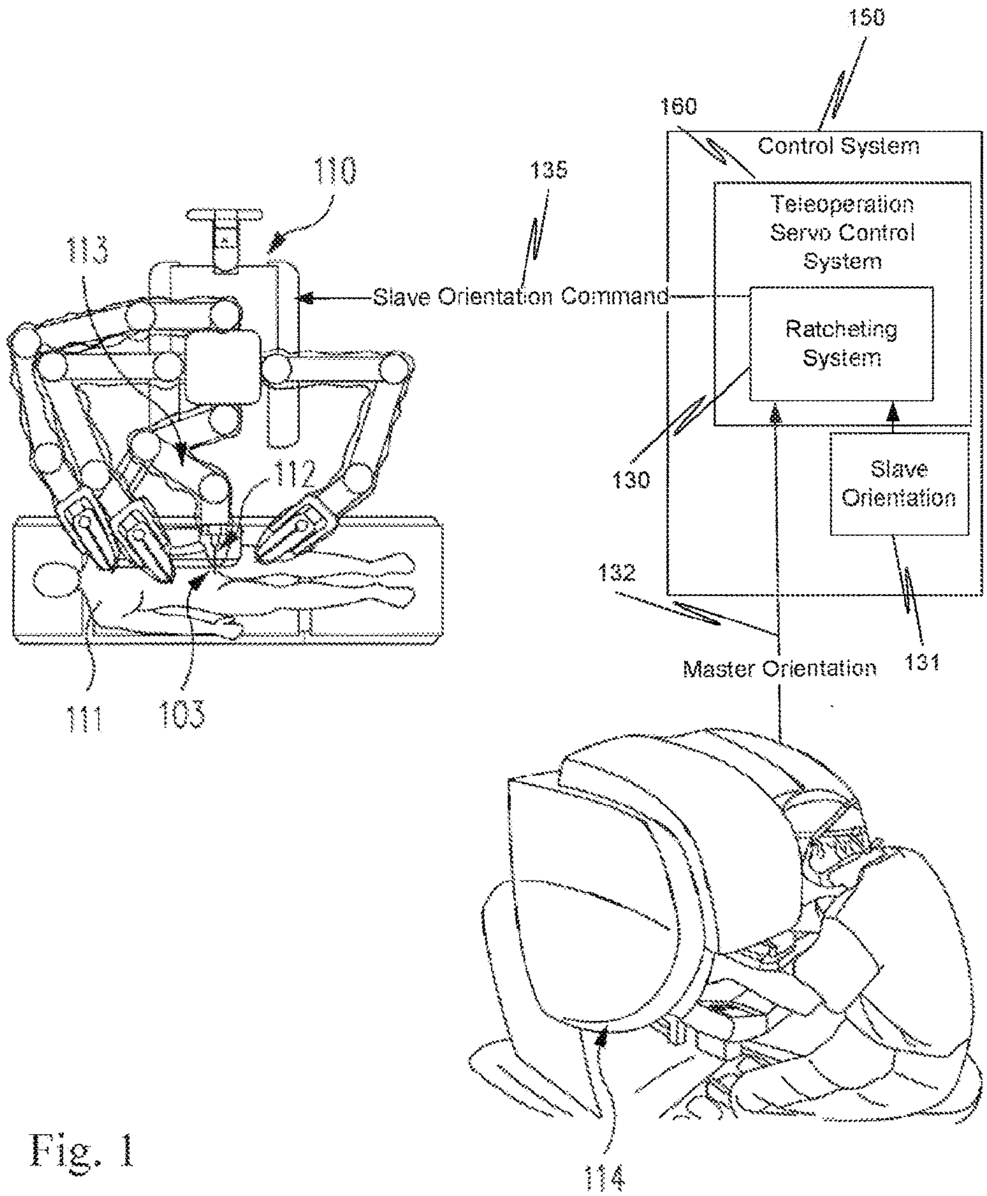

150
160
Control System
Teleoperation
Servo Control
System
Ratcheting
System
Slave
Orientation
110
113
135
Slave Orientation Command
112
130
132
131
Master Orientation
111
103
114

Fig. 1

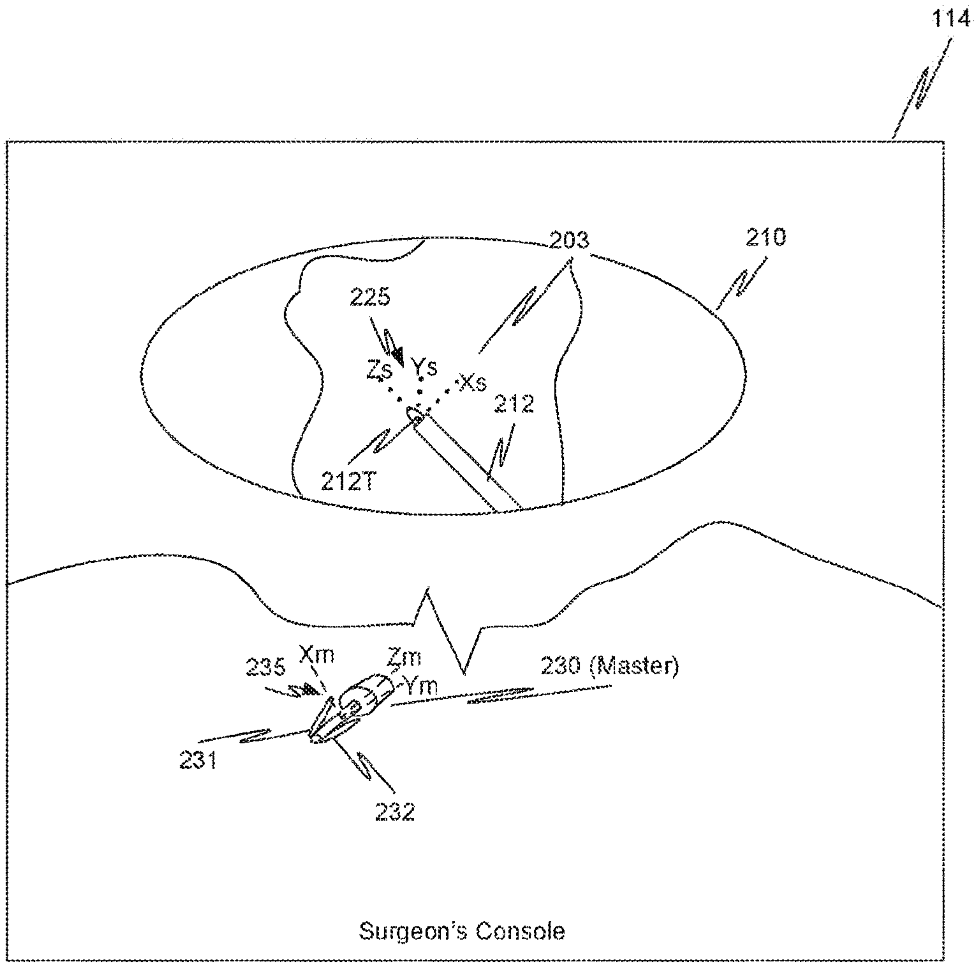


Fig. 2A

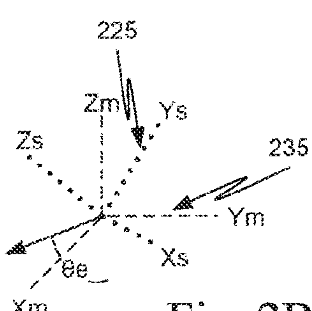


Fig. 2B

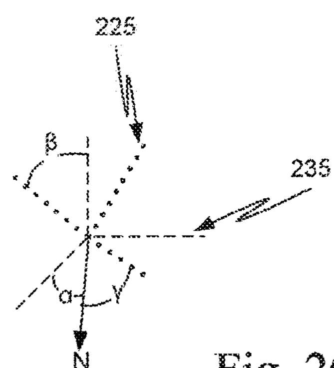


Fig. 2C

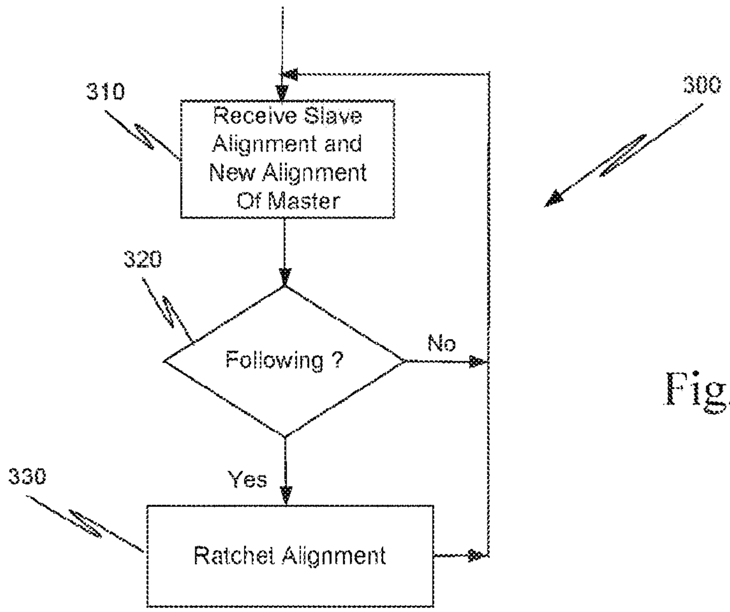

300
310
Receive Slave Alignment and New Alignment Of Master
320
Following ?
No
Yes
330
Ratchet Alignment

Fig. 3A

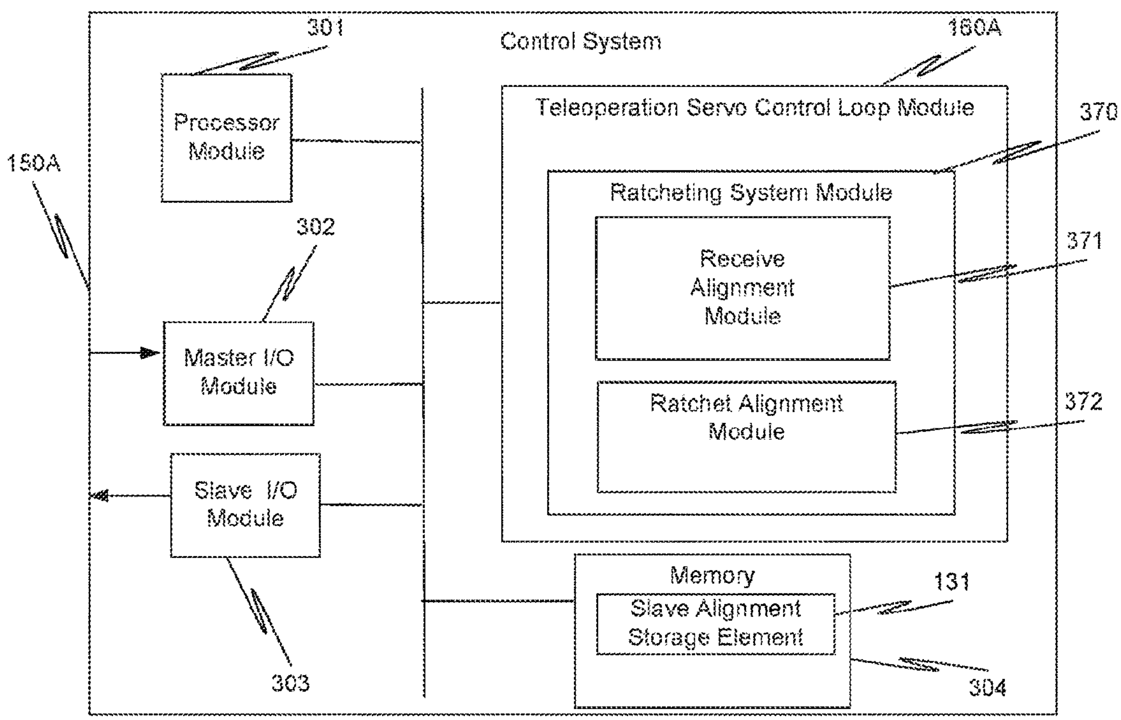

Control System
301
160A
Processor Module
Teleoperation Servo Control Loop Module
370
150A
Ratcheting System Module
302
Receive Alignment Module
371
Master I/O Module
Ratchet Alignment Module
372
Slave I/O Module
Memory
131
Slave Alignment Storage Element
303
304

Fig. 3B

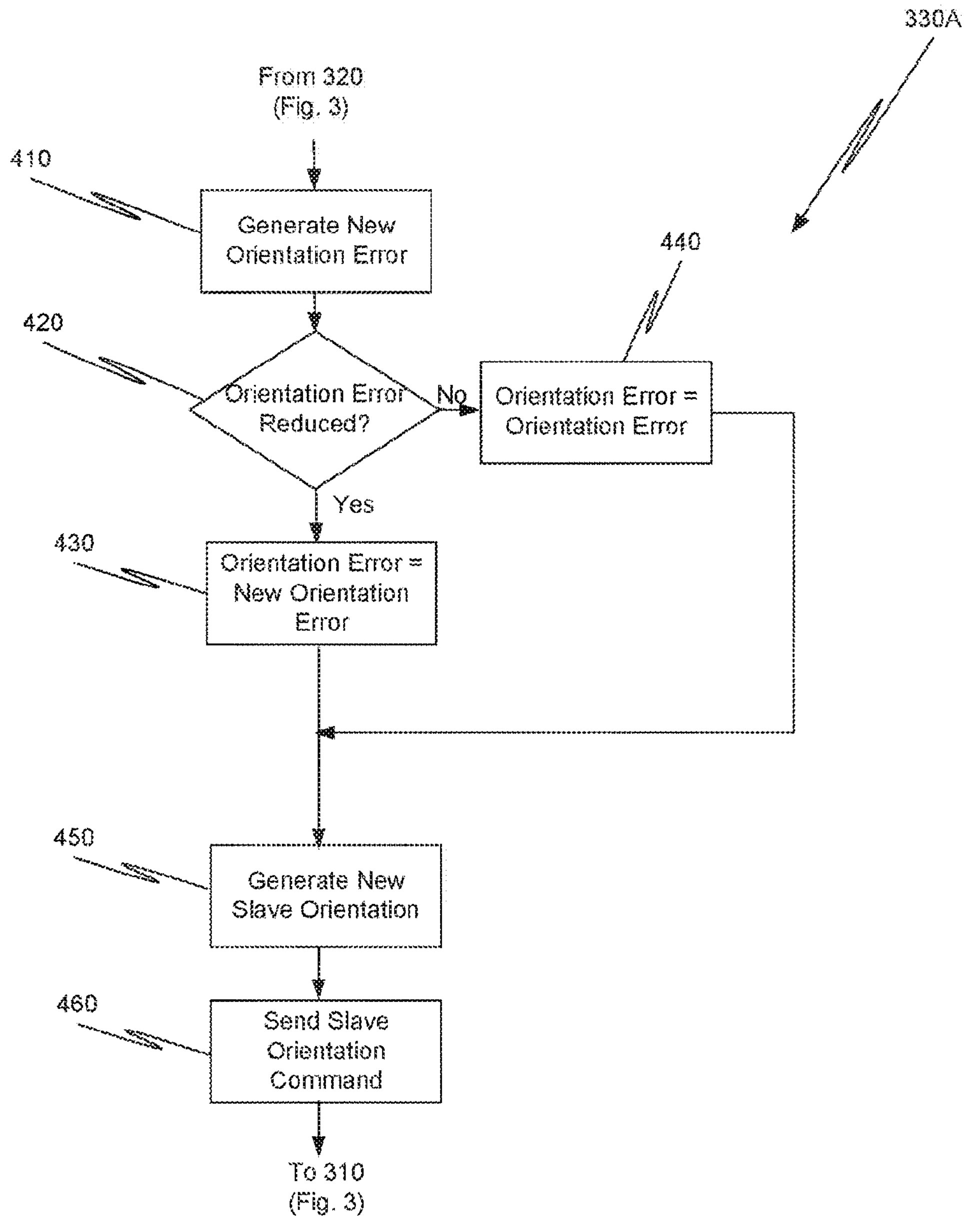

330A
From 320
(Fig. 3)
410
Generate New Orientation Error
420
Orientation Error Reduced?
No
440
Orientation Error = Orientation Error
Yes
430
Orientation Error = New Orientation Error
450
Generate New Slave Orientation
460
Send Slave Orientation Command
To 310
(Fig. 3)

Fig. 4A

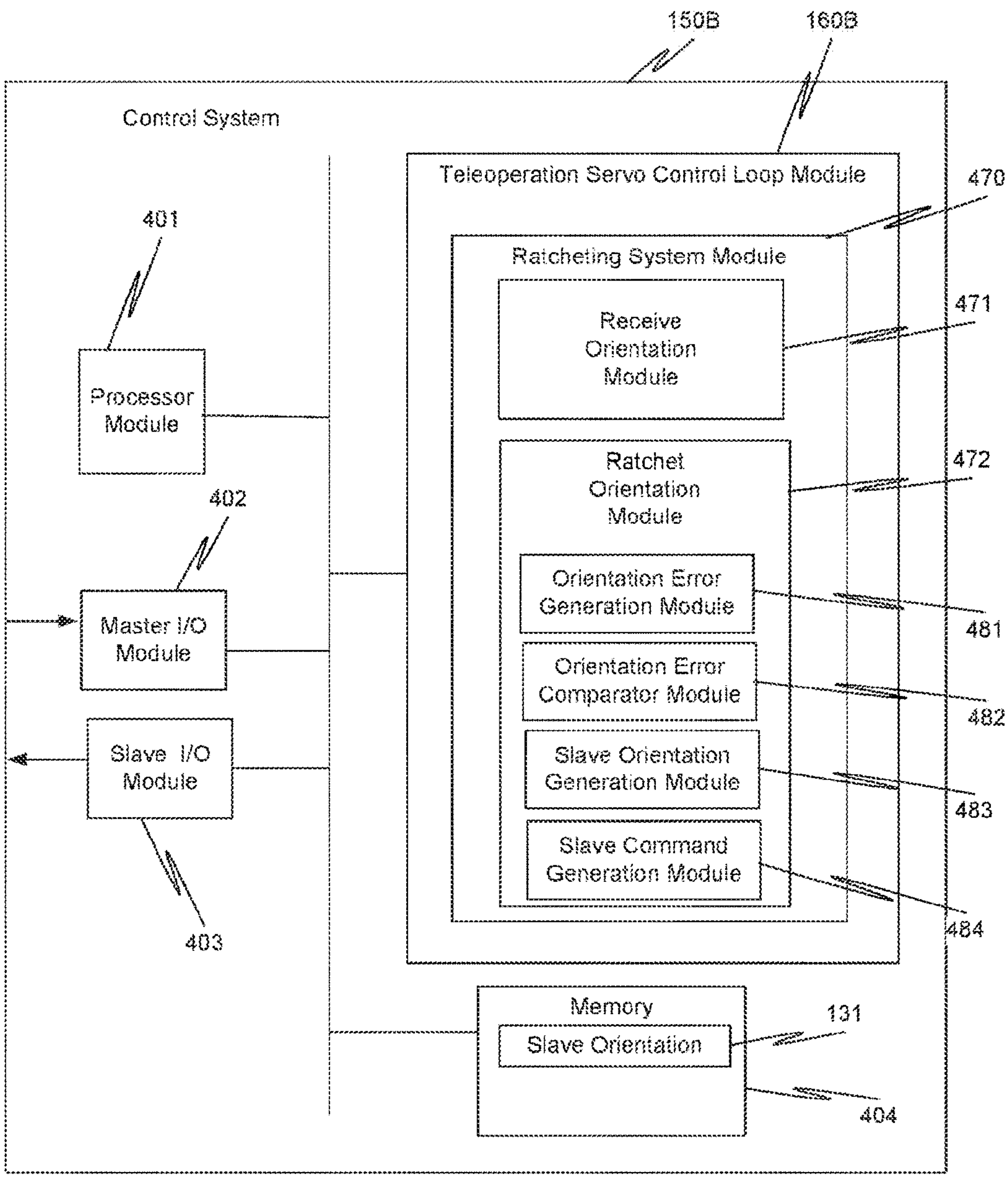

150B
160B
Control System
Teleoperation Servo Control Loop Module
470
401
Ratcheting System Module
Receive Orientation Module
471
Processor Module
Ratchet Orientation Module
472
402
Orientation Error Generation Module
481
Master I/O Module
Orientation Error Comparator Module
482
Slave I/O Module
Slave Orientation Generation Module
483
Slave Command Generation Module
484
403
Memory
Slave Orientation
131
404

Fig. 4B

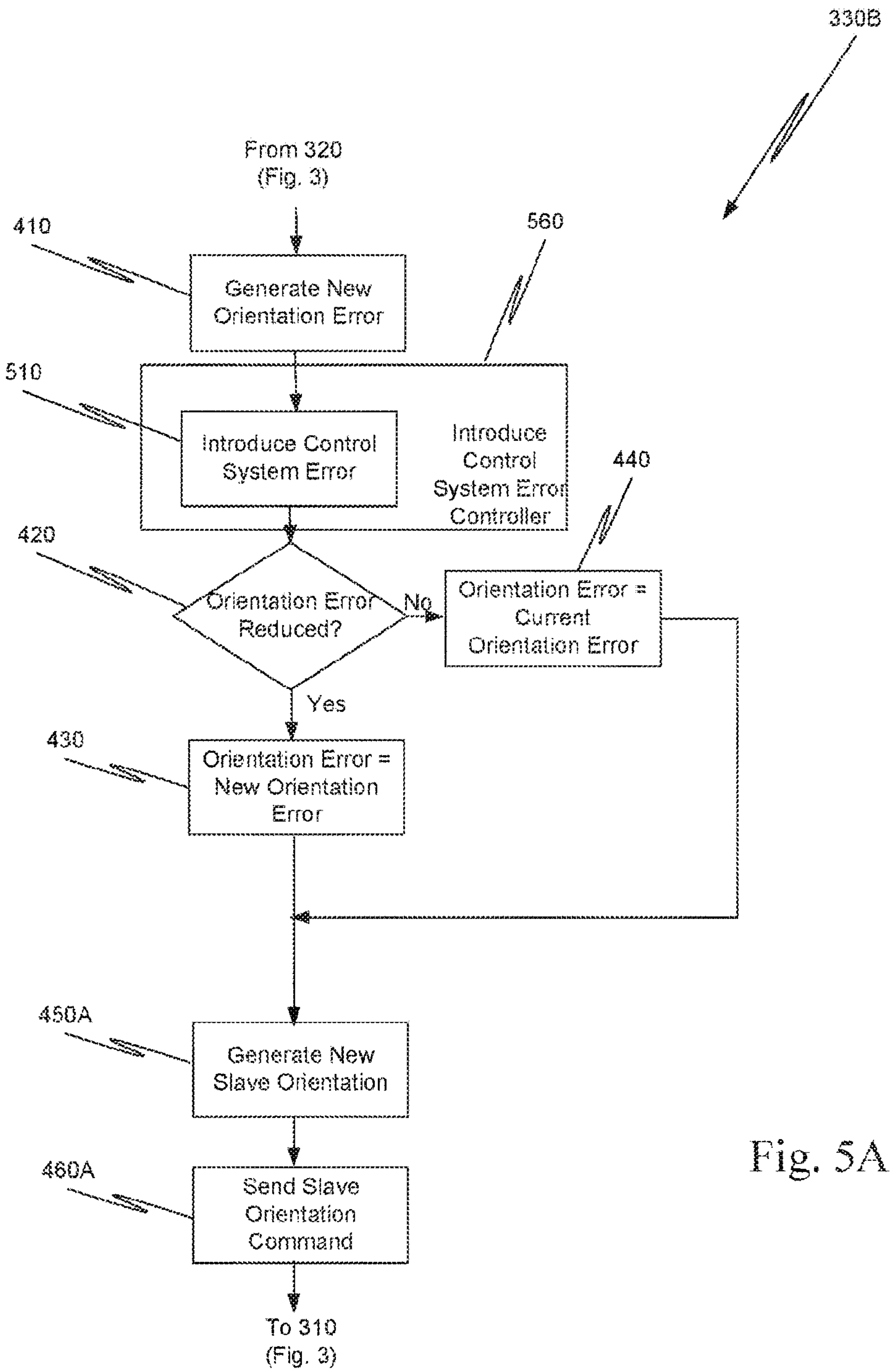

330B
From 320
(Fig. 3)
410
Generate New Orientation Error
560
510
Introduce Control System Error
Introduce Control System Error Controller
440
420
Orientation Error Reduced?
No
Orientation Error = Current Orientation Error
Yes
430
Orientation Error = New Orientation Error
450A
Generate New Slave Orientation
460A
Send Slave Orientation Command
To 310
(Fig. 3)

Fig. 5A

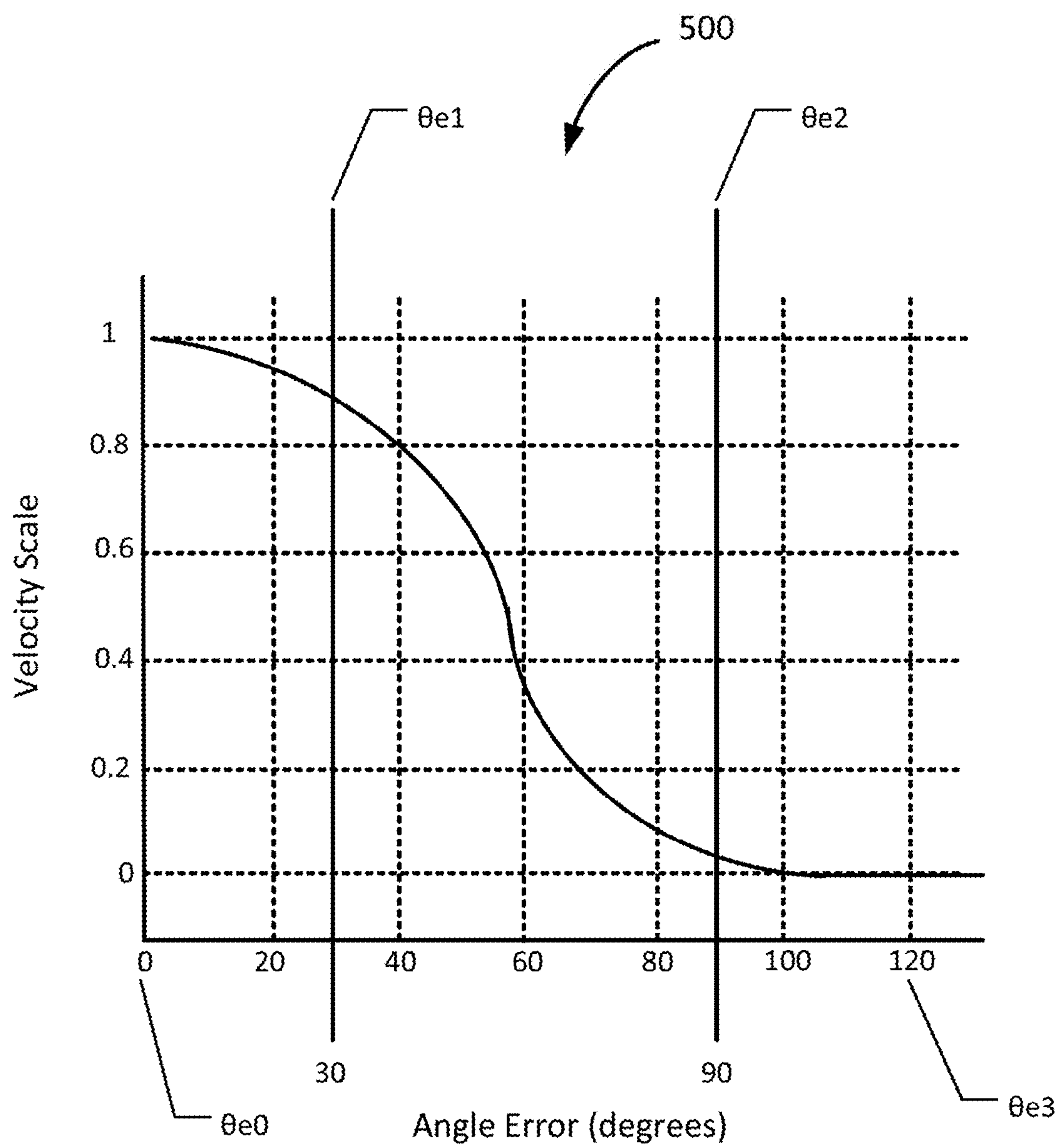
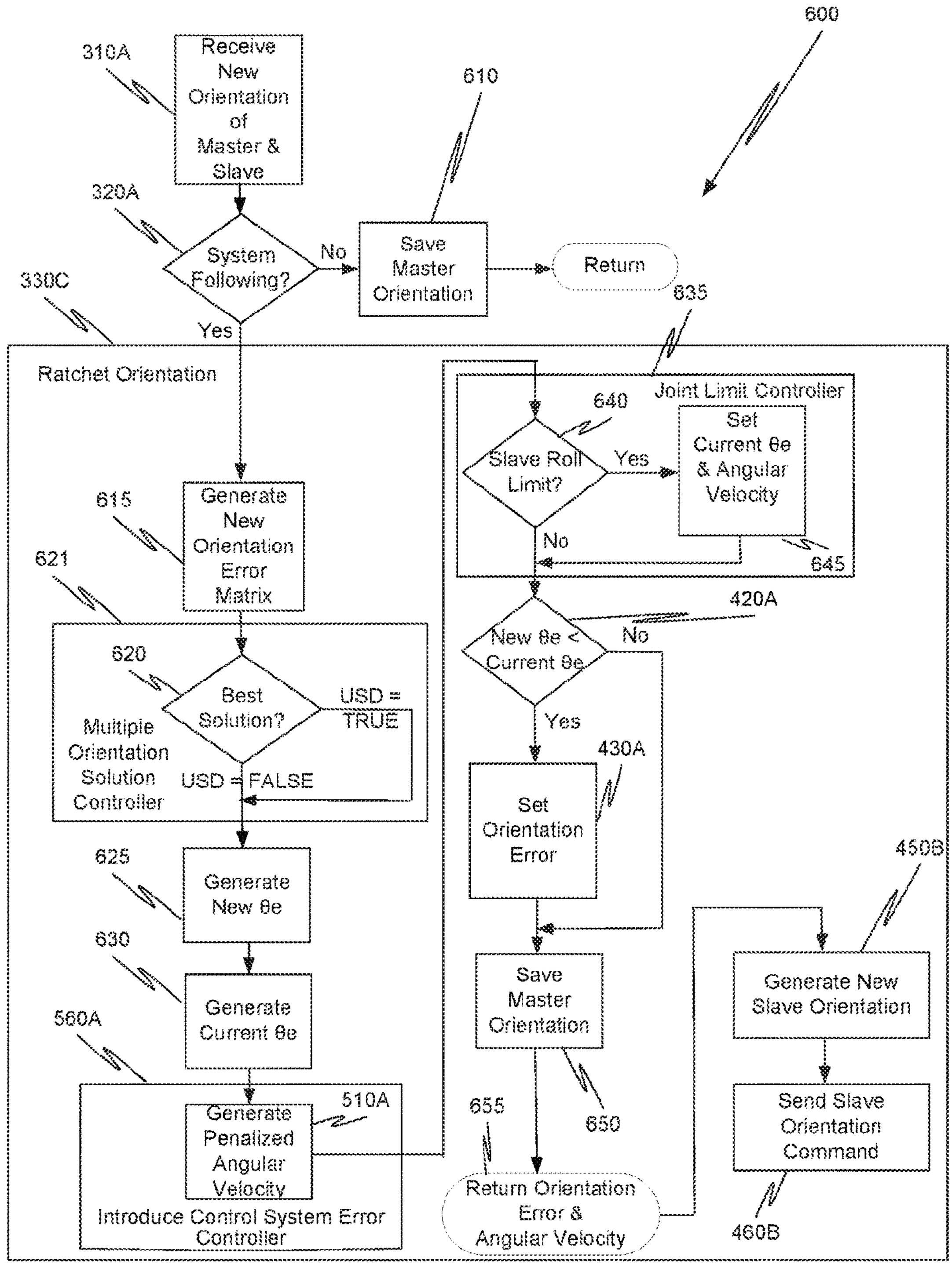
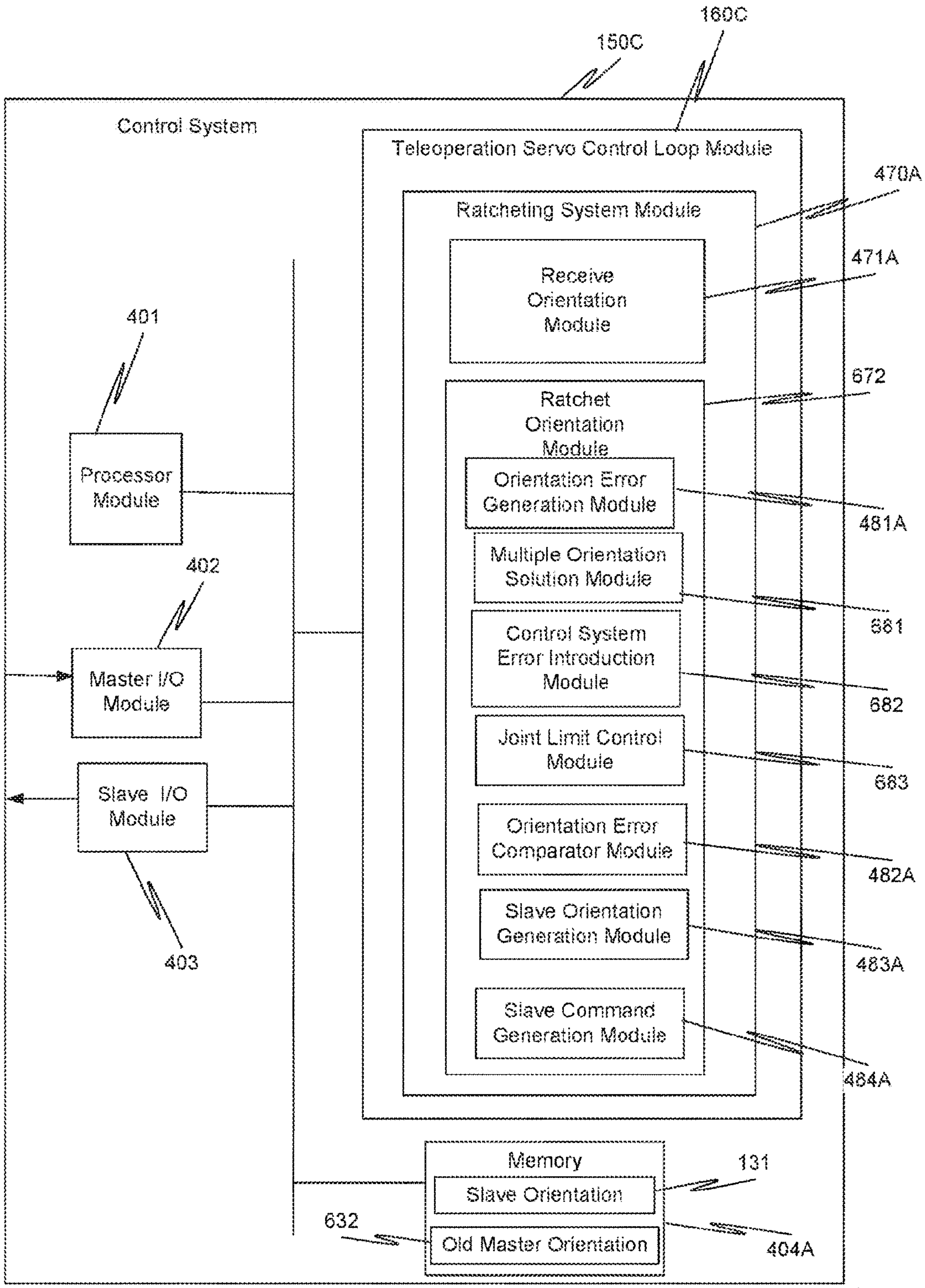

500
θe1
θe2
1
0.8
0.6
0.4
0.2
0
Velocity Scale
0
20
40
60
80
100
120
30
90
θe0
Angle Error (degrees)
θe3

Fig. 5B



600
310A
Receive New Orientation of Master & Slave
320A
System Following?
No
610
Save Master Orientation
Return
330C
Yes
Ratchet Orientation
635
Joint Limit Controller
640
Slave Roll Limit?
Yes
Set Current θe & Angular Velocity
No
645
615
Generate New Orientation Error Matrix
621
420A
New θe < Current θe
No
620
Best Solution?
USD = TRUE
Multiple Orientation Solution Controller
USD = FALSE
Yes
430A
Set Orientation Error
625
Generate New θe
450B
630
Generate Current θe
Save Master Orientation
Generate New Slave Orientation
560A
Generate Penalized Angular Velocity
510A
655
650
Send Slave Orientation Command
Return Orientation Error & Angular Velocity
Introduce Control System Error Controller
460B

Fig. 6A



160C
150C
Control System
Teleoperation Servo Control Loop Module
470A
Ratcheting System Module
Receive Orientation Module
471A
401
672
Ratchet Orientation Module
Orientation Error Generation Module
Processor Module
481A
Multiple Orientation Solution Module
402
681
Control System Error Introduction Module
Master I/O Module
682
Joint Limit Control Module
Slave I/O Module
683
Orientation Error Comparator Module
482A
403
Slave Orientation Generation Module
483A
Slave Command Generation Module
484A
Memory
131
Slave Orientation
632
Old Master Orientation
404A

Fig. 6B

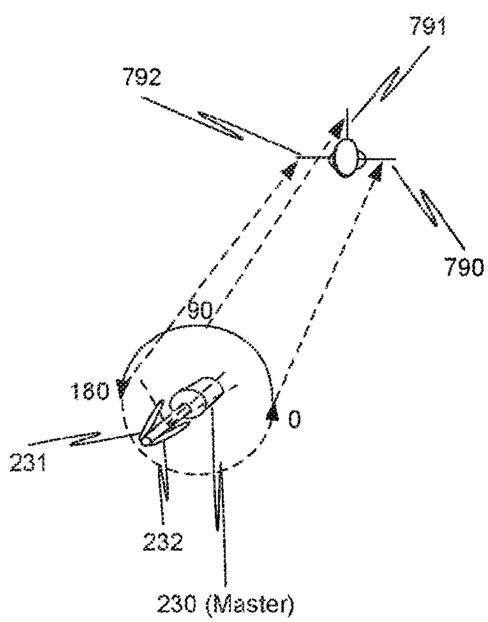


Fig. 7

RATCHETING FOR MASTER ALIGNMENT OF A TELEOPERATED MINIMALLY INVASIVE SURGICAL INSTRUMENT

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 18/309,110 (filed Apr. 28, 2023), which is a continuation of U.S. patent application Ser. No. 17/107,862 (filed Nov. 30, 2020) and now U.S. Pat. No. 11,672,619, which is a continuation of U.S. patent application Ser. No. 16/862,412 (filed Apr. 29, 2020) and now U.S. Pat. No. 10,881,473, which is a continuation of U.S. patent application Ser. No. 16/353,932 (filed Mar. 14, 2019) and now U.S. Pat. No. 10,675,109, which is a continuation of U.S. patent application Ser. No. 15/706,883 (filed Sep. 18, 2017 and now U.S. Pat. No. 10,278,783), which is a continuation of U.S. patent application Ser. No. 15/399,600 (filed Jan. 5, 2017 and now U.S. Pat. No. 9,814,537), which is a continuation of U.S. patent application Ser. No. 14/996,073 (filed Jan. 14, 2016 and now U.S. Pat. No. 9,579,164), which is a continuation of U.S. patent application Ser. No. 14/534,526 (filed Nov. 6, 2014 and now U.S. Pat. No. 9,265,584), which is a continuation of U.S. patent application Ser. No. 13/839,438 (filed Mar. 15, 2013 and now U.S. Pat. No. 8,903,549), which is a continuation of U.S. patent application Ser. No. 12/495,213 (filed Jun. 30, 2009 and now U.S. Pat. No. 8,423,186). The full disclosures of these related applications are incorporated by reference herein for all purposes.

BACKGROUND

1. Field of Invention

Aspects of this invention are related to teleoperated minimally invasive surgical systems, and more particularly are related to controlling orientation of master and slave surgical instrument tips in a teleoperated minimally invasive surgical system.

2. Related Art

The da Vinci® surgical system, manufactured by Intuitive Surgical, Inc., Sunnyvale, California, is a minimally invasive, teleoperated robotic system that offers patients many benefits, such as reduced trauma to the body, faster recovery and shorter hospital stay. One component of the da Vinci® Surgical System is a master tool manipulator that a surgeon uses to manipulate a surgical instrument, referred to as a slave surgical instrument.

The master grip of the master tool manipulator is specially designed to be both ergonomic and intuitive for controlling the slave surgical instrument. The surgeon holds the master grip in a particular way using his/her forefinger and thumb, so that targeting and grasping involves intuitive pointing and pinching motions.

To enable intuitive control of the slave surgical instrument, the master grip must be aligned in orientation with the slave surgical instrument tip in the view reference frame of the stereoscopic viewer. The motions of the slave surgical instrument tip follow master motions via teleoperation and are consistent in both directions of motion as well as absolute orientation. If orientation alignment is not achieved, the slave surgical instrument tip may still rotate in the desired direction, but the slave surgical instrument tip neither points in the same absolute direction nor rolls along the same axis as the surgeon is pointing.

The master tool manipulator uses motors in a gimbal assembly to actively align the orientation axes of the master grip with the associated slave surgical instrument tip in view coordinates. This alignment happens automatically before the surgeon engages teleoperation. Moreover, the system automatically preserves this alignment during manipulation of the camera or instrument outer axes.

Specifically, when entering following on the da Vinci® surgical system, the master grip must be aligned with the orientation of the slave surgical instrument tip before the da Vinci® surgical system operates properly in following. The present system performs a master alignment whenever the system transitions from a mode where this orientation alignment may have been compromised (after a tool change, camera clutch, slave clutch, swapping of arms in a 4th arm system etc.).

A master alignment calculates a set of master wrist joint angles that cause the orientation of the master grip to match the orientation of the slave surgical instrument tip, without changing the master grip position. The master wrist joints are then commanded to match the calculated angles using the motors.

The da Vinci® surgical system checks that the master and slave orientations match before allowing the user to enter following. If the orientations don't match (presumably because the user has over powered the master and not allowed the master to complete the alignment) a warning message is displayed and the master alignment is attempted again. This often slows down the surgeon's entry into following and requires a powered master tool manipulator with motors in the gimbal assembly to move master wrist joints into the proper orientation.

SUMMARY OF THE INVENTION

A minimally invasive surgical system includes a slave surgical instrument having a slave surgical instrument tip and a master grip. The master grip is coupled to the slave surgical instrument tip by a teleoperation servo control system. In one aspect, a ratcheting system, within the teleoperation servo control system, seamlessly and continuously improves the alignment, in a common coordinate frame of reference, of the master grip with respect to the slave surgical instrument tip as the master grip is moved.

The ratcheting system results in intuitive alignment between the master grip and the slave surgical instrument tip. Also, the ratcheting system provides a direct association between what the surgeon is doing, manipulating the master grip, and what the surgeon is seeing at a surgeon's console, movement of the slave surgical instrument tip in the display. This is achieved without the delays associated with the conventional powered alignments before following could be entered. Also, the ratcheting system, in one aspect, eliminates the need for the powered master grip and permits use of lower cost readily available components as the master grip.

In one aspect, the slave surgical instrument tip and the master grip have Cartesian position components and orientation components in a common coordinate reference frame. The ratcheting system can achieve alignment for all components, a subset of components, e.g., the orientation components or the Cartesian components, or in a component-wise fashion for a particular set of components.

A ratcheting system, in the teleoperation servo control system, is (i) coupled to the master grip to receive the alignment of the master grip in a common coordinate frame, and (ii) coupled to the slave surgical instrument. The ratcheting system controls the motion of the slave by continuously reducing the alignment error in the common coordinate frame, as the master grip moves. This is done without autonomous motion of the slave surgical instrument tip and without autonomous motion of the master grip.

In one aspect, the alignment error in the common coordinate frame is an orientation error. The orientation error comprises an angle. In one aspect, the angle is an angle θ_e defined as:

$$\theta_e=\cos^{-1}[0.5*(R_{\Delta 11}+R_{\Delta 22}+R_{\Delta 33}-1)],$$

where $R_{\Delta 11}$, $R_{\Delta 22}$, $R_{\Delta 33}$ are diagonal elements of a relative rotation matrix R_Δ. In another aspect, the angle is one Euler angle in a set of Euler angles.

In another aspect, the ratcheting system includes an introduce control loop error controller that introduces a control system error in the alignments of the slave surgical instrument tip and the master grip in the common frame of reference. For example, an angular velocity of the slave surgical instrument is penalized based upon an amount of misalignment in the common reference frame between the slave surgical instrument tip and the master grip. In still another aspect, the ratcheting system includes a roll-joint limit controller for determining whether motion of the slave surgical instrument has reached a joint limit and constraining motion of the slave surgical instrument tip upon reaching the joint limit. In still yet another aspect, the ratcheting system includes multiple orientation solutions, a best orientation controller selects one solution from the multiple orientation solutions that is closest to the orientation of the master grip.

A method using the above minimally surgical system includes controlling motion of a slave surgical instrument tip in the minimally invasive surgical system with motion of a master grip in the minimally invasive surgical system. In this method, a ratcheting system in the minimally invasive surgical system receives an alignment of the slave surgical instrument tip and an alignment of the master grip, both in a common frame of reference. The ratcheting system ratchets the alignment of the slave surgical instrument tip to the alignment of the master grip by continuously reducing an alignment error between the alignments, as the master grip moves, without autonomous motion of the slave surgical instrument tip and without autonomous motion of the master grip.

In one aspect, the ratcheting includes moving the slave surgical instrument tip and the master grip in a same relative way upon engagement of following by the minimally invasive surgical system irrespective of the alignments in the common reference frame. The ratcheting also includes bleeding off the alignment error in the common frame of reference by using a new alignment error when the motion of the master grip reduces the alignment error in the common reference frame, and by using a current alignment error in the common reference frame when the motion of the master grip does not reduces the alignment error thereby continuously reducing the alignment error between the alignments in the common reference frame.

The ratcheting system also generates a new alignment for the slave surgical instrument using the new alignment error, and sends a command to the slave surgical instrument based on the new alignment.

In another aspect, the ratcheting system introduces a control error between the slave surgical instrument alignment and the master grip alignment. The introduction of a control error further includes penalizing a commanded angular velocity for the slave surgical instrument tip based on the current alignment error.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic view of a minimally invasive surgical robot which includes a teleoperation servo control system with a ratcheting system.

FIG. **2**A is diagrammatic view of parts of the surgeon's console of FIG. **1** for a minimally invasive surgical robot of FIG. **1**.

FIG. **2**B illustrates the orientations of the master grip and the slave grip and rotation angle error θ_e between the two orientations.

FIG. **2**C illustrates the orientations of the master grip and the slave grip and the orientation error has been decomposed into a set of Euler angles.

FIG. **3**A is a process flow diagram for the ratcheting system.

FIG. **3**B is a block diagram of a control system including the modules used to implement the ratcheting system.

FIG. **4**A is a process flow diagram for one aspect of the ratchet alignment process of FIG. **3**A.

FIG. **4**B is a block diagram of a control system including the modules used to implement the ratchet alignment process.

FIG. **5**A is a process flow diagram for another aspect of the ratchet alignment process of FIG. **3**A.

FIG. **5**B is an illustration of an angular velocity penalty profile.

FIG. **6**A is a process flow diagram for another aspect of the ratcheting system.

FIG. **6**B is a block diagram of control system including the modules used to implement the ratcheting system of FIG. **6**A.

FIG. **7** is an illustration of corner-case handling of roll-joint limits for the slave surgical instrument tip.

In the drawings, the first digit of a figure number indicates the figure in which the element with that figure number first appeared.

DETAILED DESCRIPTION

Aspects of this invention replace the powered master tool manipulator, such as that used in the da Vinci® Surgical Robot System manufactured by Intuitive Surgical, Inc. of Sunnyvale, California with an unpowered master tool manipulator that includes at least one master grip. In minimally invasive surgical system **100**, a surgeon, at a console **114**, grasps a master grip (not shown) between the thumb and forefinger so that targeting and grasping still involves intuitive pointing and pinching motions. The motion of the master grip is used by control system **150**, as described more completely below, to move an end-effector of slave surgical instrument **112**.

Unlike the conventional system that required the surgeon to wait until the alignment of the master grip and the slave surgical instrument end-effector, in a common frame of reference, were positioned so that following could be entered, a ratcheting system **130**, within a teleoperation servo control system **160** of control system **150**, is activated when the surgeon starts to move the master grip. Irrespective of the alignment between the master grip and the end-effector of slave surgical instrument **112** in the common frame of reference, teleoperation servo control system **160** enters following between the master grip and the surgical instrument end-effector, sometimes called a slave surgical instrument tip, and activates ratcheting system **130**.

Ratcheting system **130** seamlessly and continuously improves the alignment of the master grip with respect to the slave surgical instrument tip, in the common frame of reference, as the master grip is moved. Ratcheting system **130** ratchets the movement of the slave surgical instrument tip to continuously and seamlessly reduce any alignment error, in the common frame of reference, between the slave surgical instrument tip and the master grip. Ratcheting system **130** achieves the alignment without autonomous motion of either the master grip, or the slave surgical instrument tip.

Ratcheting system **130** results in intuitive alignment between the master grip and the slave surgical instrument tip as viewed by the surgeon. Also, ratcheting system **130** provides a direct association between what the surgeon is doing, manipulating the master grip, and what the surgeon is seeing at console **114**, movement of the slave surgical instrument tip in the display. This is achieved without the delays associated with the conventional powered alignments before following could be entered. Also, ratcheting system **130** eliminates the need for the powered master grip and permits use of lower cost readily available components as the master grip.

Console **114** (FIGS. **1** and **2**A) includes a master display, which displays at least a stereoscopic image **210** (FIG. **2**A) of a surgical site **103** of patient **111**. Stereoscopic image **210** typically includes an image **203** of surgical site **103**, an image **212** of a part of surgical instrument **112**, and an image of a tip **212**T of slave surgical instrument **112**. Console **114** also includes one or more foot pedals (Not shown).

Console **114** (FIG. **1**) is connected to a control system **150** that is turn is connected to a cart **110**, which supports a plurality of robotic arms that includes robotic arm **113**. Slave surgical instrument **112** is held and positioned by robotic arm **113**. While it is not shown in FIG. **1**, an endoscope, held by another of the robotic arms, is typically used to provide image **210**.

The surgeon sits comfortably and looks into the master display on console **114** throughout surgery. The surgeon performs a medical procedure by manipulating at least master grip **230** (FIG. **2**A). In response to master alignment information **132** from master grip **230**, teleoperation servo control system **160** in control system **150** (FIG. **1**) causes corresponding robotic arm **113** to position slave surgical instrument **112** using a slave command **135**. Typically, console **114** includes at least two master grips and each master grip controls a different robotic arm and attached surgical instrument. Herein a single master grip **230** is considered. In view of this description, ratcheting system **130** can be implemented for any desired number of master grips.

The master display is positioned on console **114** (FIG. **1**) near the surgeon's hands so that image **210** (FIG. **2**A), which is seen in the master display, is oriented so that the surgeon feels that she or he is actually looking directly down onto surgical site **103**. Image **212** of tool **112** appears to be located substantially where the surgeon's hands are located and oriented substantially as the surgeon would expect tool **112** to be based on the position of her/his hand. However, the surgeon cannot see the position or orientation of master grip **230** while viewing image **210**.

The real-time image from the endoscope is projected into perspective image **210** such that the surgeon can manipulate a surgical instrument end-effector of tool **112**, through its associated master grip **230**, as if viewing the workspace in substantially true presence. By true presence, it is meant that the presentation of an image is a true perspective image simulating the viewpoint of an operator that is physically manipulating the surgical instrument. Thus, control system **150** transforms the coordinates of surgical instrument **112** to a perceived position so that the perspective image is the image that the surgeon would see if the endoscope were looking directly at surgical tool **112** from the surgeon's eye-level during an open cavity procedure.

Control system **150** performs various functions in system **100**. Control system **150** receives the images from an endoscope and generates the stereoscopic image that the surgeon sees. In a conventional manner, control system **150** maps the slave alignment with respect to tip of the endoscope and maps the master alignment with respect to an aspect of the surgeon into the common frame of reference, sometimes called common reference frame, which is used by ratcheting system **130**. See for example, U.S. Pat. No. 6,424,885, entitled "Camera Referenced Control in a Minimally invasive Surgical Apparatus," of Niemeyer et al. issued on Jul. 23, 2002, which is incorporated herein by reference in its entirety.

Control system **150** uses teleoperation servo control system **160** to translate and to transfer the mechanical motion of master grip **230** to an associated robotic arm **113** through control commands **135** so that the surgeon can effectively manipulate slave surgical instrument **112**. The functions performed by teleoperation servo control system **160** are equivalent to the conventional functions when considered in conjunction with ratcheting system **130** that is also included in control system **150**.

The number of surgical tools used at one time and consequently, the number of robotic arms being used in system **100** generally depends on the medical procedure to be performed and the space constraints within the operating room, among other factors. If it is necessary to change one or more of the tools being used during a procedure, an assistant may remove the tool no longer being used from its robot arm, and replace the tool with another tool from a tray in the operating room.

Although described as a control system **150**, it is to be appreciated that control system **150** may be implemented in practice by any combination of hardware, software that is executed on a processor, and firmware. Also, its functions, as described herein, may be performed by one unit, or divided up among different components, each of which may be implemented in turn by any combination of hardware, software that is executed on a processor, and firmware. When divided up among different components, the components may be centralized in one location or distributed across system **100** for distributed processing purposes.

When there are only two master grips in system **100**, and when the surgeon wants to control movement of a slave surgical instrument different from the two slave surgical instruments coupled to the two master grips, the surgeon may lock one or both of the two slave surgical instruments in place. The surgeon then associates one or both of the master grips with other slave surgical instruments held by other of the robotic arms and ratcheting system **130** becomes active with respect to those instruments.

Master grip **230** provides an alignment that is mapped into the common frame of reference, but is not powered, or at least does not include a powered wrist. However, the features of master grip **230**, as described more completely below, can be used with a master grip that includes a powered wrist. As used herein, a powered wrist means a wrist that includes at least one motor to control the positioning of the wrist. The motor can be used to compensate for gravity and friction and to provide range of motion force-feedback, but any powered alignment capability is turned-off.

Master grip **230** includes two levers **231**, **232**, which the surgeon typically grasps between the thumb and forefinger. As the surgeon moves master grip **230**, in one aspect, master grip alignment information **132** is provided to ratcheting system **130** in the common reference frame (See FIG. **2**B for example). In this aspect, slave surgical instrument tip **212**T has a slave alignment and ratcheting system **130** also receives this slave alignment mapped into the common reference frame. The two alignments used by ratcheting system **130** are in a common reference frame.

Thus, in one aspect of method **300** (FIG. **3**A) is performed by ratcheting system **130**. In this aspect, ratcheting system **130** includes a ratcheting system module **370** (FIG. **3**B) that in turn includes a receive alignment module **371** and a ratchet alignment module **372**.

A receive new alignment of master and slave operation **310**, associated with receive orientation module **371**, receives the master grip alignment and slave surgical instrument tip alignment in the common frame of reference. Ratcheting system **130** waits in following check operation **320** until following is initiated. Following check operation **320** should not be interpreted as requiring continuous polling, but rather simply interpreted as nothing is done with respect to the alignments in the common frame of reference until following is initiated.

Check operation **320** is used for illustration only and should not be viewed as limiting. The particular technique used to determine whether following is initiated could be based on an interrupt, an event, a particular flag or bit changing state, etc.

Upon engagement of following between master grip **230** and slave surgical instrument tip **212**T, ratchet alignment process **330**, which is associated with ratchet alignment module **372**, generates commands that result in slave surgical instrument tip **212**T moving in the same relative way as master grip **230** is moved irrespective of any alignment error in the common frame of reference between master grip **230** and slave surgical instrument tip **212**T.

Note that for convenience, slave surgical instrument tip **212**T is used in this description, as this is what the surgeon sees moving. The movement of this image corresponds directly to the movement of the slave surgical instrument tip itself. One knowledgeable in the field understands that movement of the image is a direct result of movement of the tip itself by the robot arm in response to a command from control system **150**, as described herein.

As both master grip **230** and slave surgical instrument tip **212**T move, ratchet alignment process **330** bleeds off any alignment error in the common reference frame between master grip **230** and slave surgical instrument tip **212**T. For example, when the surgeon moves master grip **230** in a way that reduces the alignment error, ratchet alignment process **330** uses the reduced alignment error in the following between master grip **230** and slave surgical instrument tip **212**T. Conversely, when the surgeon moves master grip **230** in a way that increases the alignment error, ratchet alignment process **330** uses the current alignment error, and not the increased alignment error, in the following between master grip **230** and slave surgical instrument tip **212**T.

Thus, ratchet alignment process **330** seamlessly and continuously improves the absolute alignment of master grip **230** with respect to slave surgical instrument tip **212**T. Ratchet alignment process **330** achieves the continuous improvement in absolute alignment without causing autonomous motion of either master grip **230** or slave surgical instrument tip **212**T.

Ratcheting system **130** can ratchet an alignment error in the common reference frame that is either a position error or an orientation error. In the following examples, ratcheting of an orientation error in a common frame of reference is considered. However, the orientation error examples are illustrative only and are not intended to be limiting to the specific aspects described. In view of this disclosure, one knowledgeable in the field can apply the same principles to ratchet a position error.

In the following examples, as the surgeon moves master grip **230**, in one aspect, a master grip orientation **235** in the common frame of reference is provided to ratcheting system **130**. In this aspect, slave surgical instrument tip **212**T has a slave orientation **225** in the common frame reference, which is equivalent to the orientation of the slave surgical instrument tip itself. Ratcheting system **130** also receives this slave orientation in the common frame of reference. In this aspect, the z-axis of master grip **230** is on the roll axis and points away from the hand. The corresponding z-axis on the slave is, for example, along the centerline of the jaws and indicates where the jaws are pointing.

In one aspect, orientation **235** of master grip **230** in the common frame of reference is defined in teleoperation servo control system **160** by a master grip rotation matrix R_m, which in this example is a three-by-three matrix. Similarly, orientation **225** of slave surgical instrument tip **212**T in the common frame of reference is defined in teleoperation servo control system **160** by a slave surgical instrument tip rotation matrix R_s, which in this example also is a three-by-three matrix. Master grip rotation matrix R_m and slave surgical instrument tip rotation matrix R_s are orthonormal rotation matrices.

With these matrix representations of orientations **235** and **225**, the orientation error in the common frame of reference is a relative rotation matrix R_Δ. Relative rotation matrix R_Δ is defined as:

$$R_\Delta = R_S^T * R_m \tag{1}$$

where matrix R_s^T is the transpose of slave surgical instrument tip rotation matrix R_s. It follows from the definitions of matrix R_s^T and matrix R_m, taken with definition (1) that relative rotation matrix R_Δ is a three-by-three matrix:

$$R_\Delta = \begin{pmatrix} R_{\Delta 11} & R_{\Delta 12} & R_{\Delta 13} \\ R_{\Delta 21} & R_{\Delta 22} & R_{\Delta 23} \\ R_{\Delta 31} & R_{\Delta 32} & R_{\Delta 33} \end{pmatrix}$$

When orientation **235** of master grip **230** and orientation **225** of slave surgical instrument tip **212**T are aligned in the common frame of reference, relative rotation matrix R_Δ is an identity matrix, i.e., diagonal elements $R_{\Delta 11}$, $R_{\Delta 22}$, $R_{\Delta 33}$ have a value of one and all other elements have a value of zero.

With these definitions of master grip rotation matrix R_m, slave surgical instrument tip rotation matrix R_s, and relative rotation matrix R_Δ, subsequent master grip orientations are mapped to corresponding slave orientation commands, in the common frame of reference, via:

$$R_S = R_m * R_\Delta^T \quad (2)$$

where matrix R_Δ^T is the transpose of relative rotation matrix R_Δ.

As described above, with a current relative rotation matrix $R_{\Delta\text{-}Current}$ and a new relative rotation matrix $R_{\Delta\text{-}New}$, a decision must be made on which of the two relative rotation matrices to use in the mapping to the corresponding slave orientation command. New relative rotation matrix $R_{\Delta\text{-}New}$ is used when

$$R_{\Delta-New} < R_{\Delta-Current}$$

However, it has been recognized that a scalar quantity can be used to determine which relative rotation matrix to use. Thus, a technique for comparing multi-dimension matrices is not needed to determine when new relative rotation matrix $R_{\Delta\text{-}New}$ is less than current relative rotation matrix $R_{\Delta\text{-}Current}$.

As illustrate in FIG. **2**B, the orientation error between orientation **235** of master grip **230** and orientation **225** of slave surgical instrument tip **212**T, in the common frame of reference, is represented by a scalar rotation angle error θ_e. Rotation angle error θ_e is the angle through which slave surgical instrument tip orientation **225** must be rotated to coincide with master grip orientation **235** and so represents the misalignment.

Rotation angle error θ_e is defined as:

$$\theta_e = \cos^{-1}[0.5 * (R_{\Delta 11} + R_{\Delta 22} + R_{\Delta 33} - 1)] \quad (3)$$

Recall, as described above, when master grip orientation **235** and slave surgical instrument tip orientation **225** are aligned, diagonal elements $R_{\Delta 11}$, $R_{\Delta 22}$, $R_{\Delta 33}$ have a value of one. Thus, when the two orientations are aligned, rotation angle error θ_e is zero.

In this aspect, ratchet alignment process **330** for ratcheting system **130** is implemented as ratchet orientation process **330**A (FIG. **4**A) in association with a ratcheting system module **470**. Ratcheting system module **470** includes a receive orientation module **471** and a ratchet orientation module **472** (FIG. **4**B).

Upon entering following, generate new orientation error process **410**, which is associated with orientation error generation module **481**, accesses master grip rotation matrix R_m and slave surgical instrument tip rotation matrix R_s.

Next, process **410** uses master grip rotation matrix R_m and slave surgical instrument tip rotation matrix R_s to generate a new relative rotation matrix $R_{\Delta\text{-}New}$ based on definition (1) above. Here, slave surgical instrument tip rotation matrix R_s is the current orientation of slave surgical instrument tip **212**T and is stored for example, in slave orientation element **131** in memory **404** (FIG. **4**B), while master grip rotation matrix R_m is a new orientation of master grip **230**. The diagonal elements of new relative rotation matrix $R_{\Delta\text{-}New}$ are used in definition (3) above to generate a new rotation angle error $\theta_{e\text{-}New}$. After generation of new rotation angle error $\theta_{e\text{-}New}$, process **410** transfers to orientation error reduced check operation **420** that is associated with orientation error comparator module **482** (FIG. **4**B).

Orientation error reduced check operation **420** determines whether new rotation angle error $\theta_{e\text{-}New}$ is less than current rotation angle error $\theta_{e\text{-}Current}$, e.g., check operation **420** is implemented as a comparator. If new rotation angle error $\theta_{e\text{-}New}$ is equal to or greater than current rotation angle error $\theta_{e\text{-}Current}$, check operation **420** passes to set orientation operation **440**. Conversely, if new rotation angle error $\theta_{e\text{-}New}$ is less than current rotation angle error $\theta_{e\text{-}Current}$, check operation passes processing to set orientation operation **430**.

The use of two set orientation operations **430**, **440** is for ease of illustration only and is not intended to be limiting. A single set orientation operation could be used for the instances in which rotation angle error θ_e is reduced, for example. Also, note that in the first pass through ratchet orientation process **330**A, check operation **420** may simply pass processing to set orientation error operation **430**. Alternatively, in initialization, current rotation angle error θ_e-Current can be set to a large value so that new rotation angle error $\theta_{e\text{-}New}$ is always less than current rotation angle error $\theta_{e\text{-}Current}$ in the first pass. The particular aspect used to handle the first pass through process **330**A is not critical so long as no autonomous motion is introduced.

Set orientation error operation **440** is effectively a no-op, because current rotation angle error $\theta_{e\text{-}Current}$ and current relative rotation matrix $R_{\Delta\text{-}Current}$ are maintained as the current rotation angle error and the current relative rotation matrix, respectively. Thus, operation **440** can be removed and processing simply transfers from check operation **420** directly to generate new slave orientation **450**.

Set orientation error operation **430**, which is associated with comparator module **482**, sets current rotation angle error $\theta_{e\text{-}Current}$ to new rotation angle error $\theta_{e\text{-}New}$. Operation **430** also sets current relative rotation matrix $R_{\Delta\text{-}Current}$ to new relative rotation matrix $R_{\Delta\text{-}New}$ and then transfers to generate new slave orientation operation **450**.

Generate new slave orientation **450**, which is associated with slave generation orientation module **483**, first generates a transpose matrix R_Δ^T of current relative rotation matrix $R_{\Delta\text{-}Current}$. Next, a new slave orientation matrix R_s is obtained by combining transpose matrix R_Δ^T and master grip rotation matrix R_m according to definition (2), above. Thus, operation **450** transforms the master orientation into a slave orientation.

Generate new slave orientation **450** transfers processing to send slave orientation command operation **460**, which is associated with slave command generation module **484**. Using new slave orientation R_s, operation **460** sends a command, via slave input/output (I/O) module **403**, which results in slave surgical instrument tip **212**T being moved. The movement depends upon which relative rotation matrix R_Δ was used in the current iteration of process **330**A.

In process **330**A, When the surgeon moves master grip **230** in a way that reduces the alignment error in the common reference frame between master grip **230** and slave surgical instrument tip **212**T, e.g., reduces rotation angle error θ_e, ratchet alignment process **330**A (FIG. **4**A) uses the reduced alignment error in the following between master grip **230** and slave surgical instrument tip **212**T. Conversely, when the surgeon moves master grip **230** in a way that increases the alignment error in the common reference frame between master grip **230** and slave surgical instrument tip **212**T, ratchet alignment process **330**A uses the current alignment error, and not the increased alignment error, in the following between master grip **230** and slave surgical instrument tip **212**T.

Thus, ratchet alignment process **330**A seamlessly and continuously improves the absolute alignment of master grip **230** with respect to slave surgical instrument tip **212**T. Ratchet alignment process **330**A achieves the continuous improvement in absolute alignment without autonomous motion of either master grip **230** or slave surgical instrument tip **212**T.

If master grip **230** and the slave surgical instrument tip were rigidly connected, relative rotation matrix R_Δ would be a constant. In reality, master grip **230** and the slave surgical instrument tip are not rigidly connected, but are coupled through teleoperation servo control system **160**. Whenever master grip **230** and the slave surgical instrument tip are in motion, there is always a small amount of control error. This control error can be absorbed using process **330**A and alignment obtained between master grip **230** and slave surgical instrument tip **212**T.

However, this approach is highly dependent on the stiffness of the servo control loop. Under normal conditions in a teleoperated minimally invasive surgical system with a stiff servo control loop, the incremental improvements may be too small and thus take a long time to reach satisfactory alignment. Even in such systems, ratcheting system **130** is still used, but an introduce control system error controller **560** (FIG. **5**A) introduces a subtle control error between master grip orientation **235** and slave surgical instrument tip orientation **225**, in the common frame of reference, without resulting in autonomous motion of slave surgical instrument tip.

Techniques for introducing such a subtle control error by introduce control system error controller **560** include, but are not limited to:

1. Penalizing slave angular velocity based on the amount of rotation angle error θ_e. This introduces control error by artificially slowing down motion of the slave based on rotation angle error θ_e.
2. Imposing artificial joint limits on the motion of slave surgical instrument tip rotation matrix R_s, when rotation angle error θ_e is greater than a permissible threshold. This results in control error between master and slave whenever the slave reaches an artificial joint limit. The permissible range of motion for the slave can be gradually widened to the full range of slave motion as alignment improves.
3. Low-pass filtering the sensed master grip rotation matrix R_m. This permits control error to be induced and absorb fast and/or discontinuous motions of master grip **230**. The low-pass filter cutoff may be a function of rotation angle error θ_e, such that responsiveness improves as rotation angle error θ_e decreases.
4. Low-pass filtering the commanded slave surgical instrument tip rotation matrix R_s. This introduces control error between master grip **230** and slave surgical instrument tip **212**T, which can absorb fast and/or discontinuous orientation commands of slave surgical instrument tip **212**T. The low-pass filter cutoff may be a function of rotation angle error θ_e, such that responsiveness improves as rotation angle error θ_e decreases.

FIG. **5**A illustrates another implementation of ratchet orientation process **330**B in ratcheting system **130**. Ratchet orientation process **330**B uses one of the above techniques or another equivalent technique to introduce a control system error between the orientations of the slave surgical instrument tip and the master grip, in the common frame of reference, via introduce control system error process **510**. The other processes **410**, **420**, **430**, **440**, **450**A and **460**A are similar to the corresponding process described above with respect to FIG. **4**A and so that description is not repeated.

In this example, introduce control system error operation **510** in controller **560** introduces the control system error after generation of new rotation angle error $\theta_{e\text{-}New}$ in process **410**. This location in process **330**B is illustrative only and is not intended to be limiting to this specific location in process **330**B. Upon selection of a particular technique to introduce control system error, introduce control system error operation **510** can be placed at an appropriate position within process **330**B. Also, an introduce control system error module is included within ratchet orientation module **472** (FIG. **4**B) in this example.

In one aspect, operation **510** introduces control error by artificially adjusting the commanded angular velocity of the slave surgical instrument tip based on current rotation angle error $\theta_{e\text{-}Current}$. Many different techniques can be used for penalizing the commanded angular velocity.

In one aspect of operation **510**, current rotation angle error $\theta_{e\text{-}Current}$ is used in combination with an angular velocity penalty profile to generate an angular velocity scale factor for penalizing the commanded angular velocity of the slave instrument tip. In this aspect the angular velocity scale factor varies between zero for unacceptable rotation angle errors and one for a rotation angle error of zero.

The angular velocity may be penalized using an angular velocity penalty profile which smoothly varies between zero and one as rotation angle error θ_e changes. More generally, any continuous and monotonic angular velocity penalty profile can be used so long as the profile does not introduce autonomous motion and does not produce unexpected movement of the slave tip. As used here, continuous means that the first derivative of the profile exists at any point in the profile.

In one aspect, an angular velocity penalty profile is selected based on the experience of the surgeon. In another aspect, a single angular velocity penalty profile is used for all surgeons. In still yet another aspect, the angular velocity penalty profile is surgeon specific.

One angular velocity penalty profile suitable for use is a sigmoid shape curve. FIG. **5**B depicts an angular velocity penalty profile **500** that is a sigmoid shape curve with two distinct inflection points θ_{e1} and θ_{e2}, respectively.

In this example, first inflection point θ_{e1} is placed at 30 degrees and second inflection point θ_{e2} is placed at 90 degrees. Angle θ_{e0} is the angle at which the weight, more specifically referred to as the angular velocity scale factor, is a one, while angle θ_{e3} is the angle at which the weight becomes zero and remains zero for any larger misalignments.

The misalignment angle associated with inflection point θ_{e1} is selected to represent the user tolerance to misalignment, whereas the misalignment angle associated with inflection point θ_{e2} is selected to represent a maximum usable misalignment angle so that angles larger than inflection point θ_{e2} are considered unusable alignments. Whenever rotation angle error θ_e is greater than inflection point θ_{e2}, the commanded angular velocity of the slave surgical instrument tip is scaled towards zero, which results in little or no motion of the slave surgical instrument tip. This allows relative rotation matrix R_Δ to be readily updated as the operator rotates master grip **230** towards slave surgical instrument tip **212**T.

As rotation angle error θ_e decreases towards inflection point θ_{e1}, the commanded angular velocity is gradually increased, allowing for more responsive motion of the slave surgical instrument tip while still inducing enough control error to further improve relative rotation matrix R_Δ. Once rotation angle error θ_e becomes less than inflection point θ_{e1}, slave surgical instrument tip **212**T is perceived by the surgeon to be well aligned with master grip **230**. Therefore, the angular motion of the slave surgical instrument tip **212**T is allowed to be more responsive to the motion of master grip **230**. Additional small alignment corrections continue to be made until relative rotation matrix R_Δ becomes the identity matrix and rotation angle error θ_e goes to zero.

With respect to artificial joint limits, artificial joint limits on slave motion are defined as a function of the alignment error in the common frame of reference, e.g., as a function of rotation angle error θ_e. When the alignment error is large, e.g., greater than ninety degrees, artificial joint limits are imposed on motion of slave surgical instrument tip **212**T that allow instrument tip **212**T to make small motions about the current position of instrument tip **212**T.

As master grip **230** moves towards slave surgical instrument tip **212**T, slave surgical instrument tip **212**T moves in the same relative direction until an artificial joint limit is encountered. When an artificial joint limit is encountered, slave surgical instrument tip **212**T remains fixed in position at the artificial joint limit. This allows ratcheting system **130** to aggressively reduce the alignment error as master grip **230** continues to move in the direction of slave surgical instrument tip **212**T.

In one aspect, the artificial joint limits are gradually widened as the alignment error decreases. This makes the alignment process more seamless and continuous.

If, for example, low-pass filtering of the sensed master grip rotation matrix R_m is used to introduce a control system error, master grip rotation matrix R_m changes at a lower frequency. For example, humans can make controlled motions up to around 20 Hz. The master orientation can be aggressively filtered down, e.g. to one to five Hertz, to make the orientation changes more sluggish when alignment is poor. Again, a monotonic penalty profile could be used to move between zero Hertz and twenty Hertz as a function of the current orientation error.

Conversely, if, for example, low-pass filtering of commanded slave surgical instrument tip rotation matrix R_s is used to introduce a control system error, slave surgical instrument tip rotation matrix R_s changes at a lower frequency. In view of these examples, one knowledgeable in the field can select an appropriate low-pass filter so that the ratcheting seamlessly and continuously improves the absolute alignment of master grip **230** with respect to slave surgical instrument tip **212**T. Ratchet alignment process **330**B achieves the continuous improvement in absolute alignment without autonomous motion of either master grip **230** or slave surgical instrument tip **212**T.

In another aspect, method **600** (FIG. **6**A) is performed by ratcheting system **130**. In this aspect, ratcheting system **130** includes a ratcheting system module **470**A (FIG. **6**B). Ratcheting system module **470**A includes a receive orientation module **471**A and ratchet orientation module **672**. As explained more completely below, ratchet orientation process **330**C (FIG. **6**A), which is associated with ratchet orientation module **672**, penalizes slave angular velocity based on the magnitude of rotation angle error θ_e; includes a roll joint limit controller; and determines how a surgeon has grasped master grip **230**, e.g., right side up or upside down.

Receive new orientation of master and slave operation **310**A, associated with receive orientation module **471**A, receives master grip orientation **235** and slave surgical instrument tip orientation **225**. Operation **310**A transfers to check operation **320**A.

System following check operation **320**A determines whether system following has been initiated. If system following has not been initiated, save master orientation operation **610** saves the received master orientation in old master orientation storage location **632** in memory **404**A and processing is returned from the ratcheting system. Thus, until following is initiated, the ratcheting system maintains the most recent orientation of master grip **230** in the common frame of reference.

When system following is initiated, check operation **320**A transfers to generate new orientation error matrix operation **615**, which is associated with orientation error generation module **481**A (FIG. **6**B) in ratchet orientation module **672**. Operation **610** uses master grip rotation matrix R_m and slave surgical instrument tip rotation matrix R_s to generate a new relative rotation matrix $R_{\Delta\text{-}New}$ based on definition (1) above. Here, slave surgical instrument tip rotation matrix R_s is the current orientation of slave surgical instrument tip **212**T in the common frame of reference and is stored for example, in slave orientation element **131** of memory **404**A (FIG. **6**B), while master grip rotation matrix R_m is a new orientation of master grip **230**. Upon completion, operation **615** transfers to best solution check operation **620**, which is associated with multiple orientation solution module **681** in ratchet orientation module **672**.

Best solution check operation **620** determines which of a set of multiple solutions for the orientation best matches the current orientation of master grip **230** in the common frame of reference. For example, with respect to the orientation of how the surgeon grasped master grip **230**, two possible solutions are considered, right side up and upside down (USD). Thus, in one aspect, check operation **620** is implemented in a multiple orientation solution controller **621** that includes an upside down (USD) controller.

Assuming the surgeon used her/his right hand to grasp master grip **230**, when the thumb is on lever **231** (FIG. **2**A) and the forefinger is on lever **232** so that a top of the surgeon's wrist is visible to the surgeon, this is referred to as right side up. Conversely, when the thumb is on lever **232** and the forefinger is on lever **231** so that a bottom of the surgeon's wrist is visible to the surgeon, this is referred to as upside down. Thus, the two solutions for the grasping orientation are 180° apart along the roll axis. To determine which of the two orientation solutions to use in process **330**C, the cosine of rotation angle error θ_e is determined for each of the orientations. If the cosine for the upside down orientation is larger than the cosine for the right side up orientation, the upside down orientation is set to true and otherwise is set to false.

Thus, using definition (3) above, in one aspect, check operation **620** performs the following operations:

$$\cos(\theta_e\_s) = [0.5 * (R_{\Delta 11} + R_{\Delta 22} + R_{\Delta 33} - 1)]$$

$$\cos(\theta_e\_f) = [0.5 * (-1 * R_{\Delta 11} - R_{\Delta 22} + R_{\Delta 33} - 1)]$$

The orientation in the two dimensions is upside down when $\cos(\theta_e\_f)$ is greater than $\cos(\theta_e\_s)$ and upside-down orientation flag USD is set to true. Conversely, when $\cos(\theta_e\_f)$ is less than or equal to $\cos(\theta_e\_s)$, upside-down orientation flag USD is set to false.

Generate new rotation angle error θ_e operation **625** and generate current rotation angle error θ_e operation **630** are associated with orientation error generation module **481**A. Operations **625** and **630** generate a new rotation angle error $\theta_{e\text{-}New}$ and a current rotation angle error $\theta_{e\text{-}Current}$ using the state of upside down orientation flag USD, a new relative rotation matrix $R_{\Delta\text{-}New}$, and a current relative rotation matrix $R_{\Delta\text{-}Current}$.

Specifically, if upside-down orientation flag USD is set to true, operation **625** first rotates current relative rotation matrix $R_{\Delta\text{-}Current}$ in the two dimensions, and then determines current rotation angle error $\theta_{e\text{-}Current}$, as explained above. If upside-down orientation flag USD is set to false, operation **625** determines current rotation angle error $\theta_{e\text{-}Current}$ without any rotation. Current rotation angle error $\theta_{e\text{-}Current}$ is checked and (1) if the value is greater than pi, current rotation angle error $\theta_{e\text{-}Current}$ is set to pi, or (2) if the value is less than zero, current rotation angle error $\theta_{e\text{-}Current}$ is set to zero. Thus, current rotation angle error $\theta_{e\text{-}Current}$ is bounded between zero and pi.

Similarly, if upside-down orientation flag USD is set to true, operation **630** first rotates new relative rotation matrix $R_{\Delta\text{-}New}$ in the two dimensions, and then determines new rotation angle error $\theta_{e\text{-}New}$, as explained above. If upside-down orientation flag USD is set to false, operation **630** determines new rotation angle error $\theta_{e\text{-}New}$ without any rotation. New rotation angle error $\theta_{e\text{-}New}$ is checked and (1) if the value is greater than pi, new rotation angle error $\theta_{e\text{-}New}$ is set to pi, or (2) if the value is less than zero, new rotation angle error $\theta_{e\text{-}New}$ is set to zero. Thus, new rotation angle error $\theta_{e\text{-}New}$ also is bounded between zero and pi.

Following the determination of the rotation angle errors in operations **625** and **630** based on the best solution, a control system error is introduced in generate penalized angular velocity operation **510**A, which is associated with control system error introduction module **682** in ratchet orientation module **672** (FIG. **6**B).

In this aspect, operation **510**A is implemented in an introduce control system error controller **560**A, which in turn is associated with control system error introduction module **682**. Penalizing the angular velocity is an example of a one type of control system error that can be introduced by introduce control system error controller **560**A. In general, introduce control system error controller **560**A introduces a control error, such as those described above.

In this aspect of generate penalized angular velocity operation **510**A, the angular velocity is penalized by multiplying the angular velocity sensed from master grip **230** by the angular velocity scale factor from penalty curve **500** based on current rotation angle error $\theta_{e\text{-}Current}$, as described above. Following completion of operation **510**A, processing transfers to joint limit control process, which is implemented in a roll-joint limit controller **635**. Roll-joint limit controller **635** is associated with joint limit control module **683** in ratchet orientation module **672**.

Roll-joint limit controller **635** determines whether a slave surgical instrument joint has reached a limit in a given direction and whether the sensed motion from master grip **230** is trying to move the slave surgical instrument tip in that given direction. In this aspect, slave roll limit check operation **640**, in roll-joint limit controller **635**, determines whether the roll joint in the slave surgical instrument has reached a roll limit, and if the sensed motion from master grip **230** is trying to rotate slave surgical instrument tip **212**T in that roll direction.

In check operation **640**, the upper and lower roll limits are predefined. Old master grip rotation matrix $R_{m\text{-}old}$, which was stored in old master orientation location **632**, is transposed. A relative master grip rotation matrix $R_{m\Delta}$ is defined as:

$$R_{m\Delta} = R_{m-old}^T * R_m$$

Thus, relative master grip rotation matrix $R_{m\Delta}$ is a three-by-three matrix:

$$R_{m\Delta} = \begin{pmatrix} R_{m\Delta11} & R_{m\Delta12} & R_{m\Delta13} \\ R_{m\Delta21} & R_{m\Delta22} & R_{m\Delta23} \\ R_{m\Delta31} & R_{m\Delta32} & R_{m\Delta33} \end{pmatrix}$$

The master grip roll direction is defined as:

$$\text{Master\_roll\_dir} = [R_{\Delta21} - R_{\Delta12}].$$

Next, check operation **640** determines first whether the position of slave surgical instrument tip **212**T is less than the lower roll joint limit plus a tolerance and master roll direction Master_roll_dir is less than zero. If the result of this first determination is true, the lower roll joint limit has been reached and the direction of the master grip rotation is in the direction of that lower roll limit. Thus, the slave surgical instrument tip motion is constrained.

If the result of this first determination is false, check operation **640** determines second whether the position of the slave surgical instrument tip is greater than the upper roll joint limit minus a tolerance and master roll direction Master_roll_dir is greater than zero. If the result of this second determination is true, the upper roll joint limit has been reached and the direction of the master grip rotation is in the direction of that upper roll limit. Thus, the slave surgical instrument motion is constrained.

When the slave surgical instrument motion is constrained, slave roll limit check operation **640** transfers to set current rotation angle error and angular velocity operation **645**, and otherwise to rotation angle error reduced check operation **420**A. Set current rotation angle error and angular velocity operation **645** sets current rotation angle error $\theta_{e\text{-}Current}$ to a value larger than any possible physical value, and sets the commanded angular velocity to zero. Set current rotation angle error and angular velocity operation **645** transfers processing to orientation error reduced check operation **420**A.

Orientation error reduced check operation **420**A determines whether new rotation angle error $\theta_{e\text{-}New}$ is less than current rotation angle error $\theta_{e\text{-}Current}$, e.g., check operation **420** is implemented as a comparator. If new rotation angle error $\theta_{e\text{-}New}$ is equal to or greater than current rotation angle error $\theta_{e\text{-}Current}$, check operation **420**A passes to save master orientation operation **650**. Conversely, if new rotation angle error $\theta_{e\text{-}New}$ is less than current rotation angle error $\theta_{e\text{-}Current}$, check operation **420**A passes processing to set orientation error operation **430**A.

Set orientation error operation **430**A, which is associated with comparator module **482**A, sets current rotation angle error $\theta_{e\text{-}Current}$ to new rotation angle error $\theta_{e\text{-}New}$. Operation **430**A also sets current relative rotation matrix $R_{\Delta\text{-}Current}$ to new relative rotation matrix $R_{\Delta\text{-}New}$ and then transfers to save master orientation operation **650**, which saves master grip rotation matrix R_m. in element **632** (FIG. **6**B). Operation **650** transfers processing to generate new slave orientation operation **450**B (FIG. **6**A).

Generate new slave orientation **450**B, which is associated with slave generation orientation module **483**A (FIG. **6**B), first generates a transpose matrix R_{Δ}^T of current relative rotation matrix $R_{\Delta\text{-}Current}$. Next, a new slave orientation matrix R_s is obtained by combining transpose matrix R_Δ^T and master grip rotation matrix R_m according to definition (2), above.

Generate new slave orientation **450**B transfers processing to send slave orientation command operation **460**B (FIG. **6**A), which is associated with slave command generation module **484**A. Using new slave orientation R_s, operation **460** sends a command including the slave orientation and the commanded angular velocity, in the common frame of reference, via slave input/output (I/O) module **403**, which results in slave surgical instrument tip **212**T being moved as directed by that command. The movement depends upon which relative rotation matrix R_Δ was used in the current iteration of process **330**C and the commanded angular velocity.

When the surgeon moves master grip **230** in a way that reduces the alignment error between master grip **230** and slave surgical instrument tip **212**T, e.g., reduces rotation angle error θ_e, ratchet alignment process **330**C (FIG. **6**A) uses the reduced alignment error in the following between master grip **230** and slave surgical instrument tip **212**T while accounting for how the surgeon grasped master grip **230** and whether a roll joint limit was encountered. Conversely, when the surgeon moves master grip **230** in a way that increases the alignment error between master grip **230** and slave surgical instrument tip **212**T, ratchet alignment process **330**C uses the current alignment error, and not the increased alignment error, in the following between master grip **230** and slave surgical instrument tip **212**T.

Thus, ratchet alignment process **330**C seamlessly and continuously improves the absolute alignment of master grip **230** with respect to slave surgical instrument tip **212**T. Ratchet alignment process **330**C achieves the continuous improvement in absolute alignment without autonomous motion of either master grip **230** or slave surgical instrument tip **212**T.

In method **600**, roll-joint limit controller **635** was used to handle a corner-case for a slave range of motion. This corner-case is considered further with respect to FIG. **7**. FIG. **7** illustrates a technique for introducing corner-case joint limits. In this example, there is a roll joint limit at zero degrees and another roll joint limit at one hundred-eighty degrees. Thus, when master grip **230** is at zero degrees, slave surgical instrument tip is positioned as shown by slave surgical instrument tip **790**; at ninety degree, slave surgical instrument tip is positioned as shown by slave surgical instrument tip **791**; and at one hundred-eighty degrees, slave surgical instrument tip is positioned as shown by slave surgical instrument tip **792**.

If the surgeon continued to rotate master grip **230** in the counter clockwise direction back to zero degrees, slave tip **792** suddenly might move to the orientation of slave tip **790**, e.g., there would be autonomous motion. However, with corner-case joint limits on the motion of the slave surgical instrument tip such motion is inhibited. For example, when the orientation of master grip **230** comes within a predetermined tolerance of a joint limit, the commanded angular velocity of the slave surgical instrument tip is set to zero and current rotation angle error $\theta_{e\text{-}Current}$ is set to an artificially large number so that new relative rotation matrix $R_{\Delta\text{-}New}$ is used. This essentially allows the master orientation to slip relative to the orientation of the slave surgical instrument tip when the slave surgical instrument tip is at a roll limit.

With a conventional powered master, the user would receive force feedback to indicate when a slave has reached a range of motion limit. With an unpowered master, a roll-joint limit controller, in the ratcheting system, can be used to maintain continuity of slave motion as the master drives the slave in and out of a joint limit.

In the above methods, various modules and operations and/or processes associated with those modules were described. The modules may be implemented in hardware, software that is executed on a processor, firmware or any combination of hardware, software or firmware.

When the modules include one or more instructions stored on a storage medium, the described operations and/or processes are the result of retrieval and execution of the one or more instructions on at least one processor in processor module **401** to obtain the transformation described. The particular modules described are illustrative only and are not intended to be limiting. In view of the disclosure, one knowledgeable in the field can combine modules together or separate a module into one or more additional modules as may be desired. Moreover while the modules are shown grouped in a common location this also is illustrative only.

TABLE 1 is an example of software instructions written in the C-programming language that when executed on a processor perform elements **302**A, **610**, **615**, **620**, **621**, **625**, **630**, **510**A, **560**A, **635**, **640**, **645**, **420**A, **430**A and **650**.

TABLE 1

```
#define CLAMP(val,lo,hi) (MIN(MAX((val),(lo)),(hi)))
typedef FLOAT (*Matrix3x3Ptr)[3];
/*********************************************************/
static FLOAT psm_io_rotation_angle(const Matrix3x3Ptr R,
              BOOLEAN USD)
{
  float traceR;
  float costheta;
  /* Account for USD configuration by applying
  rotation of 180 degrees Z */
  if (USD)
  {
    FLOAT Rtmp[3][3];
    static const FLOAT Rroll[3][3] =
    {
      { -1, 0, 0 },
      { 0, -1, 0 },
      { 0, 0, 1 }
    };
    Matrix_multiplyMatrixf(Rtmp, /* = */ R, 3, 3,
              /* x */ Rroll, 3, 3);
    traceR = Rtmp[0][0] + Rtmp[l][1] + Rtmp[2][2];
  }
```

TABLE 1-continued

```
    else
    {
        traceR = R[0][0] + R[l][1] + R[2][2];
    }
    costheta = 0.5f * (traceR − 1.0f);
    if (costheta > 1.0)
    {
        return 0.0;
    }
    else if (costheta < −1.0)
    {
        return M_PI;
    }
    else
    {
        return (FLOAT) acos(costheta);
    }
}
/*******************************************************/
INT psm_io_constrain_master_roll
    (const Matrix3x3Ptr Rm_old, const Matrix3x3Ptr Rm)
{
    static const FLOAT tolerance = 1.0f * M_PI / 180.0;
    FLOAT* const pos = Ptr(SYS_HW_JNTPOS, 0,
                    PSM_JNT_POS_DOFS);
    float_par* lower = Ptr(PC_JI_IK_POSLOWERLIMIT, 0,
                    PSM_JNT_POS_DOFS);
    float_par* upper = Ptr(PC_JI_IK_POSUPPERLIMIT, 0,
                    PSM_JNT_POS_DOFS);
    FLOAT Rm_old_trans[3][3];
    FLOAT Rm_delta[3][3];
    FLOAT mtm_roll_dir;
    INT constrain_roll = 0;
    //Compute the error rotation as R2 w.r.t. R1.
    Matrix_transposef(Rm_old_trans, Rm_old, 3, 3);
    /* Rm_delta = Rm_old_trans' * Rm */
    Matrix_multiplyMatrixf(Rm_delta,
                    /* = */ Rm_old_trans, 3, 3, /* x */ Rm, 3, 3);
    //Define the local error vector w.r.t. R1.
    mtm_roll_dir = Scalar_fsignf(Rm_delta[l][0] −
                        Rm_delta[0][1]);
    //Check if the PSM roll joint has reached a limit and //if the MTM
    is trying to rotate in that roll //direction
    if (pos[PSM_RO] < (lower[PSM_RO] + tolerance)
        && mtm_roll_dir < 0)
    {
        constrain_roll = 1;
    }
    else if (pos[PSM_RO] > (upper[PSM_RO] − tolerance)
            && mtm_roll_dir > 0)
    {
        constrain_roll = 1;
    }
    return constrain_roll;
}
/*******************************************************/
// Parameters used by sigmoid-shaped velocity weight
// function
#define SIGMOID_ALPHA  5.0f
#define SIGMOID_BETA    (0.3f*M_PI)
/**************************************************
* psm_io_ratchet_offset( ) *
* Conditionally updates the orientation offset *
* to improve the alignment between MTM and PSM *
**************************************************/
void psm_io_ratchet_offset(const Matrix3x3Ptr Rm,
                Matrix3x3Ptr Roff, FLOAT *rotvel)
{
    static FLOAT Rm_old[3][3];
    FLOAT Rs_trans[3][3];
    FLOAT Roff_new[3][3];
    FLOAT cur_offset;
    FLOAT new_offset;
    FLOAT cosangle_s, cosangle_f;
    FLOAT vel_weight;
    BOOLEAN USD = FALSE;
    Matrix3x3Ptr Rs = (Matrix3x3Ptr) Ptr(SYS_IO_OUT_CART,
                        3, 9);
    if (Kernel_RobustBooleanIsFALSE
                (PSM_IO_FOLLOW_DATA_VALID))
```

TABLE 1-continued

```
{
  Matrix_copyf(Rm_old, Rm, 3, 3);
  return;
}
/* Update the relative rotation offset Roff between master and slave,
if the current offset is smaller */
Matrix_transposef(Rs_trans, Rs, 3, 3);
// Compute the offset between the new MTM and new PSM
/* Roff_new = Rs' * Rm */
Matrix_multiplyMatrixf(Roff_new, /* = */ Rs_trans,
          3, 3, /* x */ Rm, 3, 3);
// Determine whether to use the straight or
// upside-down solution
cosangle_s = (FLOAT)(0.5 * (Roff_new[0][0] +
      Roff_new[l][1] + Roff_new[2][2] - 1));
cosangle_f = (FLOAT)(0.5 * (-1 * Roff_new[0][0] -
      Roff_new[l][1] + Roff_new[2][2] - 1));
USD = (cosangle_f > cosangle_s) ? TRUE : FALSE;
new_offset = psm_io_rotation_angle(Roff_new, USD);
cur_offset = psm_io_rotation_angle(Roff, USD);
/* Reduce the angular velocity based on the current
 * amount of misalignment. We are using a sigmoid
 * function as the weight, since it provides a smooth
 * transition between full velocity and no velocity.
 * The curve has been tuned to falloff near 30
 * degrees and bottom out around 90 degrees */
vel_weight = 1.0f/(1.0f + exp(SIGMOID_ALPHA*
        (cur_offset-SIGMOID_BETA)));
vel_weight = CLAMP(vel_weight, 0.0f, 1.0f);
vector_scalef(rotvel, rotvel, vel_weight,
          CART_ORI_DOFS);
/* Constrain the MTM command if the PSM has hit a roll limit */
if (psm_io_constrain_master_roll(Rm_old, Rm))
{
  cur_offset = BIG_NUM;
  vector_setf(rotvel, 0, CART_ORI_DOFS);
}
/* Conditionally update the Roff offset if we've found a smaller relative rotation*/
if (new_offset < cur_offset)
{
  Matrix_copyf(Roff, Roff_new, 3, 3);
}
// Save the most recent Rm
Matrix_copyf(Rm_old, Rm, 3, 3);
}
```

In the examples of FIGS. **2**B, **4**A, **4**B, **5**A, **5**B, **6**A and **6**B, a scalar quantity was used to determine the ratcheting of the orientation in three-dimensions in a common frame of reference. However, in another aspect, the scalar quantity can be associated with a single dimension in a common frame of reference. For example, instead of using scalar rotation angle error θ_e to specify the orientation error for three dimensions, relative rotation matrix R_Δ can be decomposed in a set of Euler angles α, β, and γ (FIG. **2**C). Line N represents the intersection of the two X-Y planes. In this instance, the ratcheting of processes **330**, **330**A, **330**B, or **330**C could be performed with respect to one of the Euler angles, e.g., Euler angle β, or the alignment error may be optimized by sequentially or concurrently ratcheting each of the Euler angles, or some subset of the set of Euler angles. For example, some minimally invasive surgical instruments could be constrained or implemented such that the orientation with respect to one of the Euler angles is of interest and so the ratcheting of the orientation would be done with respect to that Euler angle.

The above description and the accompanying drawings that illustrate aspects and embodiments of the present inventions should not be taken as limiting—the claims define the protected inventions. Various mechanical, compositional, structural, electrical, and operational changes may be made without departing from the spirit and scope of this description and the claims. In some instances, well-known circuits, structures, and techniques have not been shown or described in detail to avoid obscuring the invention.

Further, this description's terminology is not intended to limit the invention. For example, spatially relative terms—such as "beneath", "below", "lower", "above", "upper", "proximal", "distal", and the like—may be used to describe one element's or feature's relationship to another element or feature as illustrated in the figures. These spatially relative terms are intended to encompass different positions and orientations of the device in use or operation in addition to the position and orientation shown in the figures. For example, if the device in the figures is turned over, elements described as "below" or "beneath" other elements or features would then be "above" or "over" the other elements or features. Thus, the exemplary term "below" can encompass both positions and orientations of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

The singular forms "a", "an", and "the" are intended to include the plural forms as well, unless the context indicates otherwise. The terms "comprises", "comprising", "includes", and the like specify the presence of stated features, steps, operations, elements, and/or components but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups.

All examples and illustrative references are non-limiting and should not be used to limit the claims to specific implementations and embodiments described herein and their equivalents. The headings are solely for formatting and should not be used to limit the subject matter in any way, because text under one heading may cross reference or apply to text under one or more headings. Finally, in view of this disclosure, particular features described in relation to one aspect or embodiment may be applied to other disclosed aspects or embodiments of the invention, even though not specifically shown in the drawings or described in the text.

While the memory is illustrated as a unified structure, this should not be interpreted as requiring that all memory is at the same physical location. All or part of the memory can be in a different physical location than a processor. Memory refers to a volatile memory, a non-volatile memory, or any combination of the two.

A processor is coupled to a memory containing instructions executed by the processor. This could be accomplished within a computer system, or alternatively via a connection to another computer via modems and analog lines, or digital interfaces and a digital carrier line.

Herein, a computer program product comprises a medium configured to store computer readable code needed for any one or any combination of methods **300**, **330**, **330**A, **330**B, **600**, **330**C or in which computer readable code for any one or any combination of methods **300**, **330**, **330**A, **330**B, **600**, **330**C is stored. Some examples of computer program products are CD-ROM discs, DVD discs, flash memory, ROM cards, floppy discs, magnetic tapes, computer hard drives, servers on a network and signals transmitted over a network representing computer readable program code. A tangible computer program product comprises a medium configured to store computer readable instructions for any one of, or any combination of methods **300**, **330**, **330**A, **330**B, **600**, **330**C or in which computer readable instructions for any one of, or any combination of methods **300**, **330**, **330**A, **330**B, **600**, **330**C is stored. Tangible computer program products are CD-ROM discs, DVD discs, flash memory, ROM cards, floppy discs, magnetic tapes, computer hard drives and other physical storage mediums.

In view of this disclosure, instructions used in any one of, or any combination of methods **300**, **330**, **330**A, **330**B, **600**, **330**C can be implemented in a wide variety of computer system configurations using an operating system and computer programming language of interest to the user.

Further, various different minimally invasive systems and methods can be implemented in view of this disclosure.

In one aspect, a minimally invasive surgical system comprises:

- a slave surgical instrument having a slave surgical instrument tip wherein the slave surgical instrument tip has an alignment in a common coordinate frame of reference;
- a master grip, coupled to the slave surgical instrument, having an alignment in the common coordinate frame of reference,
  - wherein an alignment error in the common frame of reference is a difference in alignment in the common frame of reference between the alignment of the slave surgical instrument tip and the alignment of the master grip; and
- a ratcheting system, (i) coupled to the master grip to receive the alignment of the master grip and (ii) coupled to the slave surgical instrument, to control motion of the slave by continuously reducing the alignment error, as the master grip moves, without autonomous motion of the slave surgical instrument tip and without autonomous motion of the master grip.

The ratcheting system further includes an introduce control system error controller for introducing a control system error with respect to the alignments of the slave surgical instrument tip and the master grip.

The introduce control system error controller includes, but is not limited to, any one of or any combination of:

1. Penalizing slave angular velocity based on the amount of rotation angle error;
2. Imposing artificial joint limits on the motion of slave surgical instrument tip based on a rotation angle error.
3. Low-pass filtering the sensed master grip rotation; and
4. Low-pass filtering the commanded slave surgical instrument tip rotation.

In another aspect, the ratcheting system includes a multiple orientation solution controller for determining an orientation solution closest to an orientation of the master grip. The multiple orientation controller can be included in any combination of controllers, including but not limited to the introduce control system error controller. In one aspect, the multiple orientation solution controller includes an upside down controller.

In another aspect, a method for controlling alignment of a slave surgical instrument tip in a minimally invasive surgical system with alignment of a master grip in the minimally invasive surgical system comprises:

- receiving, by a ratcheting system in the minimally invasive surgical system, an alignment of the slave surgical instrument tip in a common frame of reference and an alignment of the master grip in the common frame of reference; and
- ratcheting, by the ratcheting system, the alignment of the slave surgical instrument tip to the alignment of the master grip by continuously reducing an alignment error in the common frame of reference between the alignments, as the master grip moves, without autonomous motion of the slave surgical instrument tip and without autonomous motion of the master grip.

In one aspect, the ratcheting further comprises:

- introducing a control system error between the slave surgical instrument tip alignment and the master grip alignment.

The introducing a control system error includes, but is not limited to, any one of or any combination of:

1. Penalizing slave angular velocity based on the amount of rotation angle error;
2. Imposing artificial joint limits on the motion of slave surgical instrument tip based on a rotation angle error.
3. Low-pass filtering the sensed master grip rotation; and
4. Low-pass filtering the commanded slave surgical instrument tip rotation.

In still another aspect, the ratcheting further comprises selecting an orientation solution from a group of orientation solutions based on an orientation, in the common frame of reference, of the master grip. In one aspect, the selecting an orientation solution is in combination with the introducing a control system error. In another aspect, the selecting an orientation solution includes selecting an upside down solution.

What is claimed is:

1. A teleoperated system comprising:

- a robotic means configured to support an instrument;
- an input means configured to be manipulated by an operator to command motion of the instrument; and

a ratcheting means configured to:
- determine first rotation values describing an orientation of the input means,
- determine second rotation values describing an orientation of the instrument,
- determine, based on the first rotation values and the second rotation values, an orientation error between the orientation of the input means and the orientation of the instrument,
- generate, based on the orientation error, a motion command for the instrument to reduce the orientation error by increasing an alignment between the input means and the instrument, and
- command the robotic means to move in accordance with the motion command.

2. The teleoperated system of claim **1**, wherein to generate the motion command, the ratcheting means is configured to:
- selectively impose, based on the orientation error, an artificial joint limit on a commanded movement of the instrument.

3. The teleoperated system of claim **2**, wherein the ratcheting means is further configured to:
- determine, based on the orientation error, the artificial joint limit, wherein the artificial joint limit widens as the orientation error decreases.

4. The teleoperated system of claim **2**, wherein the artificial joint limit allows the instrument to move in a same relative direction as the input means until the artificial joint limit is reached.

5. The teleoperated system of claim **2**, wherein the ratcheting means is further configured to:
- apply force feedback to the input means when the artificial joint limit has been reached.

6. The teleoperated system of claim **1**, wherein to generate the motion command, the ratcheting means is configured to:
- low-pass filter the first rotation values or the second rotation values, wherein a cutoff frequency for the low-pass filtering is determined based on the orientation error, and
- generate, based on the low-pass filtered first rotation values or the low-pass filtered second rotation values, the motion command.

7. The teleoperated system of claim **6**, wherein the ratcheting means determines the cutoff frequency according to a monotonic penalty profile and the orientation error.

8. The teleoperated system of claim **1**, wherein to generate the motion command, the ratcheting means is configured to:
- determine, based on the orientation error, a velocity penalty, and
- penalize, based on the velocity penalty, an angular velocity of the motion command.

9. The teleoperated system of claim **8**, wherein to determine the velocity penalty, the ratcheting means is configured to:
- apply a continuous and monotonic penalty profile.

10. The teleoperated system of claim **8**, wherein to determine the velocity penalty, the ratcheting means is configured to:
- select, based on the orientation error, a scale factor, and
- scale, based on the scale factor, the angular velocity of the motion command.

11. The teleoperated system of claim **1**, wherein the ratcheting means is further configured to use the orientation error to generate the motion command only if the orientation error is smaller than a previous orientation error between the input means and the instrument.

12. The teleoperated system of claim **1**, wherein the orientation of the instrument is an orientation of a tip of the instrument.

13. The teleoperated system of claim **1**, wherein the ratcheting means is further configured to:
- determine if the input means is right-side-up or upside-down; and
- determine the orientation error further based on whether the input means is right-side-up or upside-down.

14. The teleoperated system of claim **13**, wherein when the input means is upside-down, the ratcheting means is further configured to rotate a relative rotation matrix characterizing the orientation error before determining the orientation error.

15. A method of controlling a teleoperated system comprising a robotic means configured to support an instrument, the method comprising:
- determining, by a ratcheting means of the teleoperated system, first rotation values describing an orientation of an input means configured to be manipulated by an operator to command motion of the instrument;
- determining, by the ratcheting means, second rotation values describing an orientation of the instrument;
- determining, by the ratcheting means based on the first rotation values and the second rotation values, an orientation error between the orientation of the input means and the orientation of the instrument;
- generating, by the ratcheting means and based on the orientation error, a motion command for the instrument to reduce the orientation error by increasing an alignment between the input means and the instrument; and
- commanding, by the ratcheting means, the robotic means to move in accordance with the motion command.

16. The method of claim **15**, wherein generating the motion command comprises:
- selectively imposing, based on the orientation error, an artificial joint limit on a commanded movement of the instrument.

17. The method of claim **15**, wherein generating the motion command comprises:
- low-pass filtering the first rotation values or the second rotation values, wherein a cutoff frequency for the low-pass filtering is determined based on the orientation error; and
- generating, based on the low-pass filtered first rotation values or the low-pass filtered second rotation values, the motion command.

18. The method of claim **15**, wherein generating the motion command comprises:
- determining, based on the orientation error, a velocity penalty; and
- penalizing, based on the velocity penalty, an angular velocity of the motion command.

19. A non-transitory computer-readable medium comprising computer-readable code which, when executed by a ratcheting means associated with a teleoperated system comprising a robotic means configured to support an instrument, are adapted to cause the ratcheting means to perform a method comprising:
- determining first rotation values describing an orientation of an input means configured to be manipulated by an operator to command motion of the instrument;
- determining second rotation values describing an orientation of the instrument;

determining, based on the first rotation values and the second rotation values, an orientation error between the orientation of the input means and the orientation of the instrument;

generating, based on the orientation error, a motion command for the instrument to reduce the orientation error by increasing an alignment between the input means and the instrument; and

commanding the robotic means to move in accordance with the motion command.

20. The non-transitory computer-readable medium of claim **19**, wherein generating the motion command comprises:

selectively imposing, based on the orientation error, an artificial joint limit on a commanded movement of the instrument; or

low-pass filtering the first rotation values or the second rotation values, wherein a cutoff frequency for the low-pass filtering is determined based on the orientation error, and generating, based on the low-pass filtered first rotation values or the low-pass filtered second rotation values, the motion command; or

determining, based on the orientation error, a velocity penalty, and penalizing, based on the velocity penalty, an angular velocity of the motion command.

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