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(54) **APPLICATION OF FORCE FEEDBACK ON AN INPUT DEVICE TO URGE ITS OPERATOR TO COMMAND AN ARTICULATED INSTRUMENT TO A PREFERRED POSE**

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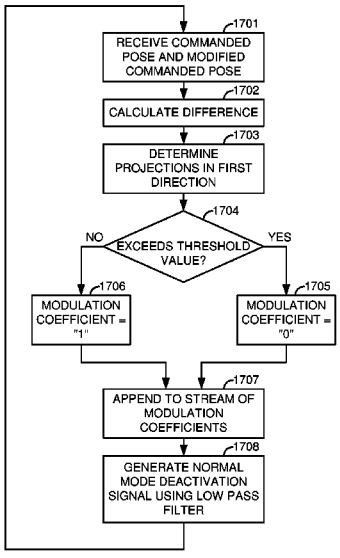
(57) **ABSTRACT**

A medical robotic system includes an entry guide with articulated instruments extending out of its distal end. A controller is configured to command manipulation an articulated instrument in response to operator manipulation of an associated input device while generating a force command to the input device that nudges the operator to command the instrument to a preferred pose. When a transition is to occur between first and second preferred poses, one is phased in while the other is phased out. Virtual barriers may be imposed to prevent the articulated instrument from being commanded to an undesirable pose.

20 Claims, 22 Drawing Sheets



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See application file for complete search history.

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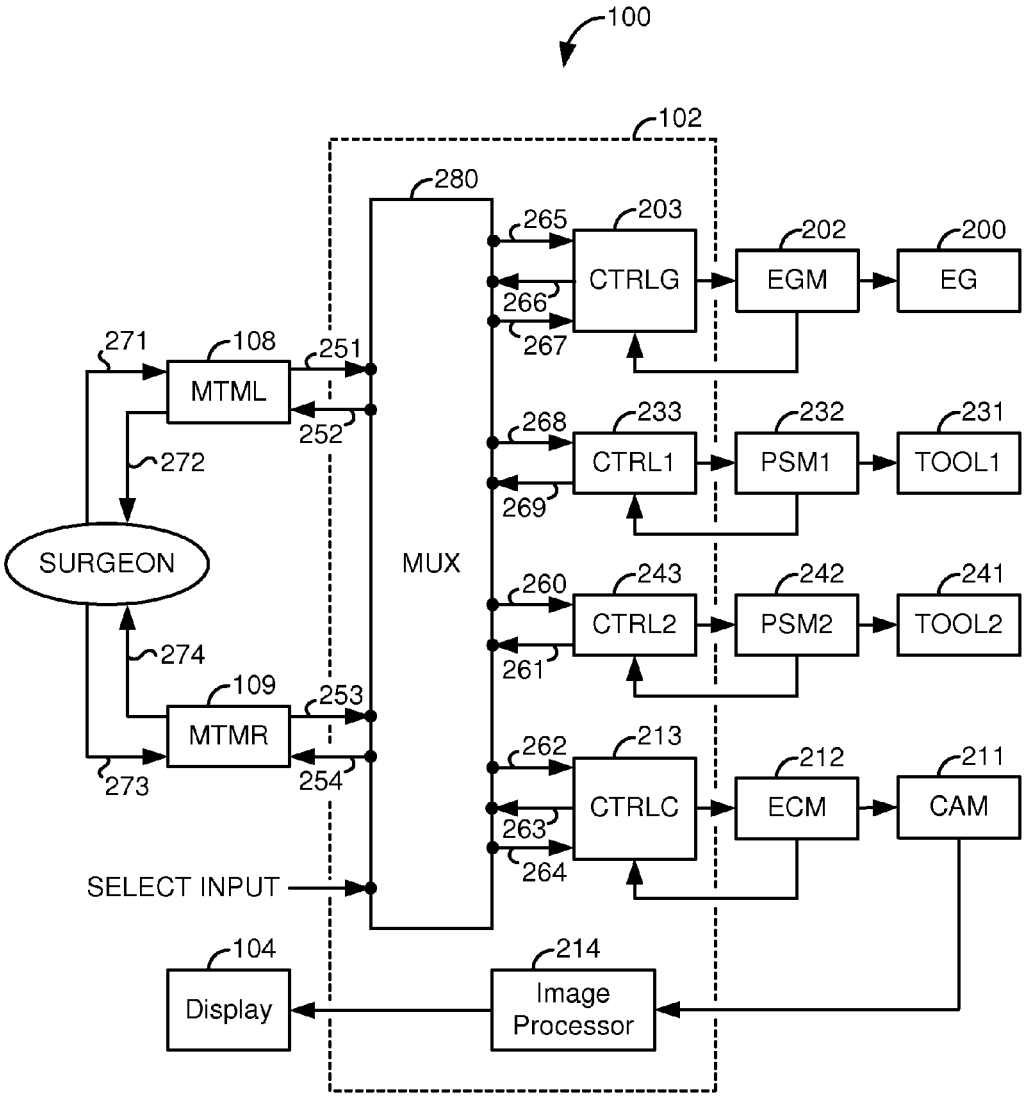
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CTRL1
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PSM1
231
TOOL1
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SURGEON
MUX
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CTRL2
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PSM2
241
TOOL2
261
274
109
MTMR
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SELECT INPUT
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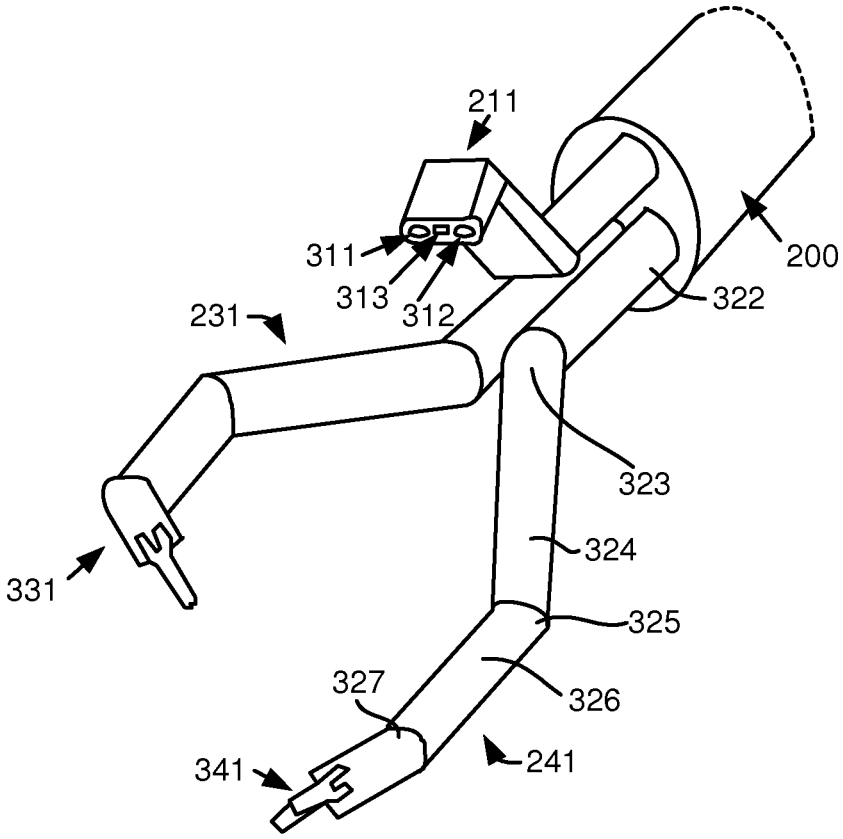
Display
214
Image Processor

fig.1



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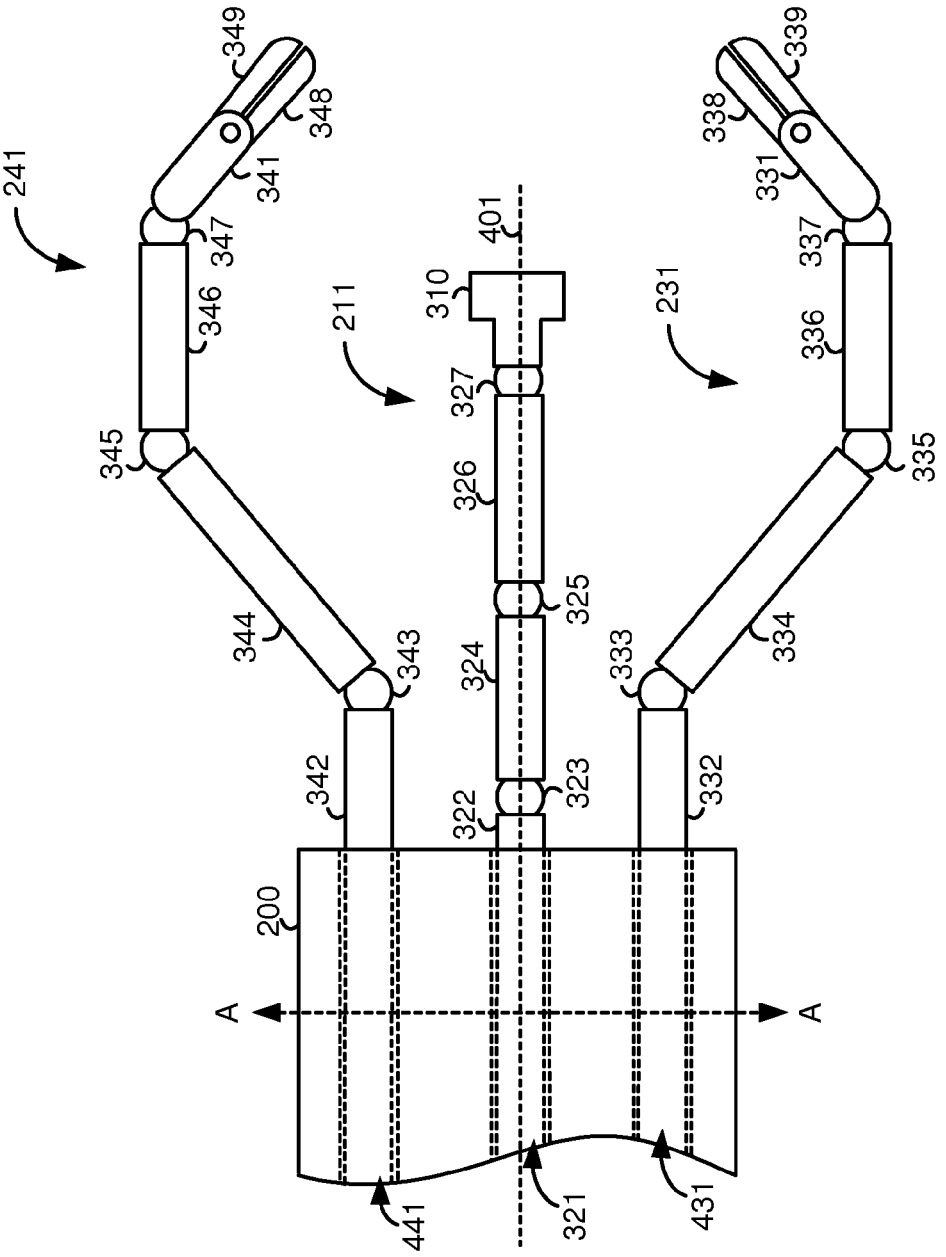
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fig.3

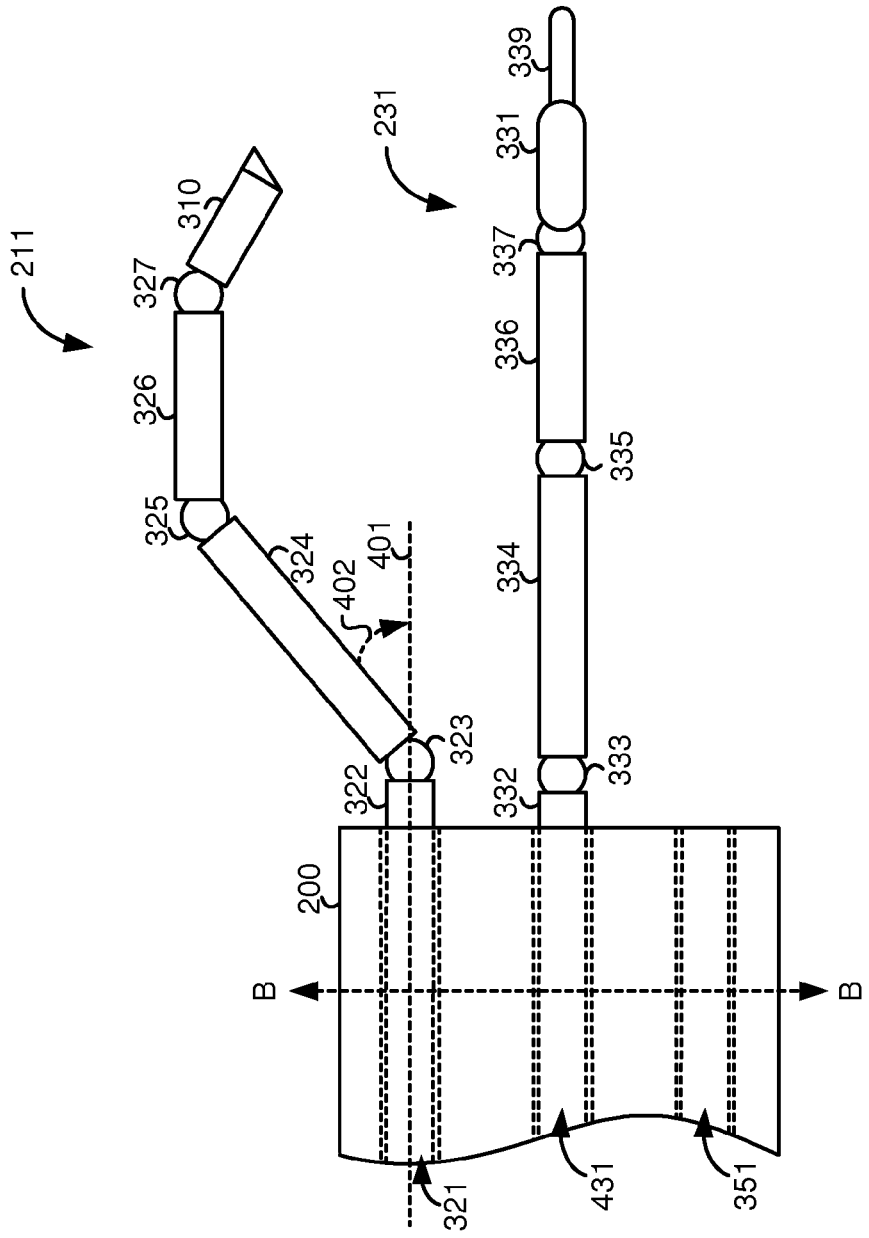
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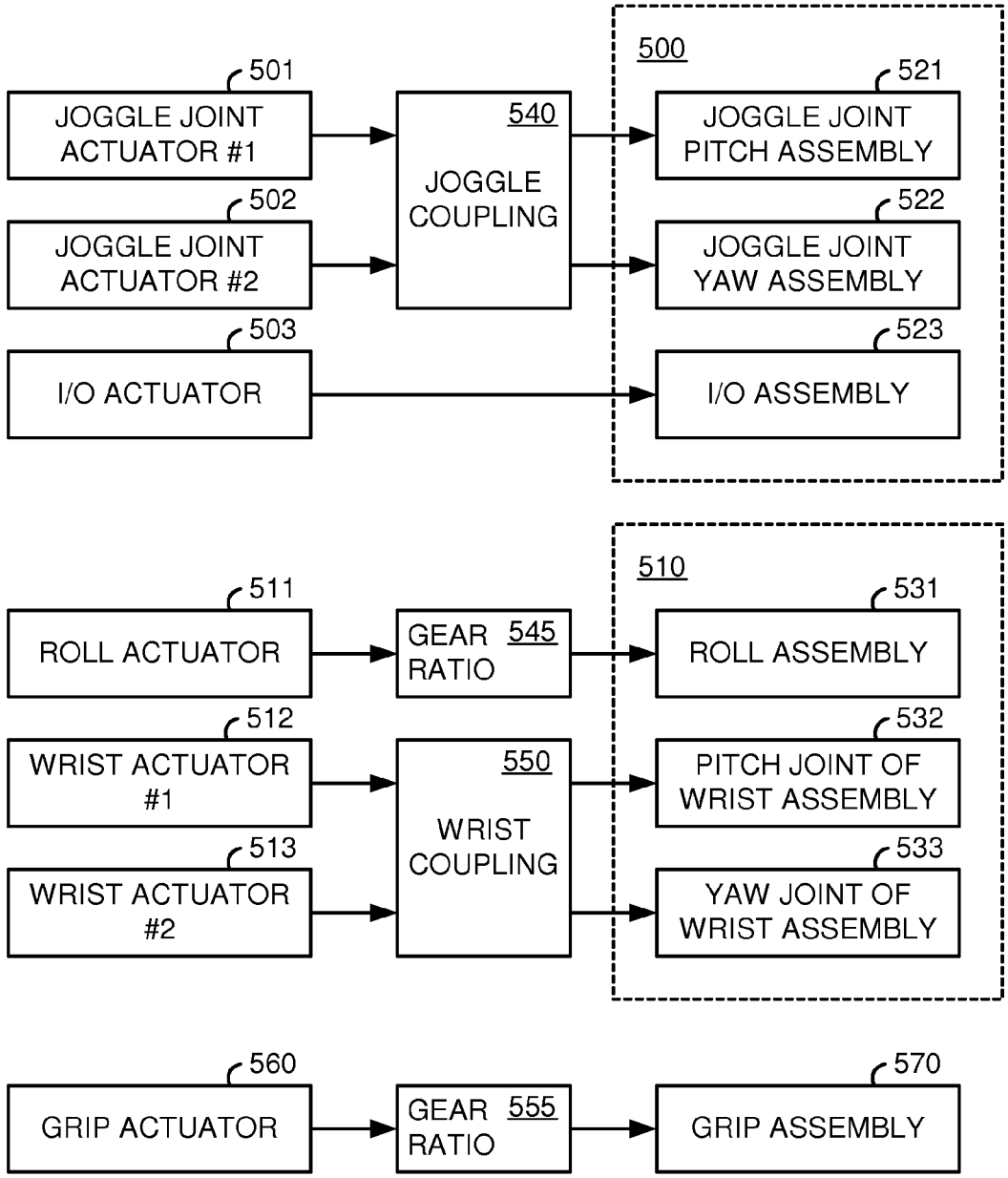
fig.4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I/O ACTUATOR
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JOGGLE COUPLING
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JOGGLE JOINT PITCH ASSEMBLY
522
JOGGLE JOINT YAW ASSEMBLY
523
I/O ASSEMBLY
510
511
ROLL ACTUATOR
512
WRIST ACTUATOR #1
513
WRIST ACTUATOR #2
GEAR RATIO 545
550
WRIST COUPLING
531
ROLL ASSEMBLY
532
PITCH JOINT OF WRIST ASSEMBLY
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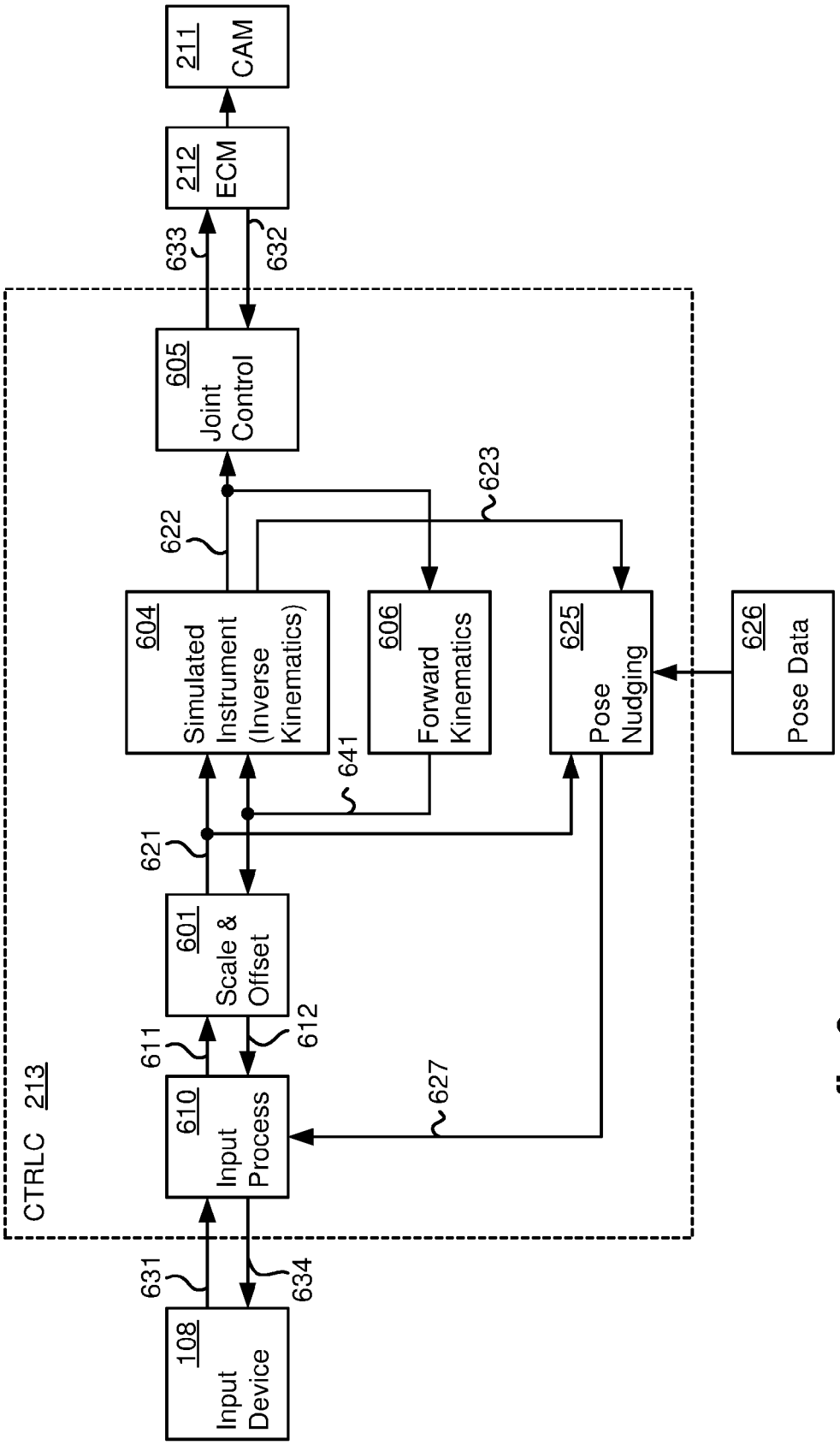
YAW JOINT OF WRIST ASSEMBLY
560
GRIP ACTUATOR
GEAR RATIO 555
570
GRIP ASSEMBLY

fig.5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622
604 Simulated Instrument (Inverse Kinematics)
606 Forward Kinematics
625 Pose Nudging
626 Pose Data
641
621
601 Scale & Offset
611
612
627
610 Input Process
CTRLC 213
631
634
108 Input Device

fig.6

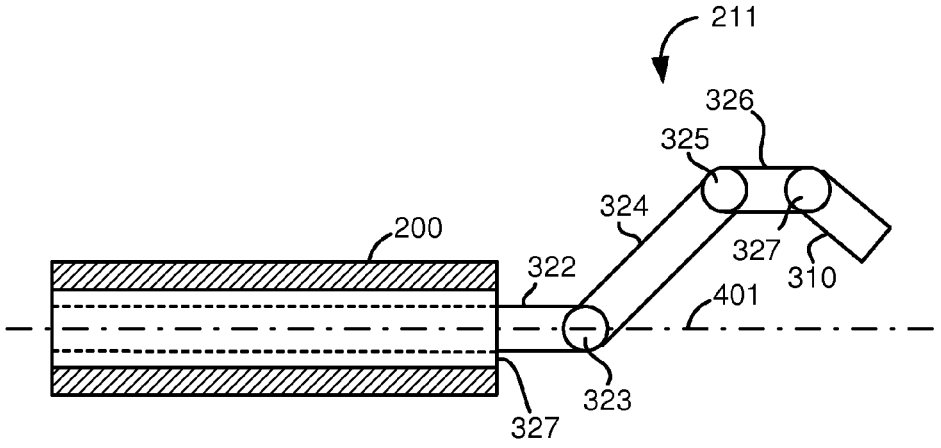
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fig.7

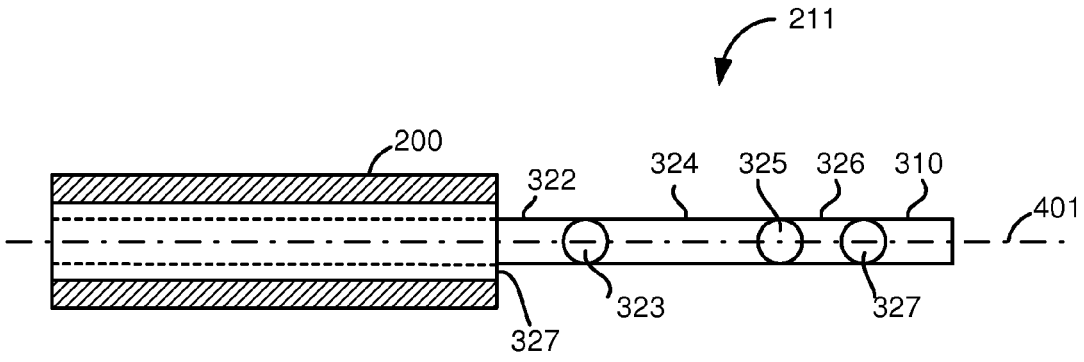
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fig.8

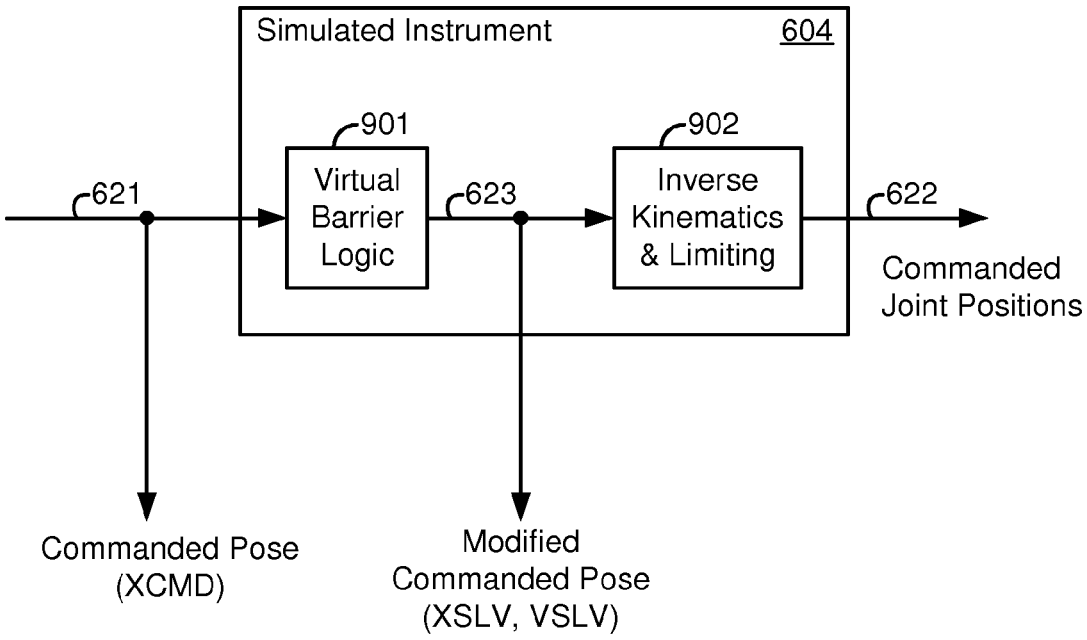

Simulated Instrument
604
901
902
621
Virtual Barrier Logic
623
Inverse Kinematics & Limiting
622
Commanded Joint Positions
Commanded Pose (XCMD)
Modified Commanded Pose (XSLV, VSLV)

fig.9

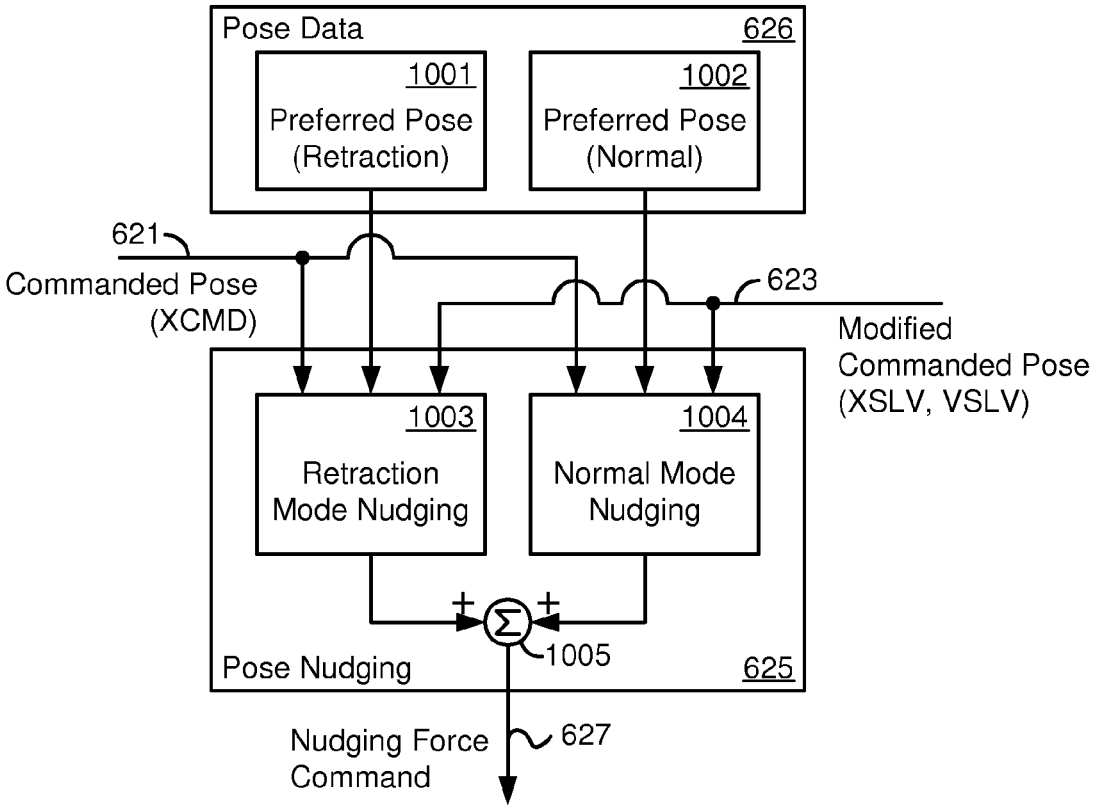

Pose Data
626
1001
Preferred Pose
(Retraction)
1002
Preferred Pose
(Normal)
621
Commanded Pose
(XCMD)
623
Modified
Commanded Pose
(XSLV, VSLV)
1003
Retraction
Mode Nudging
1004
Normal Mode
Nudging
+
+
Σ
1005
Pose Nudging
625
Nudging Force
Command
627

fig.10

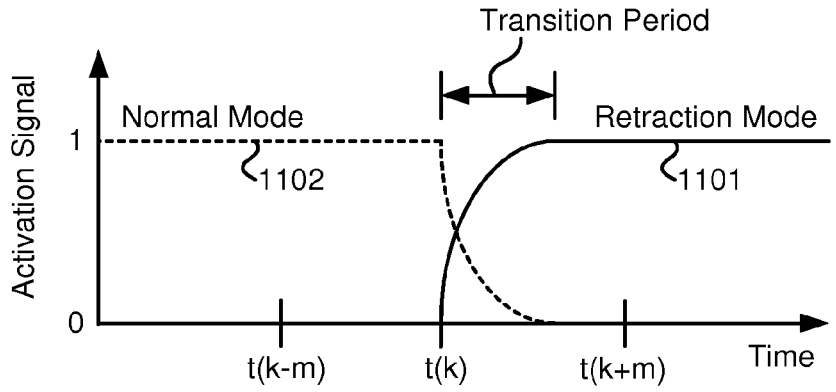
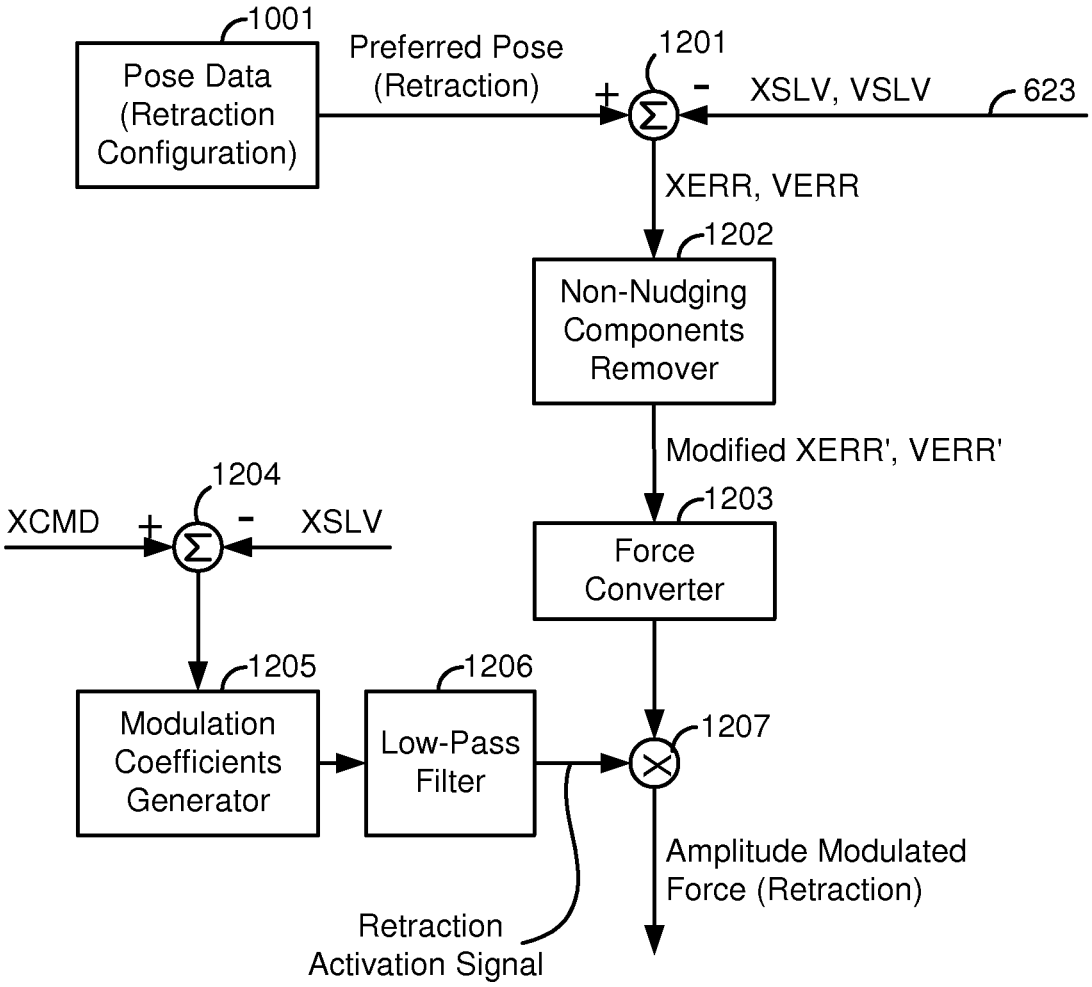

Transition Period
Activation Signal
1
0
Normal Mode
1102
Retraction Mode
1101
t(k-m)
t(k)
t(k+m)
Time

fig.11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Pose Data (Retraction Configuration)
Preferred Pose (Retraction)
1201
+
-
XSLV, VSLV
623
XERR, VERR
1202
Non-Nudging Components Remover
Modified XERR', VERR'
1204
XCMD
+
-
XSLV
1203
Force Converter
1205
Modulation Coefficients Generator
1206
Low-Pass Filter
1207
Amplitude Modulated Force (Retraction)
Retraction Activation Signal

fig.12

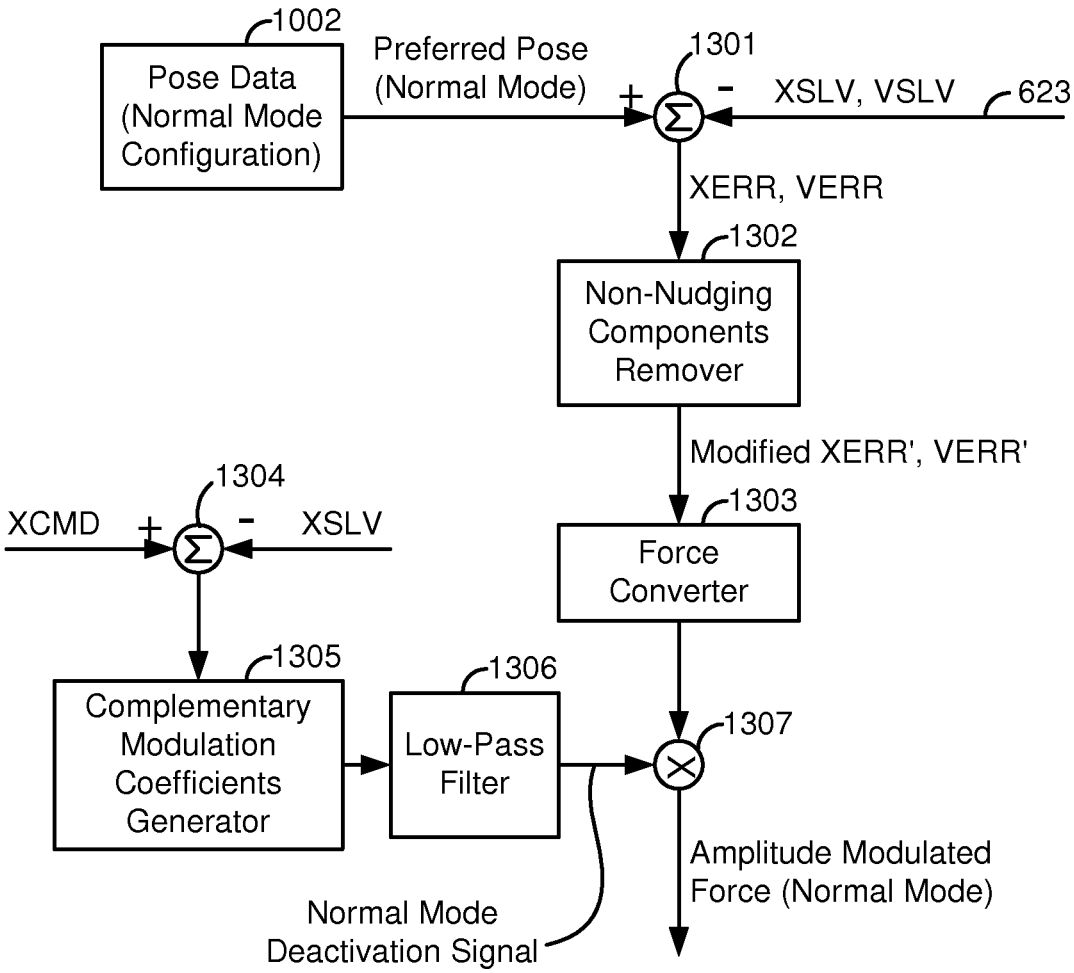
1002
Pose Data (Normal Mode Configuration)
Preferred Pose (Normal Mode)
1301
+
-
XSLV, VSLV
623
XERR, VERR
1302
Non-Nudging Components Remover
Modified XERR', VERR'
1304
XCMD
+
-
XSLV
1303
Force Converter
1305
Complementary Modulation Coefficients Generator
1306
Low-Pass Filter
1307
Amplitude Modulated Force (Normal Mode)
Normal Mode Deactivation Signal

fig.13

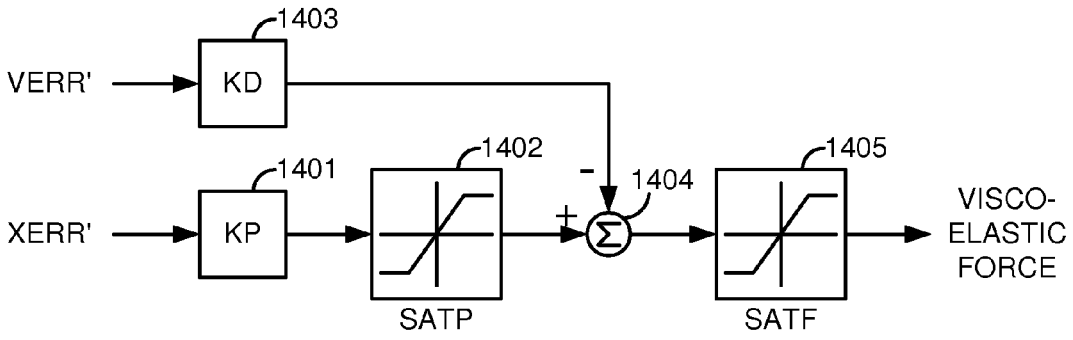
1403
VERR'
KD
1401
XERR'
KP
1402
SATP
-
+
Σ
1404
1405
SATF
VISCO-
ELASTIC
FORCE

fig.14

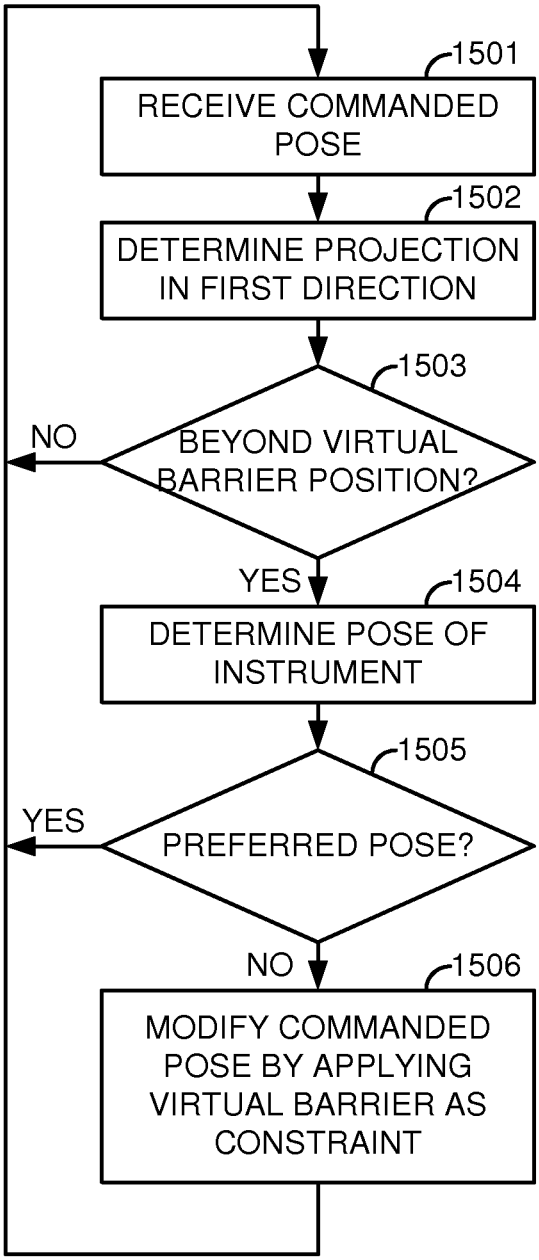
1501
RECEIVE COMMANDED POSE
1502
DETERMINE PROJECTION IN FIRST DIRECTION
1503
BEYOND VIRTUAL BARRIER POSITION?
NO
YES
1504
DETERMINE POSE OF INSTRUMENT
1505
PREFERRED POSE?
YES
NO
1506
MODIFY COMMANDED POSE BY APPLYING VIRTUAL BARRIER AS CONSTRAINT

fig.15

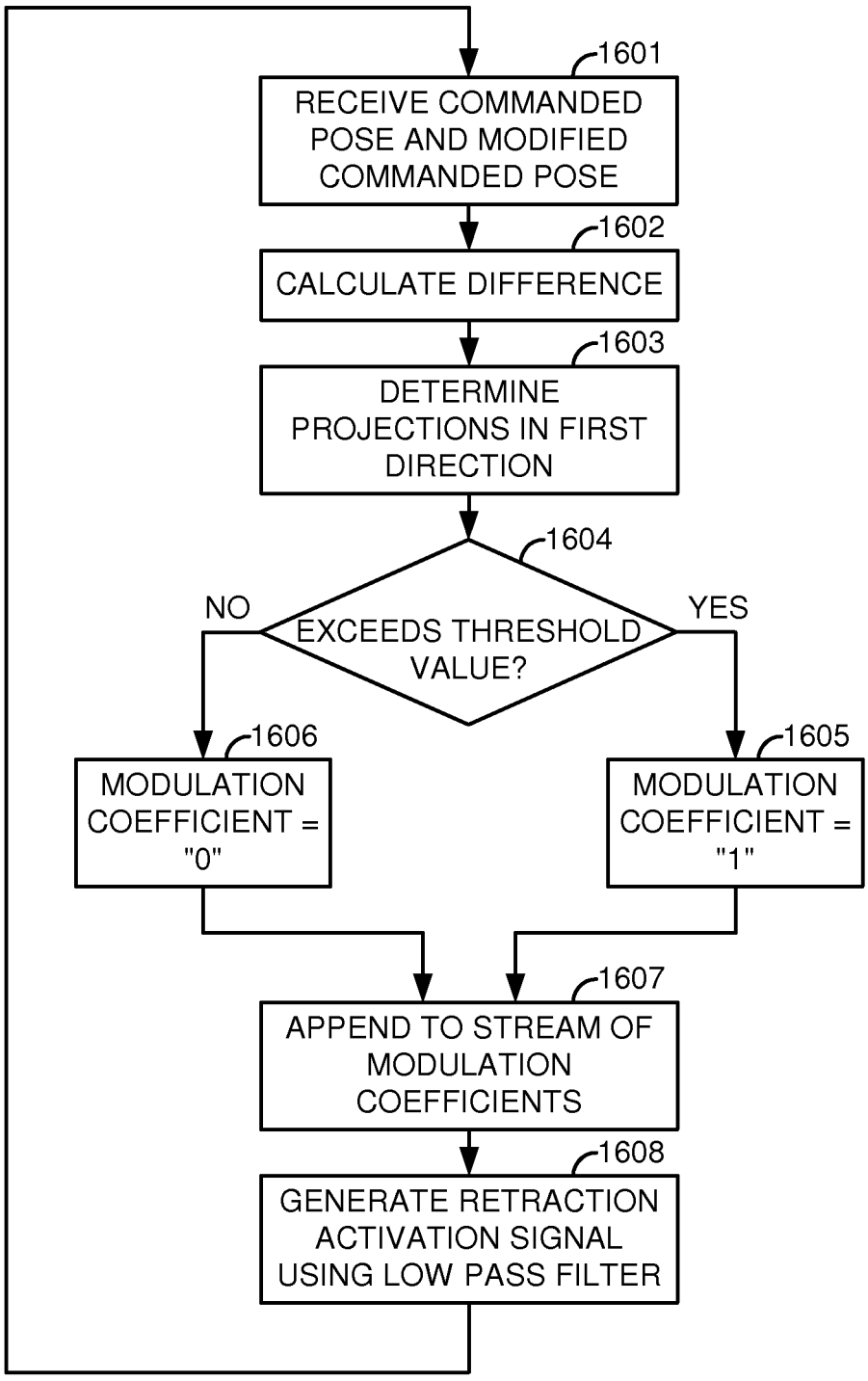
1601
RECEIVE COMMANDED POSE AND MODIFIED COMMANDED POSE
1602
CALCULATE DIFFERENCE
1603
DETERMINE PROJECTIONS IN FIRST DIRECTION
1604
EXCEEDS THRESHOLD VALUE?
NO
YES
1606
MODULATION COEFFICIENT = "0"
1605
MODULATION COEFFICIENT = "1"
1607
APPEND TO STREAM OF MODULATION COEFFICIENTS
1608
GENERATE RETRACTION ACTIVATION SIGNAL USING LOW PASS FILTER

fig.16

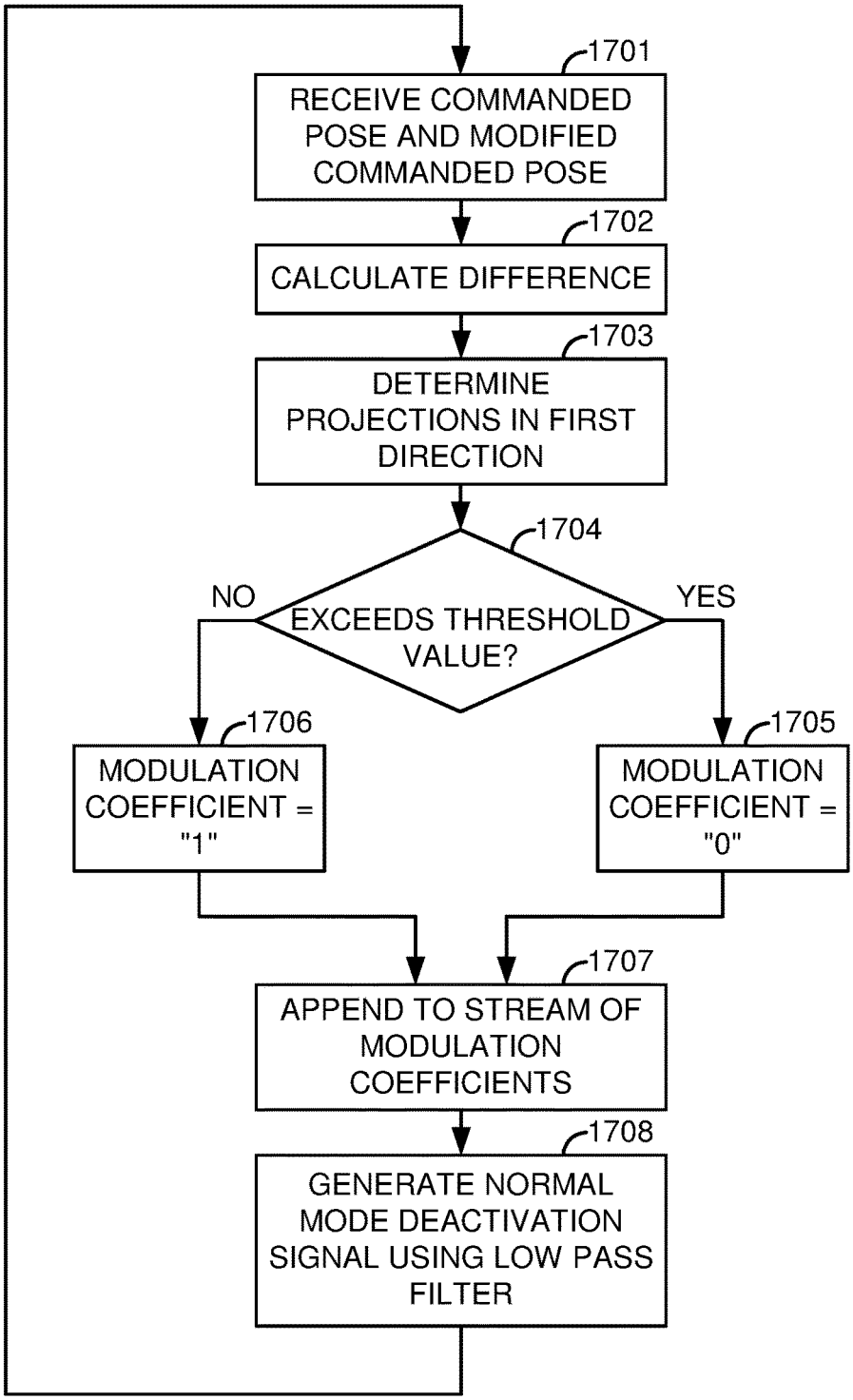
1701
RECEIVE COMMANDED POSE AND MODIFIED COMMANDED POSE
1702
CALCULATE DIFFERENCE
1703
DETERMINE PROJECTIONS IN FIRST DIRECTION
1704
EXCEEDS THRESHOLD VALUE?
NO
YES
1706
MODULATION COEFFICIENT = "1"
1705
MODULATION COEFFICIENT = "0"
1707
APPEND TO STREAM OF MODULATION COEFFICIENTS
1708
GENERATE NORMAL MODE DEACTIVATION SIGNAL USING LOW PASS FILTER

fig.17

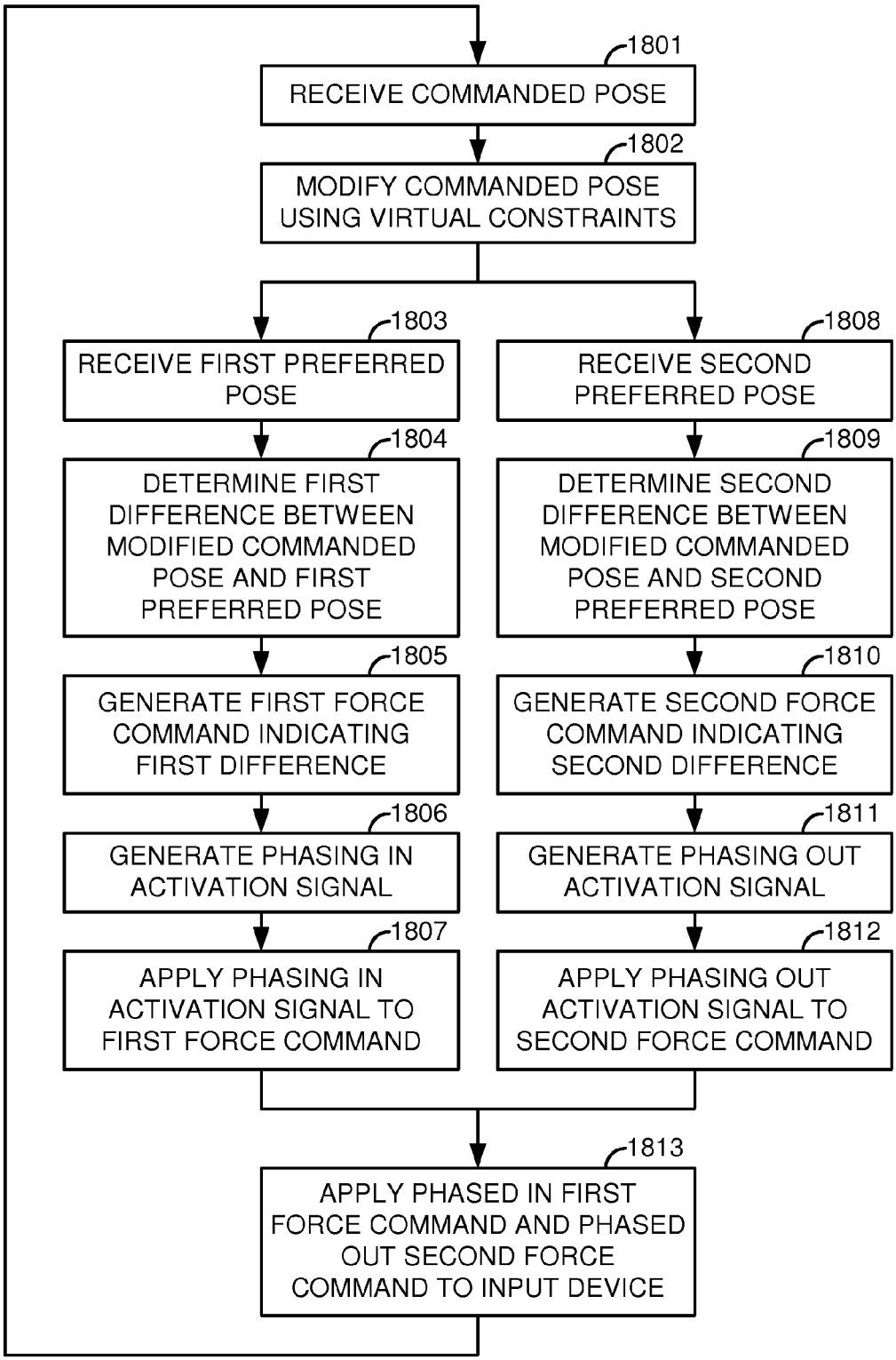
1801
RECEIVE COMMANDED POSE
1802
MODIFY COMMANDED POSE USING VIRTUAL CONSTRAINTS
1803
RECEIVE FIRST PREFERRED POSE
1804
DETERMINE FIRST DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND FIRST PREFERRED POSE
1805
GENERATE FIRST FORCE COMMAND INDICATING FIRST DIFFERENCE
1806
GENERATE PHASING IN ACTIVATION SIGNAL
1807
APPLY PHASING IN ACTIVATION SIGNAL TO FIRST FORCE COMMAND
1808
RECEIVE SECOND PREFERRED POSE
1809
DETERMINE SECOND DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND SECOND PREFERRED POSE
1810
GENERATE SECOND FORCE COMMAND INDICATING SECOND DIFFERENCE
1811
GENERATE PHASING OUT ACTIVATION SIGNAL
1812
APPLY PHASING OUT ACTIVATION SIGNAL TO SECOND FORCE COMMAND
1813
APPLY PHASED IN FIRST FORCE COMMAND AND PHASED OUT SECOND FORCE COMMAND TO INPUT DEVICE

fig.18

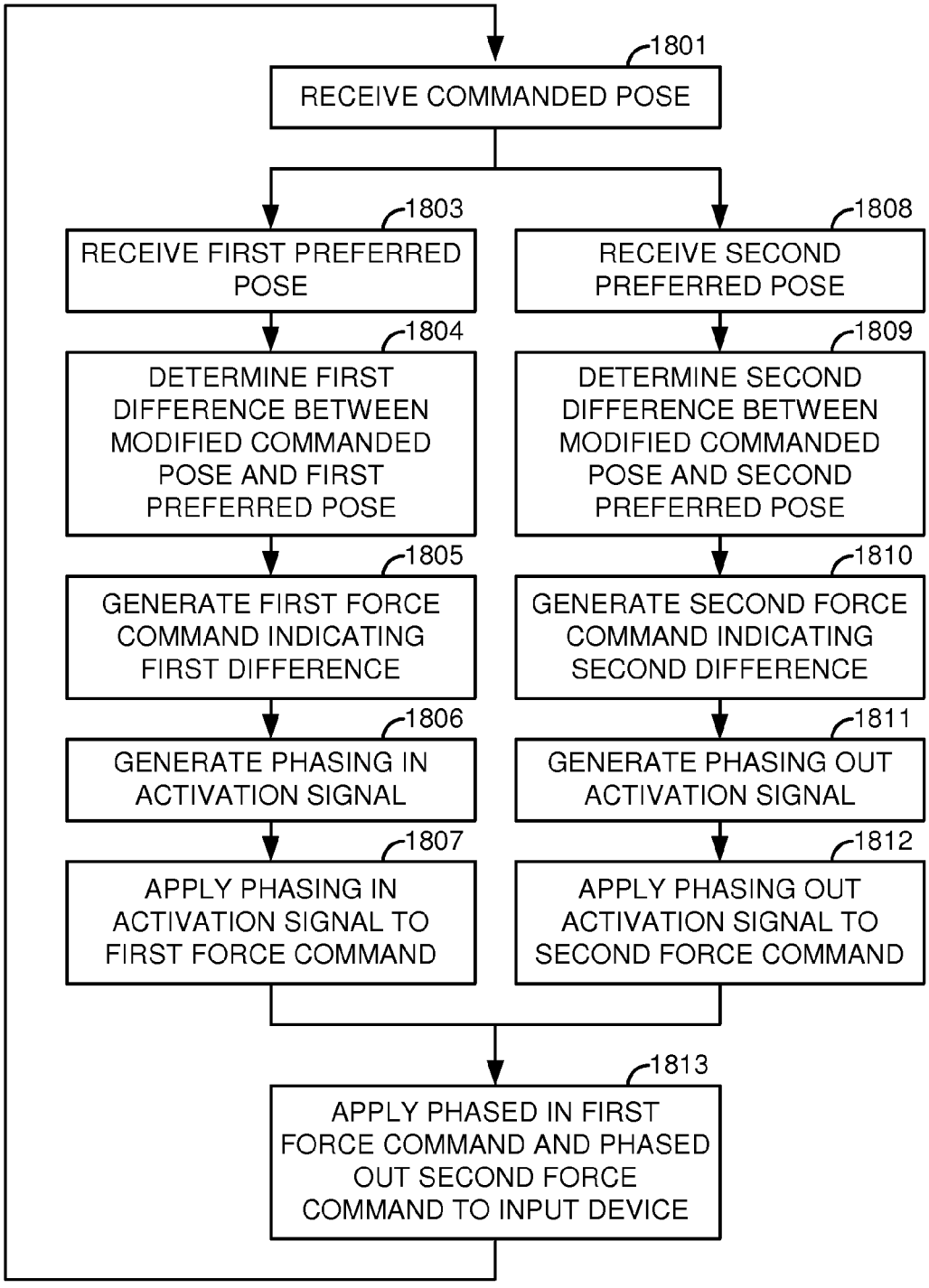
1801
RECEIVE COMMANDED POSE
1803
RECEIVE FIRST PREFERRED POSE
1804
DETERMINE FIRST DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND FIRST PREFERRED POSE
1805
GENERATE FIRST FORCE COMMAND INDICATING FIRST DIFFERENCE
1806
GENERATE PHASING IN ACTIVATION SIGNAL
1807
APPLY PHASING IN ACTIVATION SIGNAL TO FIRST FORCE COMMAND
1808
RECEIVE SECOND PREFERRED POSE
1809
DETERMINE SECOND DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND SECOND PREFERRED POSE
1810
GENERATE SECOND FORCE COMMAND INDICATING SECOND DIFFERENCE
1811
GENERATE PHASING OUT ACTIVATION SIGNAL
1812
APPLY PHASING OUT ACTIVATION SIGNAL TO SECOND FORCE COMMAND
1813
APPLY PHASED IN FIRST FORCE COMMAND AND PHASED OUT SECOND FORCE COMMAND TO INPUT DEVICE

fig.19

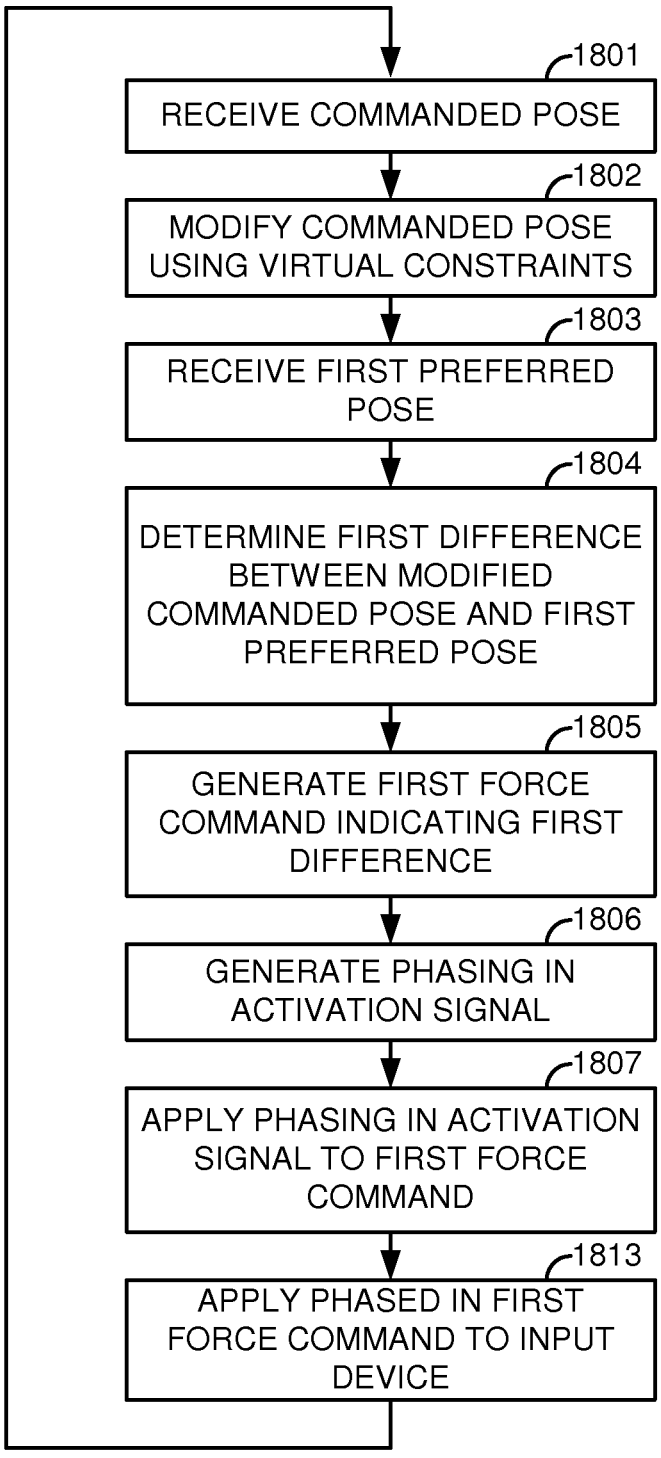
1801
RECEIVE COMMANDED POSE
1802
MODIFY COMMANDED POSE USING VIRTUAL CONSTRAINTS
1803
RECEIVE FIRST PREFERRED POSE
1804
DETERMINE FIRST DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND FIRST PREFERRED POSE
1805
GENERATE FIRST FORCE COMMAND INDICATING FIRST DIFFERENCE
1806
GENERATE PHASING IN ACTIVATION SIGNAL
1807
APPLY PHASING IN ACTIVATION SIGNAL TO FIRST FORCE COMMAND
1813
APPLY PHASED IN FIRST FORCE COMMAND TO INPUT DEVICE

fig.20

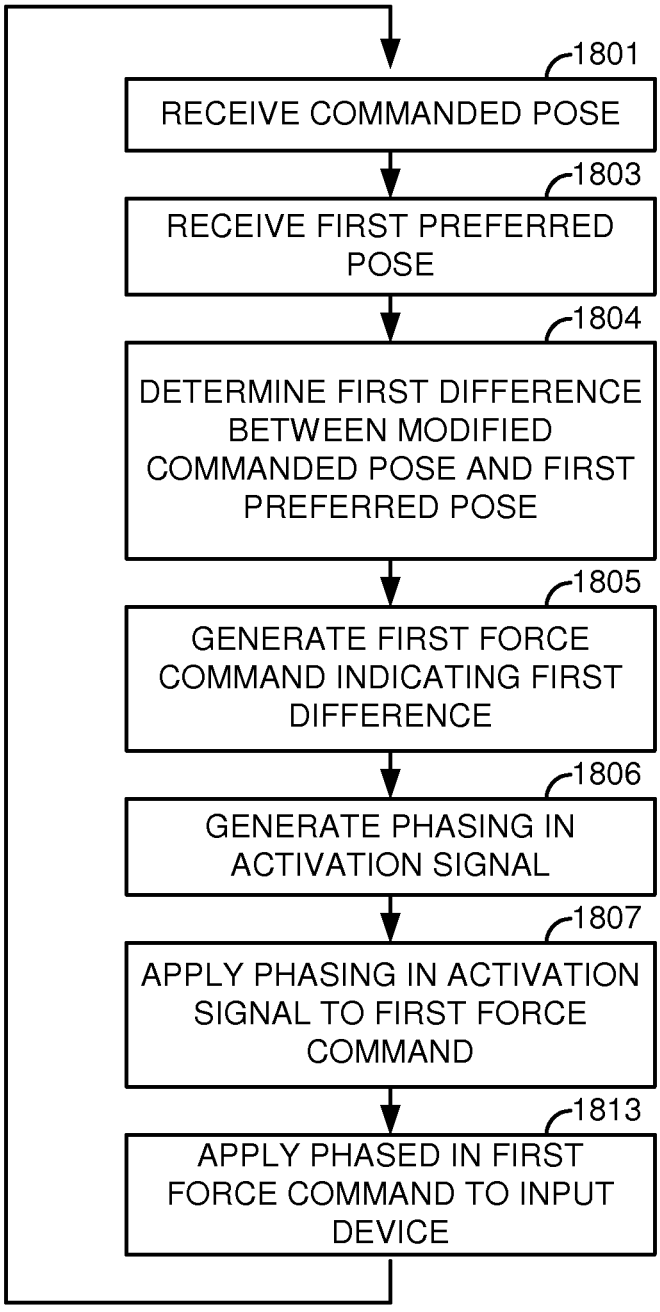
1801
RECEIVE COMMANDED POSE
1803
RECEIVE FIRST PREFERRED POSE
1804
DETERMINE FIRST DIFFERENCE BETWEEN MODIFIED COMMANDED POSE AND FIRST PREFERRED POSE
1805
GENERATE FIRST FORCE COMMAND INDICATING FIRST DIFFERENCE
1806
GENERATE PHASING IN ACTIVATION SIGNAL
1807
APPLY PHASING IN ACTIVATION SIGNAL TO FIRST FORCE COMMAND
1813
APPLY PHASED IN FIRST FORCE COMMAND TO INPUT DEVICE

fig.21

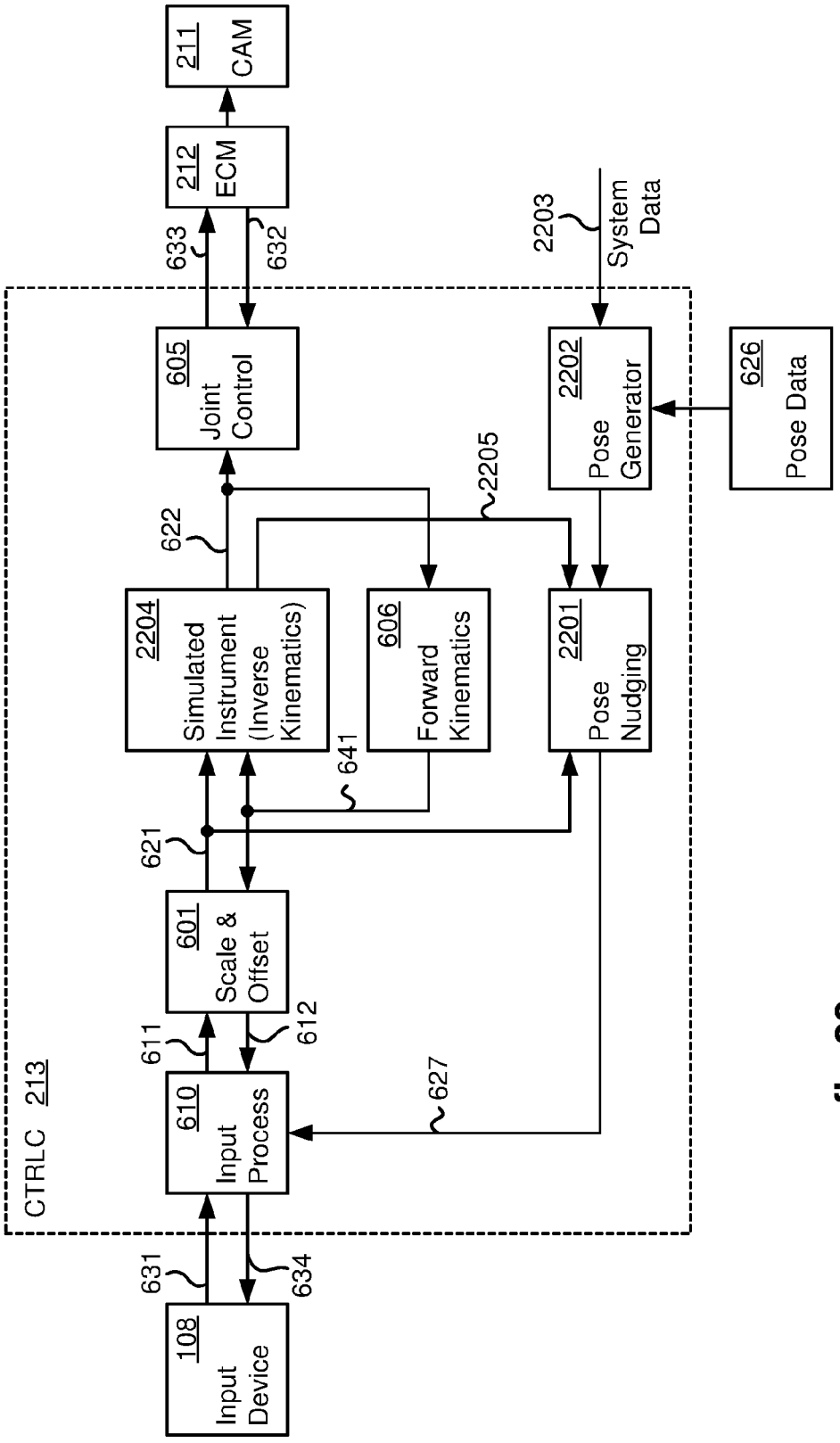
211 CAM
212 ECM
633
632
2203 System Data
605 Joint Control
2202 Pose Generator
626 Pose Data
2205
622
2204 Simulated Instrument (Inverse Kinematics)
606 Forward Kinematics
2201 Pose Nudging
641
621
601 Scale & Offset
611
612
627
610 Input Process
CTRLC 213
631
634
108 Input Device

fig.22

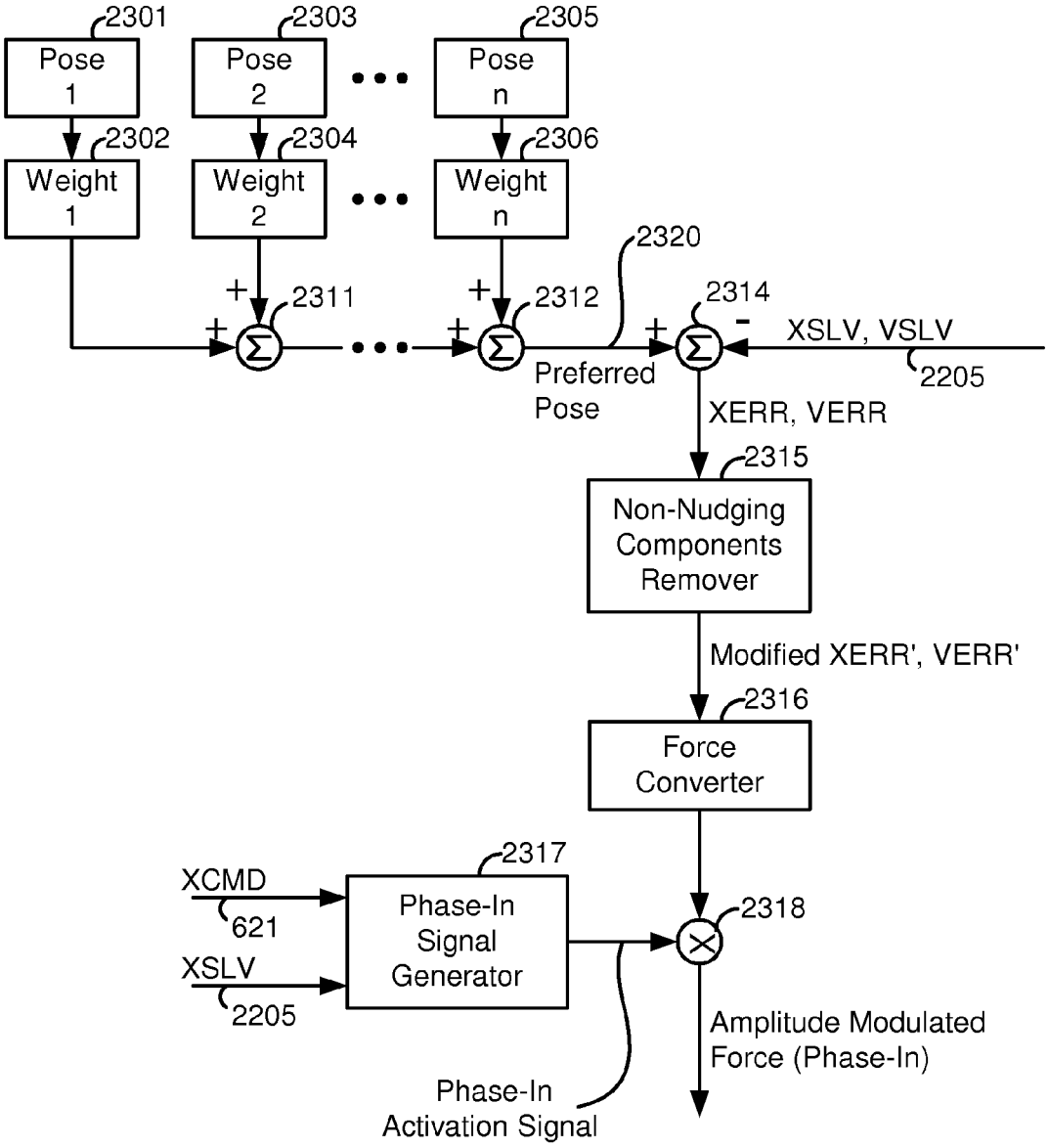
2301
Pose 1
2303
Pose 2
2305
Pose n
2302
Weight 1
2304
Weight 2
2306
Weight n
2320
2311
2312
2314
XSLV, VSLV
2205
Preferred Pose
XERR, VERR
2315
Non-Nudging Components Remover
Modified XERR', VERR'
2316
Force Converter
2317
XCMD
621
XSLV
2205
Phase-In Signal Generator
2318
Amplitude Modulated Force (Phase-In)
Phase-In Activation Signal

fig.23

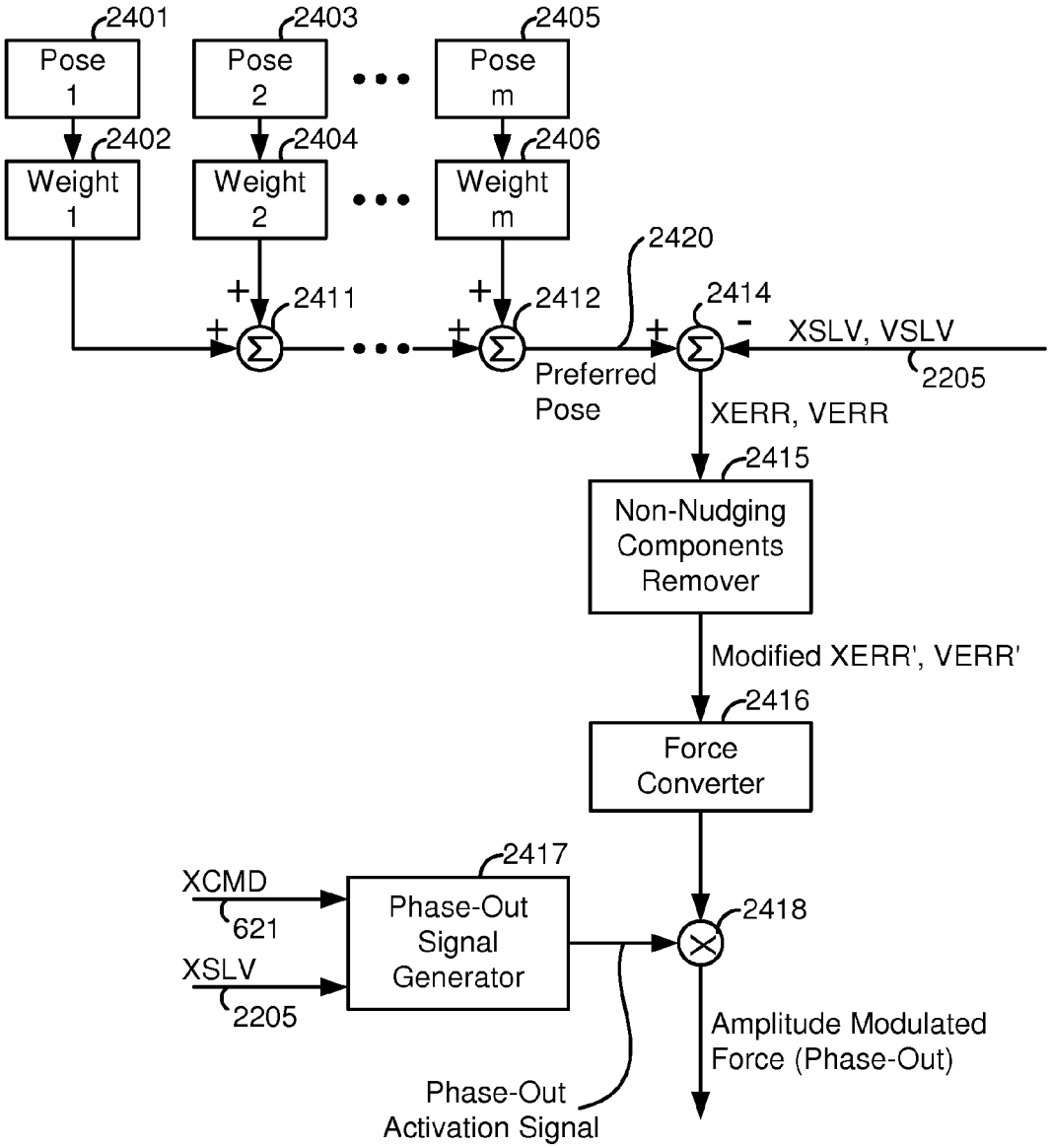
2401
Pose 1
2403
Pose 2
2405
Pose m
2402
Weight 1
2404
Weight 2
2406
Weight m
2420
2411
2412
2414
XSLV, VSLV
2205
Preferred Pose
XERR, VERR
2415
Non-Nudging Components Remover
Modified XERR', VERR'
2416
Force Converter
2417
XCMD
621
XSLV
2205
Phase-Out Signal Generator
2418
Amplitude Modulated Force (Phase-Out)
Phase-Out Activation Signal

fig.24

APPLICATION OF FORCE FEEDBACK ON AN INPUT DEVICE TO URGE ITS OPERATOR TO COMMAND AN ARTICULATED INSTRUMENT TO A PREFERRED POSE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. application Ser. No. 13/292,760 (filed Nov. 9, 2011), now U.S. Pat. No. 9,492,927, which is a continuation-in-part to U.S. application Ser. No. 12/704,669 (filed Feb. 12, 2010), now U.S. Pat. No. 8,918,211, each of which is incorporated herein by reference.

U.S. application Ser. No. 13/292,760 (filed Nov. 9, 2011) is also a continuation-in-part to U.S. application Ser. No. 12/613,328 (filed Nov. 5, 2009), now U.S. Pat. No. 9,084,623, which is a continuation-in-part to U.S. application Ser. No. 12/541,913 (filed Aug. 15, 2009), now U.S. Pat. No. 8,903,546, each of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention generally relates to medical robotic systems and in particular, to a method and system applying force feedback on an input device to urge its operator to command an articulated instrument to a preferred pose.

BACKGROUND

Medical robotic systems such as teleoperative systems used in performing minimally invasive surgical procedures offer many benefits over traditional open surgery techniques, including less pain, shorter hospital stays, quicker return to normal activities, minimal scarring, reduced recovery time, and less injury to tissue. Consequently, demand for such medical robotic systems is strong and growing.

One example of such a medical robotic system is the DA VINCI® Surgical System from Intuitive Surgical, Inc., of Sunnyvale, Calif., which is a minimally invasive robotic surgical system. The DA VINCI® Surgical System has a number of robotic arms that move attached medical devices, such as an image capturing device and Intuitive Surgical's proprietary ENDOWRIST® articulating surgical instruments, in response to movement of input devices by a surgeon viewing images captured by the image capturing device of a surgical site. Each of the medical devices is inserted through its own minimally invasive incision into the patient and positioned to perform a medical procedure at the surgical site. The incisions are placed about the patient's body so that the surgical instruments may be used to cooperatively perform the medical procedure and the image capturing device may view it without their robotic arms colliding during the procedure.

To perform certain medical procedures, it may be advantageous to use a single entry aperture, such as a minimally invasive incision or a natural body orifice, to enter a patient to perform a medical procedure. For example, an entry guide may first be inserted, positioned, and held in place in the entry aperture. Articulated instruments such as an articulated camera instrument and a plurality of articulated surgical tool instruments, which are used to perform the medical procedure, may then be inserted into a proximal end of the entry guide so as to extend out of its distal end. Thus, the entry guide accommodates a single entry aperture for multiple instruments while keeping the instruments bundled together as it guides them toward the work site.

A number of challenges arise in medical robotic systems using such a bundled unit, however, because of the close proximity of the articulated camera and tool instruments. For example, because the camera instrument has proximal articulations (e.g., joints) that are not visible from the distal tip camera view, the surgeon can lose track of the current state of such articulations when moving the camera and consequently, their available range of motion. Also, when the articulations of the camera and tool instruments are out of view of the camera and therefore, not visible to the surgeon through its captured images, the surgeon may inadvertently drive links of the tools and/or camera instruments to crash into one another while telerobotically moving the articulated instruments to perform a medical procedure. In either case, the safety of the patient may be jeopardized and the successful and/or timely completion of the medical procedure may be adversely impacted.

OBJECTS AND SUMMARY

Accordingly, one object of one or more aspects of the present invention is a medical robotic system, and method implemented therein, that urges an operator to command a preferred pose for normal mode operation of an articulated instrument, which serves as a biasing point for operator commanded movement of the articulated instrument during normal operation of the instrument.

Another object of one or more aspects of the present invention is a medical robotic system, and method implemented therein, that applies force feedback on an input device to urge its operator to command the posing of an articulated instrument to a preferred pose with smooth transition to the preferred pose.

Another object of one or more aspects of the present invention is a medical robotic system, and method implemented therein, that applies force feedback on an input device to urge its operator to command the posing of an articulated instrument to a first preferred pose and then smoothly transition to a second preferred pose according to an activation signal.

These and additional objects are accomplished by the various aspects of the present invention, wherein briefly stated, one aspect is a method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose, the method comprising: generating a commanded pose of the articulated instrument in response to operator manipulation of an input device; generating first force commands for a plurality of degrees of freedom of the input device so as to be indicative of a difference between a first preferred pose and the commanded pose; and applying the first force commands to the plurality of degrees of freedom of the input device by phasing in their application according to a first activation signal.

Another aspect is a medical robotic system comprising: an input device; an articulated instrument; and a processor configured to generate a commanded pose of the articulated instrument in response to operator manipulation of the input device, generate first force commands for a plurality of degrees of freedom of the input device so as to be indicative of a difference between a first preferred pose and the modified commanded pose, and command application of the first force commands on the plurality of degrees of freedom of the input device so as to phase in their application according to a first activation signal.

Additional objects, features and advantages of the various aspects of the present invention will become apparent from the following description of its preferred embodiment, which description should be taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a block diagram of a medical robotic system utilizing aspects of the present invention.

FIG. **2** illustrates a perspective view of a distal end of an entry guide with a plurality of articulated instruments extending out of it in a medical robotic system utilizing aspects of the present invention.

FIGS. **3-4** respectively illustrate top and right side views of articulated instruments extending out of a distal end of an entry guide in a medical robotic system utilizing aspects of the present invention.

FIG. **5** illustrates a block diagram of interacting components of an articulated instrument manipulator and an articulated instrument as used in a medical robotic system utilizing aspects of the present invention.

FIG. **6** illustrates a block diagram of an instrument controller for operator commanded movement of an articulated instrument in a medical robotic system utilizing aspects of the present invention.

FIG. **7** illustrates a side view of an articulated instrument extending out of a distal end of an entry guide in a preferred pose for normal operation as used in a medical robotic system utilizing aspects of the present invention.

FIG. **8** illustrates a side view of an articulated instrument extending out of a distal end of an entry guide in a preferred pose for retraction back into the entry guide as used in a medical robotic system utilizing aspects of the present invention.

FIG. **9** illustrates a block diagram of a simulated instrument block of the instrument controller of FIG. **6** as used in a medical robotic system utilizing aspects of the present invention.

FIG. **10** illustrates a block diagram of pose data and pose nudging blocks of the instrument controller of FIG. **6** as used in a medical robotic system utilizing aspects of the present invention.

FIG. **11** illustrates activation signals for normal mode operation and retraction mode as a function of time as used in a medical robotic system utilizing aspects of the present invention.

FIG. **12** illustrates a block diagram of the retraction mode nudging block of FIG. **10** as used in a medical robotic system utilizing aspects of the present invention.

FIG. **13** illustrates a block diagram of the normal mode nudging block of FIG. **10** as used in a medical robotic system utilizing aspects of the present invention.

FIG. **14** illustrates a block diagram of the force converter block of FIGS. **12** and **13** as used in a medical robotic system utilizing aspects of the present invention.

FIG. **15** illustrates a flow diagram of a method for modifying a commanded pose of an articulated instrument by applying a virtual barrier as a constraint as usable in a method for urging operator manipulation of an input device to command the articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **16** illustrates a flow diagram of a method for generating a retraction mode activation signal usable in a method for urging operator manipulation of an input device to command the articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **17** illustrates a flow diagram of a method for generating a normal mode deactivation signal usable in a method for urging operator manipulation of an input device to command the articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **18** illustrates a flow diagram of a first embodiment of a method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **19** illustrates a flow diagram of a second embodiment of a method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **20** illustrates a flow diagram of a third embodiment of a method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **21** illustrates a flow diagram of a fourth embodiment of a method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose utilizing aspects of the present invention.

FIG. **22** illustrates a block diagram of an alternative instrument controller for operator commanded movement of an articulated instrument in a medical robotic system utilizing aspects of the present invention.

FIG. **23** illustrates a block diagram of a "phase-in" nudging block providing a first nudging force command which is to be phased-in as a force to be applied against an input control device, as used in a medical robotic system utilizing aspects of the present invention.

FIG. **24** illustrates a block diagram of a "phase-out" nudging block providing a second nudging force command which is to be phased-out as a force being applied against an input control device, as used in a medical robotic system utilizing aspects of the present invention.

DETAILED DESCRIPTION

FIG. **1** illustrates a block diagram of a medical robotic system **100**. An entry guide (EG) **200** is configured to be inserted through an entry aperture such as a minimally invasive incision or a natural body orifice in a Patient. Articulated instruments such as a first articulated surgical tool (TOOL**1**) **231**, second articulated surgical tool (TOOL**2**) **241**, and an articulated stereo camera (CAM) **211** may be inserted through and extend out of a distal end of the entry guide **200**. As shown in FIG. **2**, the camera **211** has a stereo pair of image capturing devices **311**, **312** and a fiber optic cable **313** (coupled at its proximal end to a light source) housed in its tip. The surgical tools **231**, **241** have end effectors **331**, **341**. Although only two tools **231**, **241** are shown, the entry guide **200** may guide additional tools as required for performing a medical procedure at a work site in the Patient. Additional details on the articulated instruments **211**, **231**, **241** are provided in reference to FIGS. **3** and **4** below.

Each of the devices **231**, **241**, **211**, **200** is manipulated and controlled by its own manipulator and controller. In particular, the articulated camera instrument **211** is manipulated by a camera manipulator (ECM) **212** which is controlled by camera instrument controller (CTRLC) **213**, the first articulated surgical tool **231** is manipulated by a first tool manipulator (PSM**1**) **232** which is controlled by tool instrument controller (CTRL**1**) **233**, the second articulated surgical tool **241** is manipulated by a second tool manipulator (PSM**2**) **242** which is controlled by tool instrument controller (CTRL**2**) **243**, and the entry guide **200** is manipulated by an

entry guide manipulator (EGM) **202** which is controlled by entry guide controller (CTRLG) **203**. The controllers **203**, **233**, **243**, **213** are implemented in processor **102** as master/slave control systems as described in reference to FIG. **6** below.

Each of the articulated instrument manipulators **232**, **242**, **212** is a mechanical assembly that carries actuators and provides a mechanical, sterile interface to transmit motion to its respective articulated instrument. Each articulated instrument **231**, **241**, **211** is a mechanical assembly that receives the motion from its manipulator and, by means of a cable transmission, propagates it to the distal articulations (e.g., joints). Such joints may be prismatic (e.g., linear motion) or rotational (e.g., they pivot about a mechanical axis). Furthermore, the instrument may have internal mechanical constraints (e.g., cables, gearing, cams and belts, etc.) that force multiple joints to move together in a pre-determined fashion. Each set of mechanically constrained joints implements a specific axis of motion, and constraints may be devised to pair rotational joints (e.g., joggle joints). Note also that in this way the instrument may have more joints than the available actuators.

The entry guide manipulator (EGM) **202** is usable to robotically insert and retract the entry guide **200** into and out of the entry aperture. It may also be used to robotically pivot the entry guide **200** in pitch, roll and yaw relative to a longitudinal axis of the entry guide **200** about a pivot point (also referred to as a remote center "RC"). A setup arm may be used to hold and position the entry guide **200** so that its remote center RC is positioned at the entry aperture.

Two input devices **108**, **109** are provided for manipulation by a Surgeon. Each of the input devices **108**, **109** may be selectively associated with one of the devices **211**, **231**, **241**, **200** so that the associated device may be controlled by the input device through its controller and manipulator. The Surgeon (or an Assistant) may perform such selection in a conventional manner, such as interacting with a menu on a Graphical User Interface (GUI), providing voice commands recognized by a voice recognition system, inputting such associations into the system **100** using an input device such as a touchpad, or interacting with special purpose buttons provided on the input devices **108**, **109**. Using any one of such association mechanisms, a select input is generated and provided to a multiplexer (MUX) **280**, which is implemented in the processor **102**. The value of the select input (e.g., combination of 1's and 0's) indicates which association (i.e., cross-switching) is selected.

For example, a first value for the select input to the multiplexer **280** places the left and right input devices **108**, **109** in "tool following modes" wherein they are respectively associated with the first and second surgical tools **241**, **231** so the Surgeon may perform a medical procedure on the Patient while the entry guide **200** is locked in place. In this configuration, the multiplexer **280** cross-switches to respectively connect output and input **251**, **252** of the input device **108** to input and output **260**, **261** of the tool controller **243**; and respectively connect output and input **253**, **254** of the input device **109** to input and output **268**, **269** of the tool controller **233**.

When the camera **211** is to be repositioned by the Surgeon, either one or both of the left and right input devices **108**, **109** may be associated with the camera **211** using a second value for the select input so that the Surgeon may move the camera **211** through its controller **213** and manipulator **212**. Similarly, when the entry guide **200** is to be repositioned by the Surgeon, either one or both of the left and right input devices **108**, **109** may be associated with the entry guide **200** using a third value for the select input so that the Surgeon may move the entry guide **200** through its controller **203** and manipulator **202**. In any case, disassociated devices are soft-locked in place by its respective controller.

The images captured by the camera instrument **211** are processed by an image processor **214** and displayed on a display screen **104** so as to provide a telepresence experience to the Surgeon, as described for example in U.S. Pat. No. 6,671,581 "Camera Referenced Control in a Minimally Invasive Surgical Apparatus," which is incorporated herein by reference. Thus, a Surgeon using the medical robotic system **100** may perform a medical procedure on the Patient by manipulating input devices **108**, **109** to cause corresponding movement of associated surgical tools **231**, **241** while the Surgeon views images of the work site on the display screen **104**.

Although described as a processor, it is to be appreciated that the processor **102** may be implemented in practice by any combination of hardware, software 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 and firmware distributed throughout the system.

For additional details on the construction and operation of general aspects of a medical robotic system such as described herein, see, e.g., U.S. Pat. No. 6,493,608 "Aspects of a Control System of a Minimally Invasive Surgical Apparatus," and U.S. Pat. Application Pub. No. U.S. 2008/007129 "Minimally Invasive Surgical System," which are incorporated herein by reference.

FIGS. **3-4** respectively illustrate, as examples, top and right side views of a distal end of the entry guide **200** with the articulated camera instrument **211** and articulated surgical tool instruments **231**, **241** extending outward. The articulated camera **211** extends through passage **321** and the articulated surgical tools **231**, **241** respectively extend through passages **431**, **441** of the entry guide **200**. The camera **211** includes a tip **311**, first, second, and third links **322**, **324**, **326**, first and second joint assemblies (also referred to herein simply as "joints") **323**, **325**, and a wrist assembly **327**. The first joint assembly **323** couples the first and second links **322**, **324** and the second joint assembly **325** couples the second and third links **324**, **326** so that the second link **324** may pivot about the first joint assembly **323** in pitch and yaw while the first and third links **322**, **326** remain parallel to each other.

The first and second joints **323**, **325** are referred to as "joggle joints", because they cooperatively operate together so that as the second link **324** pivots about the first joint **323** in pitch and/or yaw, the third link **326** pivots about the second joint **325** in a complementary fashion so that the first and third links **322**, **326** always remain parallel to each other. The first link **322** may also rotate around its longitudinal axis in roll as well as move in and out (e.g., insertion towards the work site and retraction from the worksite) through the passage **321**. The wrist assembly **327** also has pitch and yaw angular movement capability so that the camera's tip **311** may be oriented up or down and to the right or left, and combinations thereof.

The joints and links of the tools **231**, **241** are similar in construction and operation to those of the camera **211**. In particular, the tool **231** includes an end effector **331** (having jaws **338**, **339**), first, second, and third links **332**, **334**, **336**, first and second joint assemblies **333**, **335**, and a wrist assembly **337** that are driven by actuators such as described

in reference to FIG. **5** (plus an additional actuator for actuating the end effector **331**). Likewise, the tool **241** includes an end effector **341** (having jaws **348**, **349**), first, second, and third links **342**, **344**, **346**, first and second joint assemblies **343**,**345**, and a wrist assembly **347** that are also driven by actuators such as described in reference to FIG. **5** (plus an additional actuator for actuating the end effector **341**).

FIG. **5** illustrates, as an example, a diagram of interacting parts of an articulated instrument (such as the articulated camera **211** and the articulated surgical tools **231**, **241**) and its corresponding instrument manipulator (such as the camera manipulator **212** and the tool manipulators **232**, **242**). Each of the instruments includes a number of actuatable assemblies **521-523**, **531-533**, **570** for effectuating movement of the instrument (including its end effector), and its corresponding manipulator includes a number of actuators **501-503**, **511-513**, **560** for actuating the actuatable assemblies.

In addition, a number of interface mechanisms may also be provided. For example, pitch/yaw coupling mechanisms **540**, **550** (respectively for the joggle joint pitch/yaw and the wrist pitch/yaw) and gear ratios **545**, **555** (respectively for the instrument roll and the end effector actuation) are provided in a sterile manipulator/instrument interface to achieve the required range of motion of the instrument joints in instrument joint space while both satisfying compactness constraints in the manipulator actuator space and preserving accurate transmissions of motion across the interface. Although shown as a single block **540**, the coupling between the joggle joint actuators **501**, **502** (differentiated as #1 and #2) and joggle joint pitch/yaw assemblies **521**, **522** may include a pair of coupling mechanisms—one on each side of the sterile interface (i.e., one on the manipulator side of the interface and one on the instrument side of the interface). Likewise, although shown as a single block **550**, the coupling between the wrist actuators **512**, **513** (differentiated as #1 and #2) and wrist pitch/yaw joint assemblies **532**, **533** may also comprise a pair of coupling mechanisms—one on each side of the sterile interface.

Both the joggle joint pitch assembly **521** and the joggle joint yaw assembly **522** share the first, second and third links (e.g., links **322**, **324**, **326** of the articulated camera **211**) and the first and second joints (e.g., joints **322**, **325** of the articulated camera **211**). In addition to these shared components, the joggle joint pitch and yaw assemblies **521**, **522** also include mechanical couplings that couple the first and second joints (through joggle coupling **540**) to the joggle joint pitch and yaw actuators **501**, **502** so that the second link may controllably pivot about a line passing through the first joint and along an axis that is latitudinal to the longitudinal axis of the first link (e.g., link **322** of the articulated camera **211**) and the second link may controllably pivot about a line passing through the first joint and along an axis that is orthogonal to both the latitudinal and longitudinal axes of the first link.

The in/out (I/O) assembly **523** includes the first link (e.g., link **322** of the articulated camera **211**) and interfaces through a drive train coupling the in/out (I/O) actuator **503** to the first link so that the first link is controllably moved linearly along its longitudinal axis by actuation of the I/O actuator **503**. The roll assembly **531** includes the first link and interfaces through one or more gears (i.e., having the gear ratio **545**) that couple a rotating element of the roll actuator **511** (such as a rotor of a motor) to the first link so that the first link is controllably rotated about its longitudinal axis by actuation of the roll actuator **511**.

The instrument manipulator (e.g., camera manipulator **212**) includes wrist actuators **512**, **513** that actuate through wrist coupling **550** pitch and yaw joints **532**, **533** of the wrist assembly (e.g., wrist assembly **327** of the articulated camera **211**) so as to cause the instrument tip (e.g., camera tip **311**) to controllably pivot in an up-down (i.e., pitch) and side-to-side (i.e., yaw) directions relative to the wrist assembly. The grip assembly **570** includes the end effector (e.g., end effector **331** of the surgical tool **231**) and interfaces through one or more gears (i.e., having the gear ratio **555**) that couple the grip actuator **560** to the end effector so as to controllably actuate the end effector.

The group of instrument joints **500** is referred to as "translational joints" because by actuation of a combination of these joints, the instrument's wrist assembly may be positioned translationally within three-dimensional space using arc compensation as needed. The group of instrument joints **510** is referred to as "orientational joints" because by actuation of these joints, the instrument's tip may be oriented about the wrist assembly.

At various stages before, during, and after the performance of a medical procedure, there may be preferred poses for the articulated instruments **211**, **231**, **241** to best accomplish tasks performed at the time. For example, during normal operation, as shown in FIGS. **3** and **4**, a preferred pose for each of the surgical tools **231**, **241** may be an "elbow out, wrist in" pose to provide good range of motion while minimizing chances of inadvertent collisions with other instruments. Likewise, during normal operation, as shown in FIGS. **3** and **4**, a preferred pose for the camera instrument **211** may be a "cobra" pose in which a good view of the end effectors **331**, **341** of the surgical tool instruments **231**, **241** is provided at the camera's image capturing end. As another example, when it is desired to retract an instrument back into the entry guide **200** to perform a tool exchange (i.e., exchange the instrument or its end effector for another instrument or end effector) or for reorienting the entry guide **200** by pivoting it about its remote center, a preferred pose for the instrument prior to its retraction into the entry guide **200** is a "straightened" pose wherein the links of the instrument are aligned in a straight line such as shown in FIG. **8**.

FIG. **6** illustrates, as an example, a block diagram of the camera instrument controller (CTRLC) **213**, which controls the posing (i.e., both translationally and orientationally) of the articulated camera instrument **211** as commanded by movement of the input device **108** by the Surgeon, when the input device **108** is selectively associated with the camera instrument **211** through the multiplexer **280** as previously described in reference to FIG. **1**. The input device **108** includes a number of links connected by joints so as to facilitate multiple degrees-of-freedom movement. For example, as the Surgeon/operator moves the input device **108** from one position to another, sensors associated with the joints of the input device **108** sense such movement at sampling intervals (appropriate for the processing speed of the processor **102** and camera control purposes) and provide digital information **631** indicating such sampled movement in joint space to input processing block **610**.

Input processing block **610** processes the information **631** received from the joint sensors of the input device **108** to transform the information into corresponding desired positions and velocities for the camera instrument **211** in its Cartesian space relative to a reference frame associated with the position of the Surgeon's eyes (the "eye reference frame") by computing joint velocities from the joint position

information and performing the transformation using a Jacobian matrix and eye related information using well-known transformation techniques.

Scale and offset processing block **601** receives the processed information **611** from the input processing block **610** and applies scale and offset adjustments to the information so that the resulting movement of the camera instrument **211** and consequently, the image being viewed on the display screen **104** appears natural and as expected by the operator of the input device **108**. The scale adjustment is useful where small movements of the camera instrument **211** are desired relative to larger movements of the input device **108** in order to allow more precise movement of the camera instrument **211** as it views the work site. In addition, offset adjustments are applied for aligning the input device **108** with respect to the Surgeon's eyes as he or she manipulates the input device **108** to command movement of the camera instrument **211** and consequently, its captured image that is being displayed at the time on the display screen **104**.

A simulated instrument block **604** transforms the commanded pose **621** of the camera instrument **211** from its Cartesian space to its joint space using inverse kinematics, limiting the commanded joint positions and velocities to avoid physical limitations or other constraints such as avoiding harmful contact with tissue or other parts of the Patient, and applying virtual constraints that may be defined to improve the performance of a medical procedure being performed at the time by the Surgeon using the medical robotic system **100**. In particular, as illustrated in FIG. **9**, the commanded pose **621** may be modified by virtual barrier logic **901** (described in more detail in reference to FIG. **15** below) which implements a virtual constraint on the commanded pose **621** to generate a modified commanded pose **623**. Inverse kinematics and limiting block **902** then converts the modified commanded pose **623** from instrument Cartesian space to instrument joint space and limits the joint position and/or velocity to physical limitations or other constraints associated with or placed on the joints of the articulated camera instrument **211**.

The output **622** of the simulated instrument block **604** (which includes a commanded value for each joint of the camera instrument **211**) is provided to a joint control block **605** and a forward kinematics block **606**. The joint controller block **605** includes a joint control system for each controlled joint (or operatively coupled joints such as "joggle joints") of the camera instrument **211**. For feedback control purposes, sensors associated with each of the controlled joints of the camera instrument **211** provide sensor data **632** back to the joint control block **605** indicating the current position and/or velocity of each joint of the camera instrument **211**. The sensors may sense this joint information either directly (e.g., from the joint on the camera instrument **211**) or indirectly (e.g., from the actuator in the camera manipulator **212** driving the joint). Each joint control system in the joint control block **605** then generates torque commands **633** for its respective actuator in the camera manipulator **212** so as to drive the difference between the commanded and sensed joint values to zero in a conventional feedback control system manner.

The forward kinematics block **606** transforms the output **622** of the simulated instrument block **604** from the camera instrument's joint space back to Cartesian space relative to the eye reference frame using forward kinematics of the camera instrument **211**. The output **641** of the forward kinematics block **606** is provided to the scale and offset processing block **601** as well as back to the simulated instrument block **604** for its internal computational purposes.

The scale and offset processing block **601** performs inverse scale and offset functions on the output **641** of the forward kinematics block **606** before passing its output **612** to the input processing block **610** where an error value is calculated between its output **611** and input **612**. If no limitation or other constraint had been imposed on the input **621** to the simulated instrument block **604**, then the calculated error value would be zero. On the other hand, if a limitation or constraint had been imposed, then the error value is not zero and it is converted to a torque command **634** that drives actuators in the input device **108** to provide force feedback felt by the hands of the Surgeon. Thus, the Surgeon becomes aware that a limitation or constraint is being imposed by the force that he or she feels resisting his or her movement of the input device **108** in that direction.

A pose nudging block **625** is included in the controller **213** to generate a nudging force command **627** which is provided to the input processing block **610**. The input processing block **610** then converts the nudging force command **627** into motor torques so that the commanded nudging force is felt by the Surgeon on the input device **108** in a manner that urges the Surgeon to command the pose of the camera instrument **211** to a preferred pose provided in pose data **626**.

For the camera instrument **211**, there may be at least two preferred poses. During normal mode operation, such as when the Surgeon is performing a medical procedure on a Patient, the preferred pose for the camera instrument **211** is the "cobra" pose shown in FIGS. **3** and **4**. Looking downward at the "cobra" pose in FIG. **3**, all links **322**, **324**, **326** of the camera instrument **211** are aligned with the longitudinal axis **401** of the first link **322** so that they have maximum available range of lateral motion and provide a reference for the main insertion direction of the camera instrument **211**. Further, the joggle joints **323**, **325** are "joggled up", as shown in FIG. **4**, so that the third link **326** is displaced a distance above the longitudinal axis **401** and the wrist assembly **327** is rotated at a negative pitch angle so that the camera tip **311** is oriented downwards at an angle so that the camera is preferably viewing the center of a workspace for the end effectors **331** and **341** of tool instruments **231** and **241**, which are also extending out of the distal end of the entry guide **200** at the time. In this case, the Surgeon is preferably allowed to freely move the camera **211** forward and backward in the input/output (I/O) direction along the longitudinal axis **401** so that the camera **211** may better view the end effectors **331**, **341** as they move away from and back towards the distal end of the entry guide **200** during their use.

During retraction mode, the preferred pose for the camera instrument **211** is the "straightened" pose. FIGS. **7** and **8** respectively illustrate simplified side views of the camera instrument **211** in the "cobra" and "straightened" poses. To go from the "cobra" pose to the "straightened" pose, the joggle joints **323**, **325** rotate link **324** until it is aligned with the longitudinal axis **401** of the first link **322**. Since the link **326** is always parallel to the first link **322** due to operation of the joggle joints **323**, **325**, when the link **324** is aligned with the longitudinal axis **401**, the link **326** also is aligned with the longitudinal axis **401**. Meanwhile, the wrist joint **327** also rotates the camera tip **311** until its central axis also aligns with the longitudinal axis **401**.

FIG. **10** illustrates, as an example, a block diagram of the pose nudging block **625** and its coupling to the pose data

block **626**. In this example, the pose data block **626** comprises data stored in a non-volatile memory which is accessible to the processor **102**. The stored data for the camera instrument **211** includes data for the "straightened" pose **1001** which is used for retraction of the camera instrument **211** and data for the "cobra" pose **1002** which is used during normal mode operation of the camera instrument **211**.

The pose nudging block **625** comprises a retraction mode nudging block **1003**, a normal mode nudging block **1004**, and a summing node **1005**. A key feature of the retraction and normal mode nudging blocks **1003** and **1004** is that nudging force commands from one is phased in while nudging force commands from the other is being phased out during a transition period. A more detailed description of the retraction mode nudging block **1003** is described in reference to FIG. **12** below and a more detailed description of the normal mode nudging block **1004** is described in reference to FIG. **13**.

FIG. **12** illustrates, as an example, a block diagram of the retraction mode nudging block **1003** which continually processes incoming data. A summing node **1201** computes a difference (XERR, VERR) between the preferred "straightened" pose **1001** (i.e., the retraction configuration for the camera instrument **211**) and the modified commanded pose (XSLV, VSLV) **623** which is generated by the virtual barrier logic **901** of the simulated instrument block **608** of the instrument controller **213**. As used herein, the term "pose" means both position and orientation of the instrument as well as their positional and rotational velocities, so that the commanded pose may include both positional (XCMD) and velocity (VCMD) components, the modified commanded pose may include both positional (XSLV) and velocity (VSLV) components, the preferred pose may include both positional (XPP) and velocity (VPP) components, and the computed difference between the preferred pose and the modified commanded pose may include both positional (XERR) and velocity (VERR) components. In the computation performed in summing node **1201**, however, the velocity (VPP) components of the preferred pose (VPP) are all presumed to be zero.

To explain how the modified commanded pose (XSLV, VSLV) is generated, an example of the virtual barrier logic **901** is described in reference to FIG. **15**. In block **1501**, the logic **901** receives the commanded pose (XCMD) **621** from the scale and offset block **621** and in block **1502**, it determines the projection of the commanded pose **621** in a first direction, which in the present example is the instrument retraction direction along the longitudinal axis **401** of the first link **322** of the camera instrument **211**. In block **1503**, a determination is made whether the projection along the first direction would command the camera instrument **211** to move beyond a virtual barrier position. The virtual barrier position in this case is a position along the longitudinal axis **401** which is a threshold distance or safety margin from the distal end of the entry guide **200**. As described in US 2011/0040305 A1, the purpose of the safety margin is to prevent damage from occurring to either or both the entry guide **200** and the articulated instrument **211** when attempting to force the articulated instrument **211** back into the entry guide **200** while it is in a configuration in which it physically will not fit at the time. If the determination in block **1503** is NO, then the virtual barrier logic **901** jumps back to block **1501** to process data for a next process cycle. On the other hand, if the determination in block **1503** is YES, then in block **1504**, the current pose of the camera instrument **211** is determined sensing its joint positions and applying forward kinematics to determine their corresponding Cartesian pose. In block **1505**, a determination is then made whether the current pose of the camera instrument **211** is the preferred pose (i.e., "straightened" pose in this case). If the determination in block **1505** is YES, then the virtual barrier logic **901** doesn't modify the commanded pose (XCMD) and jumps back to block **1501** to process data for a next process cycle. On the other hand, if the determination n block **1505** is NO, then commanded pose (XCMD) is modified by applying the virtual barrier as constraint so that the camera instrument **211** is prevented from moving further in the first direction. The method then loops back to block **1501** to process data for the next process cycle. Thus, the camera instrument **211** is prevented in this way from moving beyond the virtual barrier position until the current pose is the preferred retraction pose of the camera instrument **211**.

Referring back to FIG. **12**, in block **1202**, non-nudging components of the calculated difference (XERR, VERR) are removed. In particular, translational components along the first direction and the roll rotational component about the tip **310** are removed since neither of these components affects the preferred pose (i.e., regardless of their values, the camera instrument may be placed in a "straightened" pose as shown in FIG. **8**). In block **1203**, the modified difference (XERR', VERR') generated in block **1202** is converted to generate a force command that would result in one or more forces being applied to the input device **108** so that the Surgeon is urged to command the camera instrument **211** to the preferred pose. Preferably such force command is a visco-elastic six degree-of-freedom force that would be applied to corresponding degrees-of-freedom of the input device **108**.

An example of the force converter block **1203** is illustrated in FIG. **14** by a block diagram of a Proportional-Derivative (PD) open loop system. In this PD system, the modified position difference (XERR') is multiplied by a position gain (KP) **1401** and limited by limiter **1402** to a first saturation value (SATP) to generate a first force command contribution. At the same time, the modified velocity difference (VERR') is multiplied by a derivative gain (KD) **1403** to generate a second force command contribution. A summing node **1404** calculates a difference between second and first force command contributions and a limiter **1405** limits to the difference to a second saturation value (SATF). The thus limited difference between the second and first force command contributions results in a visco-elastic six degree-of-freedom Cartesian force for nudging the Surgeon to move the input device **108** so as to command the preferred pose. Values for the first and second saturation values are selected so as to ensure that commanded motor torques on the motors of the input device **108** do not exceed their rated maximum values.

Referring back to FIG. **12**, modulator **1207** amplitude modulates the visco-elastic six degree-of-freedom Cartesian force generated by the force converter block **1203** with a retraction activation signal which resembles curve **1101** in FIG. **11**. To generate the retraction activation signal, a summing node **1204** calculates a difference between the commanded pose (XCMD) and the modified commanded pose (XSLV), ignoring velocity contributions, modulation coefficients generator **1205** generates a stream of modulation coefficients using the calculated difference, and a low-pass filter **1206** filters the stream of modulation coefficients.

An example of the generation of the retraction mode activation signal is provided in a flow diagram illustrated in FIG. **16**. Blocks **1601** and **1602** describe actions taken by the summing node **1204**. In particular, in block **1601**, the commanded pose (XCMD) and modified commanded pose (XSLV) are received, and in block **1602**, a difference

between the commanded pose (XCMD) and the modified commanded pose (XSLV) is calculated. Blocks **1603** to **1607** next describe actions taken by the modulation coefficients generator **1205**. In block **1603**, a projection of the calculated difference in a first direction (i.e., the retraction direction along the longitudinal axis **401**) is determined and in block **1604**, a determination is made whether the projection exceeds a threshold value. The threshold value in this case should be large enough to ensure that the Surgeon really intends to retract the camera instrument **211** and that it is not an inadvertent action such as may result from hand tremor. If the determination in block **1604** is YES, then in block **1605**, the current modulation coefficient is set to an integer value "1". On the other hand, if the determination in block **1604** is NO, then in block **1606**, the current modulation coefficient is set to an integer value of "0". In block **1607**, the current modulation coefficient is then appended to a stream of modulation coefficients generated in prior process periods. Block **1608** describes action taken by the low-pass filter **1206**. In particular, in block **1608**, the retraction activation signal is generated by passing the stream of modulation coefficients through the low-pass filter **1206** and the process then jumps back to block **1601** to process data for the next process cycle.

FIG. **13** illustrates, as an example, a block diagram of the normal mode nudging block **1004** which also continually processes incoming data. A summing node **1301** computes a difference (XERR, VERR) between the preferred "cobra" pose **1002** (i.e., the normal mode configuration for the camera instrument **211**) and the modified commanded pose (XSLV, VSLV) **623** which is generated by the virtual barrier logic **901** of the simulated instrument block **608** of the instrument controller **213**.

In block **1302**, non-nudging components of the calculated difference (XERR, VERR) are removed. In particular, translational components along the first direction and the roll rotational component about the tip **311** are removed since neither of these components affects the preferred pose (i.e., regardless of their values, the camera instrument may be placed in a "cobra" pose as shown in FIG. **7**). In block **1303**, the modified difference (XERR', VERR') generated in block **1302** is converted to generate a force command that would result in one or more forces being applied to the input device **108** so that the Surgeon is urged to command the camera instrument **211** to the preferred pose. Preferably such force command is a visco-elastic six degree-of-freedom force that would be applied to corresponding degrees-of-freedom of the input device **108**, whose generation is similar to that previously described in reference to FIG. **14**.

Modulator **1307** then amplitude modulates the visco-elastic six degree-of-freedom Cartesian force generated by the force converter block **1303** with a normal mode deactivation signal which resembles curve **1102** in FIG. **11**. To generate the normal mode deactivation signal, a summing node **1304** calculates a difference between the commanded pose (XCMD) and the modified commanded pose (XSLV), ignoring velocity contributions, modulation coefficients generator **1305** generates a stream of modulation coefficients using the calculated difference, and a low-pass filter **1306** filters the stream of modulation coefficients.

An example of the generation of the normal mode deactivation signal is provided in a flow diagram illustrated in FIG. **17**. Blocks **1701** and **1702** describe actions taken by the summing node **1304**. In particular, in block **1701**, the commanded pose (XCMD) and modified commanded pose (XSLV) are received, and in block **1702**, a difference between the commanded pose (XCMD) and the modified commanded pose (XSLV) is calculated. Blocks **1703** to **1707** next describe actions taken by the modulation coefficients generator **1305**. In block **1703**, a projection of the calculated difference in a first direction (i.e., the retraction direction along the longitudinal axis **401**) is determined and in block **1704**, a determination is made whether the projection exceeds a threshold value. The threshold value in this case should be large enough to ensure that the Surgeon really intends to retract the camera instrument **211** and that it is not inadvertent action such as may result from hand tremor. If the determination in block **1704** is YES, then in block **1705**, the current modulation coefficient is set to an integer value "0". On the other hand, if the determination in block **1704** is NO, then in block **1706**, the current modulation coefficient is set to an integer value of "1". Note that the modulation coefficient value assignments are opposite to those used in the generation of the retraction activation signal, which results in one of the retraction and normal mode activation signals phasing in while the other is phasing out. In block **1707**, the current modulation coefficient is then appended to a stream of modulation coefficients generated in prior process periods. Block **1708** finally describes action taken by the low-pass filter **1306**. In particular, in block **1708**, the normal mode deactivation signal is generated by passing stream of modulation coefficients through the low-pass filter **1306**. The process then jumps back to block **1701** to process data for the next process cycle.

The time constants for the low-pass filter **1206** in the retraction mode nudging block **1003** and the low-pass filter **1306** in the normal mode nudging block **1004** are preferably the same so that the phasing in and phasing out match during the transition period such as shown in FIG. **11**, where time "t(k)" represents the time that the threshold value determinations in blocks **1804** and **1704** first result in a YES determination, time "t(k-m)" represents a time prior to "t(k)" when the threshold value determinations in blocks **1804** and **1704** resulted in a NO determination, and time "t(k+m)" represents a time after "t(k)" when the threshold value determinations in blocks **1804** and **1704** still result in a YES determination.

FIG. **18** illustrates a flow diagram summarizing the first embodiment of the invention as described in detail above. In block **1801**, a commanded pose (XCMD) is received from an input device associated at the time with the articulated instrument whose pose is being commanded. In block **1802**, the commanded pose is modified using virtual constraints (such as described in reference to FIG. **15**). In blocks **1803-1807**, a first force command is generated which is to be phased in to nudge the operator of the input device to command a first (new) preferred pose (such as described in reference to FIG. **12**) while concurrently in blocks **1808-1812**, a second force command is generated which is to be phased out to nudge the operator of the input device to command a second (incumbent) preferred pose (such as described in reference to FIG. **13**). In block **1813**, the first and second force commands are applied to the input device so that initially the operator of the input device is urged to command the second preferred pose then subsequently after a phasing in and phasing out transition period the operator is urged to command the first preferred pose.

FIGS. **19-21** illustrate additional embodiments of the invention which include various combinations of some, but not all of the blocks described in reference to FIG. **18**. In particular, FIG. **19** illustrates a second embodiment that is a modification to the first embodiment, wherein the commanded pose is not modified using virtual constraints by deleting block **1802**, but performing all other blocks of the

first embodiment. FIG. **20** illustrates a third embodiment that is a modification to the first embodiment, wherein a second (incumbent) preferred pose is not active by deleting blocks **808**-**812**, but performing all other blocks of the first embodiment with block **813** modified since there is no second force command to be phased out. FIG. **21** illustrates a fourth embodiment that is a modification to the third embodiment, wherein the commanded pose is not modified using virtual constraints by deleting block **1802**, but performing all other blocks of the third embodiment.

FIGS. **22**-**24** illustrate still other embodiments of the invention which expand upon some of the previously disclosed embodiments. In particular, whereas prior embodiments disclose a single preferred pose being active at a time (outside a transition period), the embodiments shown in FIGS. **22**-**24** contemplate the possibility of multiple preferred poses being active at a time with the active preferred poses being weighted so that one or some may be more dominant than others. Further, the weightings provide an additional mechanism through which preferred poses may be transitioned in and out by making their respective weightings dynamically alterable (e.g., progressively changing from a weighting of "0" to a weighting of "1" to phase the corresponding preferred pose in and conversely, progressively changing from a weighting of "1" to a weighting of "0" to phase the corresponding preferred pose out). Also, whereas prior embodiments disclose fixed preferred poses for different operating modes, the embodiments shown in FIGS. **22**-**24** contemplate the possibility of dynamically changing preferred poses based upon system data such as the current or commanded poses of other articulated instruments. For example, the preferred pose for the camera instrument **211** may dynamically change as the poses of the end effectors **331**, **341** of the tool instruments **231**, **241** change so that the end effectors **331**, **341** remain well positioned in a field of view of the camera instrument **211**. As another example, the preferred poses of each of the articulated instruments **211**, **231**, **241** may dynamically change to avoid collisions with others of the articulated instruments **211**, **231**, **241** during the performance of a medical procedure using the articulated instruments **211**, **231**, **241**.

FIG. **22** illustrates, for example, a block diagram of an alternative instrument controller for operator commanded movement of an articulated instrument. Although the example is for the camera controller **213**, it is to be appreciated that the same general structure may be used for other device controllers **203**, **233**, **243** in the medical robotic system **100**. The functions of blocks **610**, **601**, **605**, **606** are the same as previously described in reference to FIG. **6**. The function of the simulated instrument block **2204** is generally the same as block **604** of FIG. **6** with regards to inverse kinematics and limiting, but may differ in regards to virtual constraints imposed on the commanded pose **621** to generate a modified commanded pose **2205**, because of different operating modes and/or preferred poses. Likewise, the function of pose nudging block **2201** is generally the same as block **625** with regards to summing together two pose nudging contributions wherein a first (new) preferred pose is to be phased in while a second (incumbent) preferred pose is to be phased out according to respective activation signals.

A pose generator block **2202** is included in the controller **213** to dynamically generate one or more preferred poses that are provided to the pose nudging block **2201**, as well as pass through static preferred poses when appropriate. In particular, although a static preferred pose provided by the pose data block **626** may be normally passed through, the preferred pose for the articulated camera instrument **211** may dynamically be changed from the static preferred pose as conditions, such as the poses of other tool instruments **231**, **241** around it, change. As one example, the preferred pose for the camera instrument **211** may dynamically change during normal operating mode to avoid collisions with the tool instruments **231**, **241**, which are being used and therefore, moving at the time to perform a medical procedure on a patient anatomy. To dynamically generate one or more preferred poses to be phased in (such as preferred poses **2301**, **2303**, **2305** of FIG. **23**) and one or more preferred poses to be phased out (such as preferred poses **2401**, **2403**, **2405**), the pose generator block **2202** may use a different function of one or more states of the system for each of the preferred poses to be dynamically changed. The system state information in this case is provided by system data **2203**. As one example, the system data **2203** may comprise the commanded poses of other instruments **231**, **241** in the system **100**. As another example, the system data **2203** may comprise the actual poses of the other instruments **231**, **241** as determined by applying forward kinematics to their sensed joint positions.

The pose nudging block **2201** includes "phase-in" and "phase-out" nudging blocks which respectively generate nudging forces that are to be phased-in and phased-out on the input device **108** in a similar manner as previously described with respect to the retraction mode and normal mode nudging blocks, **1003** and **1004**, of FIG. **10**.

FIG. **23** illustrates, as an example, a block diagram of the "phase-in" nudging block. A preferred pose **2320** is generated by a weighted average of a plurality of preferred poses (e.g., preferred poses **2301**, **2303**, **2305**) so that each of the preferred poses is multiplied by a corresponding weight (e.g., weights **2302**, **2304**, **2306**) with the sum of the weights equal to "1". The weights may be fixed values or preferably dynamic values so one or more of the preferred poses may be dominant at different times, in different operating modes or under different system conditions. A difference between the preferred pose **2320** and the modified commanded pose **2205** is computed by summing node **2314**. Non-nudging components of the difference are removed in block **2315** and the result provided to force converter block **2316** which generates a force command such as described in reference to block **1203** of FIG. **12**. A phase-in activation signal is generated by phase-in signal generator block **2317** so as to resemble the retraction mode activation signal **1101** in FIG. **1**I. An amplitude modulated force command, which is to be phased-in on the input device **108**, is then generated by amplitude modulator **2318** by amplitude modulating the force command generated by the force converter block **2316** with the phase-in activation signal.

Using a similar construction, FIG. **24** illustrates, as an example, a block diagram of the "phase-out" nudging block. A preferred pose **2420** in this case is generated by a weighted average of a plurality of preferred poses (e.g., preferred poses **2401**, **2403**, **2405**) so that each of the preferred poses is multiplied by a corresponding weight (e.g., weights **2402**, **2404**, **2406**) with the sum of the weights equal to "1". The weights may be fixed values or preferably dynamic values so one or more of the preferred poses may be dominant at different times, in different operating modes or under different system conditions. A difference between the preferred pose **2420** and the modified commanded pose **2205** is computed by summing node **2414**. Non-nudging components of the difference are removed in block **2415** and the result provided to force converter block **2416** which generates a force command such as described in reference to block

1203 of FIG. 12. A phase-out activation signal is generated by phase-out signal generator block 2417 so as to resemble the normal mode activation signal 1102 in FIG. 11. An amplitude modulated force command, which is provided to and is to be phased-out on the input device 108, is then generated by amplitude modulator 2418 by amplitude modulating the force command generated by the force converter block 2416 with the phase-out activation signal.

In addition to the embodiments described herein, it is to be appreciated that other embodiments may be constructed, and are fully contemplated to be within the scope of the present invention, through different combinations of their various teachings. In particular, although the various aspects of the present invention have been described with respect to preferred and alternative embodiments, it will be understood that the invention is entitled to full protection within the full scope of the appended claims.

What is claimed is:

1. A method for urging operator manipulation of an input device to command an articulated instrument to a preferred pose, the method comprising:

generating a commanded pose of the articulated instrument in response to operator manipulation of the input device;

modifying the commanded pose by applying a virtual barrier as a constraint to prevent the articulated instrument from being commanded to move beyond the virtual barrier until at least a portion of the articulated instrument which is closest to, but has not yet encountered the virtual barrier conforms with a first preferred pose;

generating a stream of modulation coefficients indicative of a difference between the commanded pose and the modified commanded pose;

generating a first activation signal by processing the stream of modulation coefficients;

generating first force commands for a first plurality of degrees of freedom of the input device so as to be indicative of a difference between the first preferred pose and the commanded pose; and

applying the first force commands to the first plurality of degrees of freedom of the input device by phasing in their application according to the first activation signal.

2. The method of claim 1, wherein generating the first activation signal comprises filtering the stream of modulation coefficients by using a low pass filter.

3. The method of claim 1,

wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction, and

wherein generating the stream of modulation coefficients comprises:

determining a difference between the commanded pose and the modified commanded pose,

projecting the difference along the first direction, and

binary coding the projected difference by setting a current modulation coefficient to a first value when the projected difference is greater than a threshold value and setting the current modulation coefficient to a second value when the projected difference is less than or equal to the threshold value.

4. The method of claim 1,

wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction, and

wherein generating the first force commands comprises:

comparing the first preferred pose to the modified commanded pose to generate Cartesian position and velocity errors;

modifying the Cartesian position and velocity errors by removing components along the first direction and about an axis of a pivotable tip of the articulated instrument; and

generating a visco-elastic six degree-of-freedom force command using the modified Cartesian position and velocity errors.

5. The method of claim 4,

wherein generating of the visco-elastic six degree-of-freedom force command comprises:

amplifying the modified Cartesian position error by a position gain to generate a first result and limiting the first result to a position saturation limit to generate a second result;

amplifying the modified Cartesian velocity error by a velocity gain to generate a third result;

generating an interim visco-elastic six-degree-of-freedom force command by subtracting the third result from the second result; and

generating the visco-elastic six degree-of-freedom force command by limiting the interim visco-elastic six-degree-of-freedom force command to a force saturation limit.

6. The method of claim 4, wherein applying the first force commands to the first plurality of degrees of freedom of the input device by phasing in their application according to the first activation signal comprises:

amplitude modulating the visco-elastic six degree-of-freedom force command with the first activation signal.

7. The method of claim 1, further comprising:

generating second force commands for a second plurality of degrees of freedom of the input device so as to be indicative of a difference between a second preferred pose and the commanded pose;

applying the second force commands to the second plurality of degrees of freedom of the input device prior to phasing in the application of the first force commands according to the first activation signal; and

phasing out application of the second force commands according to a second activation signal.

8. The method of claim 7, wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction, the method further comprising:

generating a second stream of modulation coefficients by determining a difference between the commanded pose and modified commanded pose, projecting the difference along the first direction, and binary coding the projected difference by setting a current modulation coefficient to a second value when the projected difference is greater than a threshold value and setting the current modulation coefficient to a first value when the projected difference is less than or equal to the threshold value; and

generating the second activation signal by filtering the second stream of modulation coefficients.

9. The method of claim 7, wherein the first and second activation signals are complementary signals so that the first activation signal is phased in as the second activation signal is phased out.

10. A robotic system comprising:

an input device;

an articulated instrument; and

a processor programmed to:

generate a commanded pose of the articulated instrument in response to operator manipulation of the input device,

modify the commanded pose by applying a virtual barrier as a constraint to prevent the articulated instrument from being commanded to move beyond the virtual barrier until at least a portion of the articulated instrument which is closest to, but has not yet encountered the virtual barrier conforms with a first preferred pose,

generate a stream of modulation coefficients indicative of a difference between the commanded pose and the modified commanded pose,

generate a first activation signal by processing the stream of modulation coefficients,

generate first force commands for a plurality of degrees of freedom of the input device so as to be indicative of a difference between the first preferred pose and the commanded pose, and

command application of the first force commands on the plurality of degrees of freedom of the input device so as to phase in their application according to the first activation signal.

11. The system of claim **10**, wherein the processor is programmed to generate the first activation signal by filtering the stream of modulation coefficients by using a low pass filter.

12. The system of claim **10**,

wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction, and

wherein the processor is programmed to generate the stream of modulation coefficients by:

determining a difference between the commanded pose and the modified commanded pose,

projecting the difference along the first direction, and

binary coding the projected difference by setting a current modulation coefficient to a first value when the projected difference is greater than a threshold value and setting the current modulation coefficient to a second value when the projected difference is less than or equal to the threshold value.

13. The system of claim **10**,

wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction, and

wherein the processor is programmed to generate the first force commands by:

comparing the first preferred pose to the modified commanded pose to generate Cartesian position and velocity errors,

modifying the Cartesian position and velocity errors by removing components along the first direction and about an axis of a pivotable tip of the articulated instrument, and

generating a visco-elastic six degree-of-freedom force command using the modified Cartesian position and velocity errors.

14. The system of claim **13**, wherein the processor is programmed to generate the visco-elastic six degree-of-freedom force command by:

amplifying the modified Cartesian position error by a position gain to generate a first result and limiting the first result to a position saturation limit to generate a second result,

amplifying the modified Cartesian velocity error by a velocity gain to generate a third result,

generating an interim visco-elastic six-degree-of-freedom force command by subtracting the third result from the second result, and

generating the visco-elastic six degree-of-freedom force command by limiting the interim visco-elastic six-degree-of-freedom force command to a force saturation limit.

15. The system of claim **13**, wherein the processor is programmed to command application of the first force commands on the plurality of degrees of freedom of the input device so as to phase in their application according to the first activation signal by generating an amplitude modulated force by amplitude modulating the visco-elastic six degree of freedom force with the first activation signal and commanding application of the amplitude modulated force on input device.

16. The system of claim **10**, wherein the processor is programmed to generate second force commands for a plurality of degrees of freedom of the input device so as to be indicative of a difference between a second preferred pose and the commanded pose; apply the second force commands to the plurality of degrees of freedom of the input device prior to phasing in the application of the first force commands according to the first activation signal; and phase out application of the second force commands according to a second activation signal.

17. The system of claim **16**,

wherein the constraint prevents the articulated instrument from being commanded to move beyond the virtual barrier in a first direction,

wherein the processor is programmed to generate a second stream of modulation coefficients by determining a difference between the commanded pose and the modified commanded pose, projecting the difference along the first direction, and binary coding the projected difference by setting a current modulation coefficient to a second value when the projected difference is greater than a threshold value and setting the current modulation coefficient to a first value when the projected difference is less than or equal to the threshold value, and

wherein the processor is programmed to generate the second activation signal by filtering the second stream of modulation coefficients.

18. The system of claim **17**, wherein the first and second activation signals are complementary signals so that the first activation is phased in as the second activation signal is phased out.

19. The system of claim **10**,

wherein the processor is programmed to generate the first preferred pose by using a weighted average of a first plurality of preferred poses, and

wherein at least one of the first plurality of preferred poses is a function of at least one state of the system.

20. A non-transient computer readable medium containing program instructions for causing a computer to perform the method of:

generating a commanded pose of an articulated instrument in response to operator manipulation of an input device;

modifying the commanded pose by applying a virtual barrier as a constraint to prevent the articulated instrument from being commanded to move beyond the virtual barrier until at least a portion of the articulated instrument which is closest to, but has not yet encountered the virtual barrier conforms with a first preferred pose;

generating a stream of modulation coefficients indicative of a difference between the commanded pose and the modified commanded pose;

generating a first activation signal by processing the stream of modulation coefficients;

generating first force commands so as to be indicative of a difference between the first preferred pose and the commanded pose; and

applying the first force commands to the input device by phasing in their application according to the first activation signal.

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