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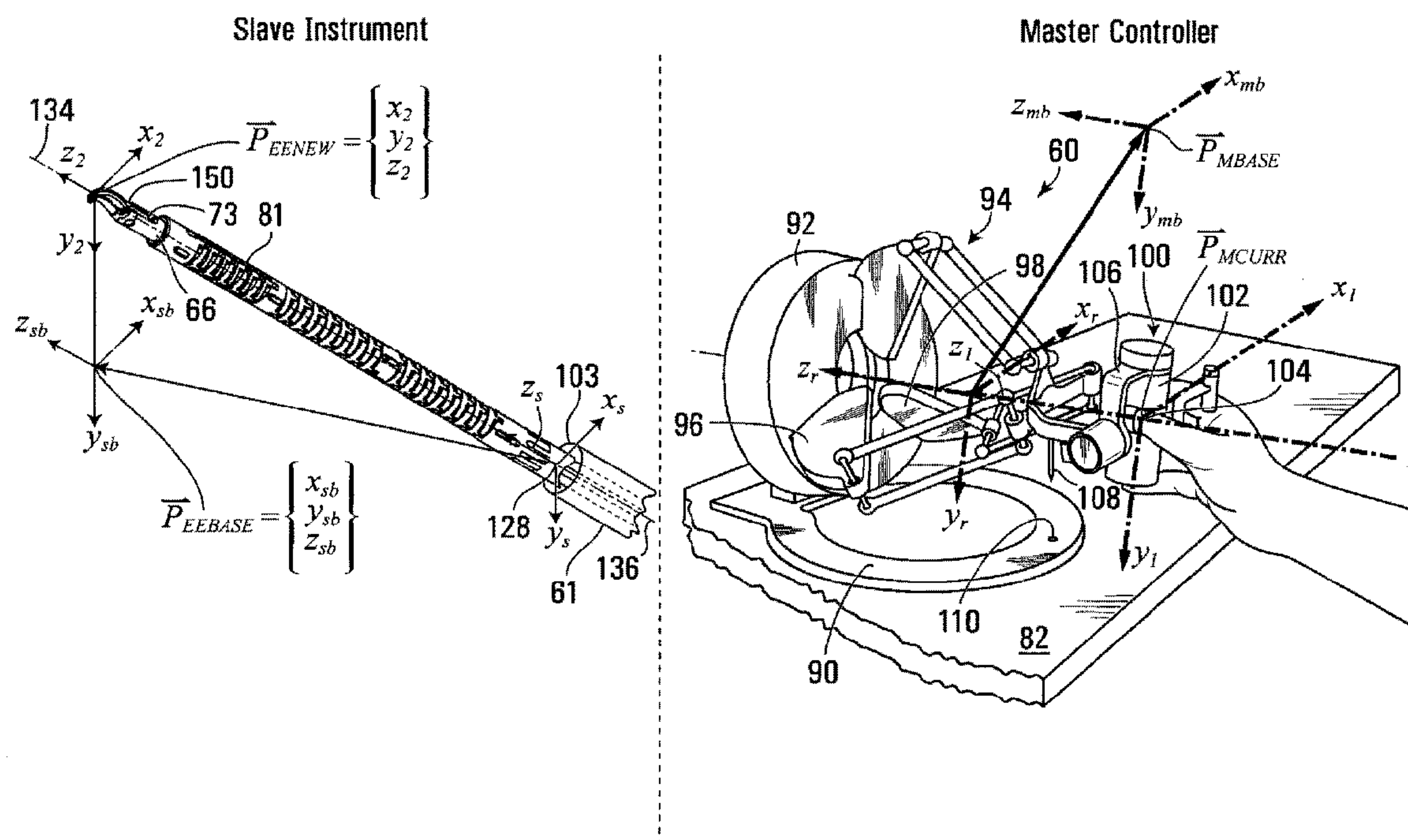
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(54) Titre : SECURITE DE DIFFERENCE D'ALIGNEMENT DANS UN SYSTEME ROBOTIQUE MAITRE-ESCLAVE
(54) Title: ALIGNMENT DIFFERENCE SAFETY IN A MASTER-SLAVE ROBOTIC SYSTEM



(57) Abrégé/Abstract:

A method and apparatus for operating a robotic control system including a master apparatus in communication with an input device having a handle and a slave system having a tool including an end effector whose position and orientation is determined in response to a position and orientation of the handle. The method involves producing a desired end effector position and orientation in response to a current position and a current orientation of the handle. The method also involves causing the input device to provide haptic feedback that impedes translational movement of the handle while permitting rotational movement of the handle and preventing movement of the end effector, when a rotational alignment difference between the handle and the end effector meets a first criterion. The method further involves re-enabling translational movement of the handle when the rotational alignment difference meets a second criterion.



ABSTRACT

A method and apparatus for operating a robotic control system including a master apparatus in communication with an input device having a handle and a slave system
5 having a tool including an end effector whose position and orientation is determined in response to a position and orientation of the handle. The method involves producing a desired end effector position and orientation in response to a current position and a current orientation of the handle. The method also involves causing the input device to provide haptic feedback that impedes translational movement of the handle while
10 permitting rotational movement of the handle and preventing movement of the end effector, when a rotational alignment difference between the handle and the end effector meets a first criterion. The method further involves re-enabling translational movement of the handle when the rotational alignment difference meets a second criterion.

ALIGNMENT DIFFERENCE SAFETY IN A MASTER-SLAVE ROBOTIC SYSTEM

BACKGROUND OF THE INVENTION

1. Field of Invention

5 This invention relates to master-slave robotic systems such as those used for laparoscopic surgery and more particularly to prevention of operator control of the surgical tools when an alignment difference between the master and slave exceeds a threshold value.

10 2. Description of Related Art

In a robotic system that allows for clutching of an end effector wherein movement of the end effector in response to movement of a handle can be selectively interrupted by the clutch mechanism such that the handle can be moved and rotated while the position and rotation of the end effector is held stationary, there is a possibility that the
15 orientation of the handle and the orientation of the end effector will come out of rotational alignment. Should this occur, the commanded end effector orientation can differ significantly from the handle orientation. When the alignment difference is large, movement of the slave instrument may not feel as though it is fundamentally linked to the motion of the master handle, from the user's perspective.

20

SUMMARY OF THE INVENTION

The disclosure describes a method of operating a robotic control system comprising a master apparatus in communication with an input device having a handle capable of translational and rotational movement and a slave system having a tool positioning
25 device holding a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle. The method involves producing a desired end effector position and a desired end effector orientation of the end effector, in response to a current position and a current orientation of the handle. The method further involves causing the input device to provide haptic
30 feedback that impedes translational movement of the handle, while permitting rotational

movement of the handle and while disabling translational and rotational movement of the end effector, when a rotational alignment difference between the handle and the end effector meets a disablement criterion. The method further involves enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion.

Producing the desired end effector position and the desired end effector orientation may include causing the master apparatus to receive current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing the current position and the current orientation respectively of the handle of the input device, and causing the master apparatus to produce new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining the desired end effector position and the desired end effector orientation, respectively of the end effector, in response to the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}).

Causing the master apparatus to receive the current handle position signals and the current handle orientation signals may involve causing the master apparatus to periodically receive the current handle position signals and the current handle orientation signals.

The method may further involve causing the master apparatus to determine the rotational alignment difference between the handle and the end effector in response to the current handle orientation signals (R_{MCURR}) and the new end effector orientation signals (R_{EENEW}).

Causing the master apparatus to determine the rotational alignment difference between the handle and the end effector may involve causing the master apparatus to determine an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

Causing the master apparatus to determine a rotational alignment difference between the handle and the end effector may further involve determining whether the angle of rotation is less than a threshold.

- 5 Causing the input device to provide haptic feedback may involve causing the master apparatus to transmit a haptic feedback signal to the input device to cause the input device to provide the haptic feedback that impedes the translational movement of the handle.
- 10 The method may involve transmitting a slave control signal to the slave system and enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion may involve transmitting the slave control signal to the slave system identifying the new end effector position and orientation signals based on the current position and orientation of the handle, and disabling movement of the end
- 15 effector in response to any movement of the handle may involve transmitting the slave control signal to the slave system identifying the new end effector position and orientation signals determined from a previous position and orientation of the handle.

20 The method may involve causing the master apparatus to receive an enablement signal.

The method may further involve generating the enablement signal such that the enablement signal selectively has an active state or an inactive state.

- 25 The method may involve causing the master apparatus to detect a change of the enablement signal from the inactive state to the active state and when the change is detected: causing the master apparatus to store the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base rotation signals (R_{MBASE}) respectively, in response to
- 30 the change of the enablement signal. The method may involve causing the master

apparatus to store the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base rotation signals (R_{EEBASE}) respectively, in response to the change of the enablement signal.

5

Causing the master apparatus to compute the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) may involve causing the master apparatus to compute the new end effector position signals and the new end effector orientation signals according to the following relations:

10

$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}; \text{ and}$$

$$R_{EENEW} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}.$$

15 The method may involve causing the slave control signal to be further dependent on the state of the enablement signal, such that the slave control signal identifies the end effector position and orientation signals based on the current position and orientation of the handle when the alignment difference is less than the disablement criterion and the enablement signal is in the active state, and the slave control signal identifies the end
20 effector position and orientation signals based on the previous position and orientation of the handle when the enablement signal is in the inactive state.

The method may further involve causing the master apparatus to produce annunciation signals for causing an annunciator to annunciate an indication of a relative rotational
25 alignment of the handle and the end effector.

Causing the master apparatus to produce annunciation signals may include causing the master apparatus to produce display control signals for causing a display to depict the relative alignment.

30

The disclosure describes a non-transitory computer readable medium encoded with codes for directing a processor to execute the any of the methods described above.

5 The disclosure further describes an apparatus for use in a robotic control system the apparatus in communication with an input device having a handle capable of translational and rotational movement and in communication with a slave system having a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle. The apparatus includes producing means for producing a desired end effector position and a desired end effector orientation of the
10 end effector, in response to a current position and a current orientation of the handle. The apparatus further includes causing means for causing the input device to provide haptic feedback that impedes translational movement of the handle, while causing rotational movement of the handle to be enabled and while causing translational movement of the end effector in response to translational movement of the handle to be
15 disabled, when a rotational alignment difference between the handle and the end effector meets a disablement criterion. The apparatus further includes enabling means for enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion.

20 The producing means may include means for receiving current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing the current position and a current orientation respectively of the handle of the input device, and means for producing new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining the desired end effector position and the desired
25 end effector orientation, respectively of the end effector, in response to the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}).

The means for receiving the current handle position signals and the current handle orientation signals may include means for periodically receiving the current handle
30 position signals and the current handle orientation signals.

The apparatus may include means for determining the rotational alignment difference between the handle and the end effector in response to the current handle orientation signals (R_{MCURR}) and the new end effector orientation signals (R_{EENEW}).

- 5 The means for determining the rotational alignment difference between the handle and the end effector may include means for determining an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

10 The apparatus may include means for determining whether the angle of rotation is less than a threshold.

Causing means may include means for transmitting a haptic feedback signal to the input device to cause the input device to provide the haptic feedback that impedes the translational movement of the handle.

15

The enabling provisions may include provisions for transmitting a slave control signal to the slave system, and the provisions for transmitting may transmit the slave control signal identifying the new end effector position and orientation signals based on the current position and orientation of the handle when the rotational alignment difference meets the enablement criterion, and the provisions for transmitting may transmit the slave control signal identifying the new end effector position and orientation signals determined from a previous position and orientation of the handle when the rotational alignment difference meets the disablement criterion.

20

25 The apparatus may include means for receiving an enablement signal.

The apparatus may include means for generating the enablement signal such that the enablement signal selectively has an active state or an inactive state.

The apparatus may include means for detecting a change of the enablement signal from the inactive state to the active state, means for storing the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base rotation signals (R_{MBASE}) respectively, in response to the change of the enablement signal, and means for storing the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base rotation signals (R_{EEBASE}) respectively, in response to the change of the enablement signal.

10 The means for producing the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) may include means for computing the new end effector position signals and the new end effector orientation signals according to the following relations:

15
$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}; \text{ and}$$
$$R_{EENEW} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}.$$

The apparatus may include means for causing the slave control signal to be further dependent on the state of the enablement signal, such that the slave control signal identifies the end effector position and orientation signals based on the current position and orientation of the handle when the alignment difference is less than the disablement criterion and the enablement signal is in the active state, and the slave control signal identifies the end effector position and orientation based on the previous position and orientation of the handle when the enablement signal is in the inactive state.

25

The apparatus may include annunciation signal means for producing annunciation signals for causing an annunciator to annunciate an indication of a relative rotational alignment of the handle and the end effector.

The annunciation signal causing means may include means for producing display control signals for causing a display to depict the relative alignment.

5 The disclosure further describes an apparatus for use in a robotic control system, the apparatus in communication with an input device having a handle capable of translational and rotational movement and in communication with a slave system having a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle. The apparatus includes at least one processor circuit configured to produce a desired end effector position and a desired
10 end effector orientation of the end effector, in response to a current position and a current orientation of the handle, to cause the input device to provide haptic feedback that impedes translational movement of the handle, while causing rotational movement of the handle to be enabled and while causing translational movement of the end effector in response to translational movement of the handle to be disabled, when a
15 rotational alignment difference between the handle and the end effector meets a disablement criterion, and to enable translational movement of the handle when the rotational alignment difference meets an enablement criterion.

The at least one processor circuit may be configured to produce the desired end
20 effector position and the desired end effector orientation by receiving current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing the current position and the current orientation respectively of the handle of the input device, and producing new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining the desired end effector position and the desired
25 end effector orientation, respectively of the end effector, in response to the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}).

The at least one processor circuit may be configured to receive the current handle position signals and the current handle orientation signals by periodically receiving the
30 current handle position signals and the current handle orientation signals.

The at least one processor circuit may be further configured to determine the rotational alignment difference between the handle and the end effector in response to the current handle orientation signals (R_{MCURR}) and the new end effector orientation signals (R_{EENEW}).

5

The at least one processor circuit may be configured to determine the rotational alignment difference between the handle and the end effector by determining an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

10

The at least one processor circuit may be further configured to determine whether the angle of rotation is less than a threshold.

15 The at least one processor circuit may be configured to cause the input device to provide haptic feedback by transmitting a haptic feedback signal to the input device to cause the input device to provide the haptic feedback that impedes the translational movement of the handle.

20 The at least one processor circuit may be configured to transmit a slave control signal to the slave system and the slave control signal may identify the new end effector position and orientation signals based on the current position and orientation of the handle when the rotational alignment difference meets an enablement criterion, and the slave control signal may identify the new end effector position and orientation signals determined from a previous position and orientation of the handle when the rotational alignment
25 difference meets the disablement criterion.

The at least one processor circuit may be further configured to receive an enablement signal.

The at least one processor circuit may be further configured to generate the enablement signal such that the enablement signal selectively has an active state or an inactive state.

- 5 The at least one processor circuit may be further configured to detect a change of the enablement signal from the inactive state to the active state and when the change is detected: store the current handle position signals ($\bar{P}_{MCURR}$) and the current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base rotation signals (R_{MBASE}) respectively, in response to the change of the enablement
- 10 signal, and store the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base rotation signals (R_{EEBASE}) respectively, in response to the change of the enablement signal.
- 15 The at least one processor circuit may be configured to compute the new end effector position signals ($\bar{P}_{EENEW}$) and the new end effector orientation signals (R_{EENEW}) by computing the new end effector position signals and the new end effector orientation signals according to the following relations:

20
$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}; \text{ and}$$

$$R_{EENEW} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}.$$

- The at least one processor circuit may be further configured to cause the slave control
- 25 signal to be further dependent on the state of the enablement signal, such that the slave control signal identifies the end effector position and orientation signals based on the current position and orientation of the handle when the alignment difference is less than the disablement criterion and the enablement signal is in the active state, and the slave control signal identifies the end effector position and orientation based on the previous

position and orientation of the handle when the enablement signal is in the inactive state.

5 The at least one processor circuit may be further configured to produce annunciation signals for causing an annunciator to annunciate an indication of a relative rotational alignment of the handle and the end effector.

10 The at least one processor circuit may be configured to produce the annunciation signals by producing display control signals for causing a display to depict the relative alignment.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

15

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the invention,

20 Figure 1 is a pictorial representation of a laparoscopic surgery system according to one embodiment of the invention;

Figure 2 is an oblique view of an input device of a master subsystem of the laparoscopic surgery system shown in Figure 1;

25 Figure 3 is a block diagram illustrating certain functionality and certain signals produced and used by the system shown in Figure 1;

30 Figure 4 is an oblique view of a tool holder with a tool in the form of an end effector held thereby, in an insertion tube of the laparoscopic surgery system shown in Figure 1;

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- Figure 5 is a schematic representation of current and previous value buffers maintained by a master apparatus of the system shown in Figure 1 and updated according to the functions shown in Figures 6, 8A and 8B;
- 5 Figure 6 is a block diagram of a storage routine executed by the master apparatus in response to detection of a signal transition of an enablement signal produced in response to user input;
- 10 Figure 7 is an oblique view of the input device shown in Figure 2 and the tool holder shown in Figure 4 showing relationships between base axes of the input device and the end effector;
- 15 Figures 8A-8B are successive portions of a flowchart representing codes executed by a master apparatus of the system shown in Figure 1, to provide for computation of an alignment difference between the input device shown in Figure 2 and the end effector shown in Figure 4 and for controlling translational movement of the end effector and for controlling the type of control signals sent to a slave subsystem of the laparoscopic surgery system shown in Figure 1, based on the computed alignment difference;
- 20 Figure 9 is a flowchart of an alternative block of code optionally replacing the block of code shown at 204 and 206 in Figure 8B;
- 25 Figure 10 is a schematic diagram of a visual representation of alignment difference between the input device and the end effector, for embodiments where alignment is defined as being when a single input device axis and a single end effector axis are coincident; and

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Figure 11 is a schematic diagram of a visual representation of alignment difference between the input device and the end effector where alignment is defined as coincidence of all axes of the input device reference frame and end effector reference frame. i.e. frame x_1, y_1, z_1 coincident with x_2, y_2, z_2 in FIG. 7.

DETAILED DESCRIPTION

Referring to Figure 1, a robotic control system in the form of a laparoscopic surgery system is shown generally at 50. The system includes a master subsystem 52 and a slave subsystem 54. The master subsystem 52 may be located anywhere in the world, but for the purposes of this description it will be considered to be in an operating room. The slave subsystem 54 is located in the operating room.

In the embodiment shown, the master subsystem 52 comprises a workstation 56 having first and second input devices 58 and 60 and a viewer 62 in communication with a master apparatus 64 comprising at least one processor. The first and second input devices 58 and 60 are operable to be actuated by respective hands of a user such as a surgeon, for example, who will perform the laparoscopic surgery by manipulating the first and second input devices of the master subsystem 52 to control corresponding laparoscopic tools 66 and 67 on the slave subsystem 54.

The viewer 62 may include an LCD display 68, for example, for displaying images acquired by a camera 70 on the slave subsystem 54, to enable the user to see the laparoscopic tools 66 and 67 inside the patient while manipulating the first and second input devices 58 and 60 to cause the tools to move in desired ways to perform the surgery. The first and second input devices 58 and 60 produce position and rotation signals that are received by the master apparatus 64 and the master apparatus produces slave control signals that are transmitted by wires 72 or wirelessly, for example, from the master subsystem 52 to the slave subsystem 54.

The slave subsystem **54** includes a slave computer **74** that receives the slave control signals from the master subsystem **52** and produces motor control signals that control motors **76** on a drive mechanism of a tool controller **78** of the slave subsystem, to
5 extend and retract wires (not shown) of respective tool positioning devices **79** and **81** to position and to rotate the tools **66** and **67**. Exemplary tool positioning devices and tools for this purpose are described in PCT patent publication WO2014201538A1. The tool positioning devices **79** and **81** extend through an insertion tube **61**, a portion of which is inserted through a small opening **63** in the patient to position end effectors **71** and **73** of
10 the tools **66** and **67** inside the patient, to facilitate the surgery.

In the embodiment shown, the workstation **56** has a support **80** having a first flat surface **82** for supporting the first and second input devices **58** and **60** in positions that are comfortable to the user whose hands are actuating the first and second input devices **58**
15 and **60**.

In the embodiment shown, the slave subsystem **54** includes a cart **84** in which the slave computer **74** is located. The cart **84** has an articulated arm **86** mechanically connected thereto, with a tool holder mount **88** disposed at a distal end of the articulated arm.

20 In the embodiment shown, the first and second input devices **58** and **60** are the same, but individually adapted for left and right hand use respectively. In this embodiment, each input device **58** and **60** is an Omega.7 haptic device available from Force Dimension, of Switzerland. For simplicity, only input device **60** will be described, it is
25 being understood that input device **58** operates in the same way.

Referring to Figure 2, generally each Omega.7 haptic device includes a base plate **90** that supports a control unit **92** having arms **94**, **96**, **98** connected to a gimbal-mounted handle **102** that can be grasped by the hand of a user and rotated about orthogonal
30 axes x_1 , y_1 and z_1 of a first Cartesian reference frame having an origin at a point

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midway along the axis of a cylinder that forms part of the handle **102**. This first Cartesian reference frame may be referred to as the handle reference frame. The origin may be referred to as the handle position **104**.

- 5 The arms **94**, **96**, **98** facilitate translational movement of the handle **102** and hence the handle position **104**, in space, and confine the movement of the handle position within a volume in space. This volume may be referred to as the handle translational workspace.
- 10 The handle **102** is mounted on a gimbal mount **106** having a pin **108**. The base plate **90** has a calibration opening **110** for receiving the pin **108**. When the pin **108** is received in the opening **110**, the haptic device is in a calibration position that is defined relative to a fixed master Cartesian reference frame comprising orthogonal axes x_r , y_r , z_r generally in the center of the handle translational workspace. In the embodiment
- 15 shown, this master reference frame has an x_r - z_r plane parallel to the flat surface **82** and a y_r axis perpendicular to the flat surface. In the embodiment shown, the z_r axis is parallel to the flat surface **82** and is coincident with an axis **112** passing centrally through the control unit **92** so that pushing and pulling the handle **102** toward and away from the center of the control unit **92** along the axis **112** in a direction parallel to the flat
- 20 surface **82** is movement in the z_r direction.

- The control unit **92** has sensors (not shown) that sense the positions of the arms **94**, **96**, **98** and the rotation of the handle **102** about each of the x_1 , y_1 and z_1 axes and produces signals representing the handle position **104** (i.e. the center of the handle **102**) in the
- 25 workspace and the rotational orientation of the handle **102** relative to the fixed master reference frame x_r , y_r , z_r . In this embodiment, these position and orientation signals are transmitted on wires **111** of a USB bus to the master apparatus **64**. More particularly, the control unit **92** produces current handle position signals and current handle orientation signals that represent the current position and orientation of the

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handle **102** by a current handle position vector $\bar{P}_{MCURR}$ and a current handle rotation matrix R_{MCURR} , relative to the fixed master reference frame x_r, y_r, z_r .

For example, the current handle position vector $\bar{P}_{MCURR}$ is a vector $\begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix}$, where $x_1, y_1,$

and z_1 represent coordinates of the controller position within the handle workspace
5 relative to the fixed master reference frame, x_r, y_r, z_r .

The current handle rotation matrix R_{MCURR} is a **3x3** matrix $\begin{bmatrix} x_{1x} & y_{1x} & z_{1x} \\ x_{1y} & y_{1y} & z_{1y} \\ x_{1z} & y_{1z} & z_{1z} \end{bmatrix}$, where the

columns of the matrix represent the axes of the handle reference frame x_1, y_1, z_1
written in the fixed master reference frame x_r, y_r, z_r . R_{MCURR} thus defines the current
rotational orientation of the handle **102** in the handle translational workspace, relative to
10 the x_r, y_r, z_r master reference frame.

The current handle position vector $\bar{P}_{MCURR}$ and current handle rotation matrix R_{MCURR} are
transmitted in the current handle position and orientation signals on wires **111** of the
USB bus, for example to the master apparatus **64** in Figure 1.

15

In addition, in the embodiment shown, the master apparatus **64** is coupled to a
footswitch **170** actuable by the user (surgeon) to provide a binary enablement signal to
the master apparatus **64**. When the footswitch **170** is not activated, i.e. not depressed,
the enablement signal is in an active state and when the footswitch **170** is depressed
20 the enablement signal is in an inactive state. The footswitch **170** thus controls the state
of the enablement signal. As will be seen below, the enablement signal allows the user
to cause the master apparatus **64** to selectively enable and disable movement of the
end effectors in response to movement of the handles **102**.

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Referring now to Figure 7, the end effector **73** and related structures are described. The fixed slave reference frame has axes x_s , y_s and z_s which intersect at a point referred to as the slave fixed base position **128**, lying on the longitudinal axis **136** of the insertion tube **61** and contained in a plane perpendicular to the longitudinal axis **136** and containing a distal edge **103** of the insertion tube **61**. The z_s axis is coincident with the longitudinal axis **136** of the insertion tube **61**. The x_s - z_s plane thus contains the longitudinal axis **136** of the insertion tube **61** and the x_s and y_s axes define a plane perpendicular to the longitudinal axis **136** of the insertion tube **61**.

In the embodiment shown, end effector **73** includes a pair of gripper jaws. Orthogonal axes x_2 , y_2 and z_2 of an end effector Cartesian reference frame have an origin at the intersection at a mid-point between gripper jaws of the end effector **73**. The origin of the end effector reference frame may be referred to as the slave end effector position **150** relative to the fixed slave reference frame x_s , y_s , z_s .

New end effector positions and end effector orientations are calculated by the end effector position and orientation calculation block **116** shown in Figure 3, in response to the current handle position signals $\bar{P}_{MCURR}$ and current handle orientation signals R_{MCURR} and are represented by a new end effector position vector $\bar{P}_{EENEW}$ and an rotation matrix R_{EENEW} , relative to the x_s , y_s , z_s fixed slave reference frame.

For example, the new end effector position vector $\bar{P}_{EENEW}$ is a vector $\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix}$, where x_2 ,

y_2 , and z_2 represent coordinates of the end effector position within the end effector workspace relative to the x_s , y_s , z_s fixed slave reference frame.

The end effector rotation matrix R_{EENEW} is a **3x3** matrix $\begin{bmatrix} x_{2x} & y_{2x} & z_{2x} \\ x_{2y} & y_{2y} & z_{2y} \\ x_{2z} & y_{2z} & z_{2z} \end{bmatrix}$, where the

columns of the R_{EENEW} matrix represent the axes of the end effector reference frame x_2 ,

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y_2, z_2 written in the fixed slave reference frame x_s, y_s, z_s . R_{EENEW} thus defines a new orientation of the end effector **73** in the workspace, relative to the x_s, y_s, z_s reference frame.

5 Referring back to Figure 1, in the embodiment shown, the master apparatus **64** is controlled by program codes stored on a non-transitory computer readable medium such as a disk drive **114**. The codes direct the master apparatus **64** to perform various functions. Referring to Figures 1 and 3, these functions may be grouped into categories and expressed as functional blocks of code including an end effector position and orientation calculation block **116**, a kinematics block **118**, a motion control block **120**, a
10 feedback force control block **122**, and a base setting block **216**, all stored on the disk drive **114** of the master apparatus **64**. For ease of description, these blocks are shown as functional blocks within the master apparatus **64** in Figure 3. These functional blocks are executed separately but in the same manner for each input device **58** and **60**. The
15 execution of these functional blocks for only input device **60** and end effector **73** will be described, it being understood they are separately executed in the same way for input device **58** and end effector **71** to achieve control of end effectors **73** and **71** by right and left hands respectively of the user.

20 Generally, the end effector position and orientation calculation block **116** includes codes that direct the master apparatus **64** to produce new end effector position and rotation signals, later referred to herein as $\bar{P}_{EENEW}$ and R_{EENEW} , and includes codes that direct the master apparatus **64** to produce a translation lock signal for receipt by the feedback force control block **122**.

25

The kinematics block **118** includes codes that direct the master apparatus **64** to produce configuration variables in response to the newly calculated end effector position and rotation signals.

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The motion control block **120** includes codes that direct the master apparatus **64** to produce the slave control signals, in response to the configuration variables.

5 The feedback force control block **122** directs the master apparatus **64** to receive the translation lock signal from the end effector position and orientation calculation block **116** and to receive the configuration variables from the kinematics block **118** and to produce a haptic feedback control signal that is provided to the control unit **92** to cause the control unit to present a force to the user if the user tries to cause translational movement of the handle **102**. This impedes translational movement of the handle **102**
10 but allows the handle **102** to be rotated to allow it to be brought into rotational alignment with the end effector **73**.

The base setting block **216** is executed asynchronously, whenever the enablement signal transitions from an inactive state to an active state, such as when the user
15 releases the footswitch **170**. The base setting block **216** directs the master apparatus **64** to set new reference positions and orientations for the handle **102** and end effector **73**, respectively as will be described below.

Referring back to Figure **1**, in the embodiment shown, the slave control signals
20 represent wire length values indicating how much certain wires of a given tool positioning device **81** of the slave subsystem **54** must be extended or retracted to cause the end effector **73** of the tool **67** to be positioned and rotated in a manner determined by positioning and rotating the corresponding input device **60**.

25 Referring to Figures **1** and **3**, the slave control signals representing the wire length values are transmitted to the slave computer **74**, which has its own computer readable medium encoded with communication interface codes **124** for directing the slave computer to receive the slave control signals from the master apparatus **64**. The computer readable medium is also encoded with motor control signal generator codes
30 **126** for causing the slave computer **74** to generate motor control signals for controlling

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the motors **76** on the tool controller **78** to extend and retract the wires controlling the attached tool positioning device **81** according to the wire length values represented by the control signals from the master apparatus **64**.

- 5 The kinematics block **118** receives newly calculated end effector position and orientation signals ($\bar{P}_{EENEW}$ and R_{EENEW}) each time the end effector position and orientation calculation block **116** is executed. In response, the kinematics block **118** produces the configuration variables described below.
- 10 Referring to Figure 3, generally, the codes in the kinematics block **118** direct the master apparatus **64** to calculate values for the above configuration variables in response to the end effector position and rotation signals $\bar{P}_{EENEW}$ and R_{EENEW} produced by the end effector position and orientation calculation block **116** and these calculated configuration values generally define a tool holder pose required to position end effector **73** at a
- 15 desired location and at a desired orientation in its workspace.

- Referring to Figure 4, the tool positioning device **81** has a first articulated segment **130**, referred to as an s-segment and a second articulated segment **132** referred to as a distal segment. The segments **130** and **132** each include a plurality of "vertebra" **324**.
- 20 The s-segment **130** begins at a distance from the insertion tube **61**, referred to as the insertion distance q_{ins} , which is the distance between the fixed slave base position **128** defined as the origin of the slave fixed base reference frame x_s, y_s, z_s and a first position **330** at the origin of a first position reference frame x_3, y_3, z_3 . The insertion distance q_{ins} represents an unbendable portion of the tool positioning device **81** that extends out
- 25 of the end of the insertion tube **61**. In the embodiment shown, the insertion distance q_{ins} may be about 10 – 20 mm, for example. In other embodiments, the insertion distance q_{ins} may be longer or shorter, varying from 0 – 100 mm, for example.

- The s-segment **130** extends from the first position **330** to a third position **334** defined as
- 30 an origin of a third reference frame having axes x_5, y_5, z_5 and is capable of

assuming a smooth S-shape when control wires (not shown) inside the s-segment **130** are pushed and pulled. The s-segment **130** has a mid-point at a second position **332**, defined as the origin of a second position reference frame having axes x_4 , y_4 , z_4 . The s-segment **130** has a length L_1 , which in the embodiment shown may be about **65** mm, for example.

The distal segment **132** extends from the third position **334** to a fourth position **336** defined as an origin of a fourth reference frame having axes x_6 , y_6 , z_6 . The distal segment **132** has a length L_2 , which in the embodiment shown may be about **23** mm, for example.

The tool **67** also has an end effector length, which in the embodiment shown is a gripper length L_3 that extends from the fourth position **336** to the end effector position **150** defined as the origin of axes x_2 , y_2 , and z_2 . The gripper length L_3 , in this embodiment, may be about **25** mm, for example. The slave base position **128**, first position **330**, second position **332**, third position **334**, fourth position **336** and end effector position **150** may collectively be referred to as tool reference positions.

As explained in PCT patent publication WO2014201538A1 by pushing and pulling on certain control wires inside the tool positioning devices **79** and **81**, the s-segment **130** can be bent into any of various degrees of an S-shape, from straight as shown in Figure **7** to a partial S-shape as shown in Figure **4** to a full S-shape. The s-segment **130** is sectional in that it has a first section **320** and a second section **322** on opposite sides of the second position **332**. The first and second sections **320** and **322** lie in a first bend plane containing the first position **330**, second position **332**, and third position **334**. The first bend plane is at an angle δ_{prox} to the x_s - z_s plane of the fixed slave reference frame. The first section **320** and second section **322** are bent in the first bend plane through opposite but equal angles θ_{prox} such that no matter the angle θ_{prox} or the bend plane angle δ_{prox} , the z_5 axis of the third position **334** is always parallel to and aligned in the same direction as the z_s axis of the fixed slave

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base position **128**. Thus, by pushing and pulling on the control wires within the tool positioning device **81**, the third position **334** can be placed at any of a number of discrete positions within a cylindrical volume in space. This volume may be referred to as the s-segment workspace.

5

In addition, the distal segment **132** lies in a second bend plane containing the third position **334** and the fourth position **336**. The second bend plane is at an angle δ_{dist} to the x_s - z_s plane of the fixed slave reference frame. The distal segment **132** is bent in the second bend plane at an angle θ_{dist} . Thus, by pushing and pulling the control wires within the tool positioning device **81**, the fourth position **336** can be placed within another volume in space. This volume may be referred to as the distal workspace. The combination of the s-segment workspace plus the distal workspace can be referred to as the tool positioning device workspace, as this represents the total possible movement of the tools **66** and **67** as effected by the respective tool positioning devices **79** and **81**.

10
15

The distance between the fourth position **336** and the end effector position **150** is the distance between the movable portion of the distal segment **132** and the tip of the gripper end effector **73** in the embodiment shown, i.e. the length L_3 . Generally, the portion of the gripper between the fourth position **336** and the end effector position **150** (L_3) will be unbendable.

20

In the embodiment shown, the end effector **73** is a gripper jaw tool that is rotatable about the z_2 axis in the x_2 - y_2 plane of the end effector reference frame, the angle of rotation being represented by an angle γ relative to the positive x_2 axis. Finally, the gripper jaws may be at any of varying degrees of openness from fully closed to fully open (as limited by the hinge). The varying degrees of openness may be defined as the "gripper".

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In summary therefore, the configuration variables provided by the kinematic block **118** codes are as follows:

5 q_{ins} : represents a distance from the slave base position **128** defined by axes x_s , y_s , and z_s to the first position **330** defined by axes x_3 , y_3 and z_3 where the s-segment **130** of the tool positioning device **81** begins;

10 δ_{prox} : represents a first bend plane in which the s-segment **130** is bent relative to the $x_s - y_s$ plane of the fixed slave reference frame;

θ_{prox} : represents an angle at which the first and second sections **320** and **322** of the s-segment **130** is bent in the first bend plane;

15 δ_{dist} : represents a second bend plane in which the distal segment **132** is bent relative to the $x_s - y_s$ plane of the fixed slave reference frame;

θ_{dist} : represents an angle through which the distal segment **132** is bent in the second bend;

20 γ : represents a rotation of the end effector **73** about axis z_2 ; and

25 Gripper: represents a degree of openness of the gripper jaws of the end effector **73**. (This is a value which is calculated in direct proportion to a signal produced by an actuator (not shown) on the handle **102** indicative of an amount of pressure the operator exerts by squeezing the handle).

To calculate the configuration variables, it will first be recalled that the end effector rotation matrix R_{EENEW} is a **3x3** matrix:

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$$\begin{bmatrix} x_{2x} & y_{2x} & z_{2x} \\ x_{2y} & y_{2y} & z_{2y} \\ x_{2z} & y_{2z} & z_{2z} \end{bmatrix}.$$

Since the last column of R_{EENEW} is the z-axis of the end effector reference frame written relative to the fixed slave reference frame x_s , y_s and z_s , the values θ_{dist} , δ_{dist} , and γ associated with the distal segment **132** can be calculated according to the relations:

$$\theta_{dist} = \frac{\pi}{2} - \text{atan2} \left(\sqrt{z_{2x}^2 + z_{2y}^2}, z_{2z} \right) \quad (2)$$

$$\delta_{dist} = -\text{atan2}(z_{2y}, z_{2x}) \quad (3)$$

If $|\delta_{dist}| > \frac{\pi}{2}$

$$\gamma = \text{atan2}(-y_{2z}, x_{2z}) - \delta_{dist} + \pi \quad (4a)$$

else

$$\gamma = \text{atan2}(y_{2z}, -x_{2z}) - \delta_{dist} \quad (4b)$$

These values can then be used to compute the locations of the third position **334**, the fourth position **336**, and the end effector position **150** relative to the fixed slave base position **128**. The locations may be expressed in terms of vectors $\bar{p}_{3/s}$ from the fixed slave base position **128** to the first position **330**, $\bar{p}_{4/3}$ from the third position **334** to the fourth position **336**, and $\bar{p}_{5/4}$ from the fourth position **336** to the end effector position **150**. $\bar{p}_{3/s}$ is then calculated from $\bar{P}_{EENEW}$ as follows:

$$\bar{p}_{3/s} = \bar{p}_{EENEW} - \bar{p}_{4/3} - \bar{p}_{5/4}, \quad (5)$$

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where:

$$\bar{p}_{4/3} \cdot \bar{i} = \frac{-L_2 \cos \delta_{dist} (\sin \theta_{dist} - 1)}{\frac{\pi}{2} - \theta_{dist}} \quad (6a)$$

$$\bar{p}_{4/3} \cdot \bar{j} = \frac{L_2 \sin \delta_{dist} (\sin \theta_{dist} - 1)}{\frac{\pi}{2} - \theta_{dist}} \quad (6b)$$

$$\bar{p}_{4/3} \cdot \bar{k} = \frac{L_2 \cos(\theta_{dist})}{\frac{\pi}{2} - \theta_{dist}} \quad (6c)$$

5

$$\bar{p}_{5/4} \cdot \bar{i} = L_3 \cos(\delta_{dist}) \cos(\theta_{dist}) \quad (7a)$$

$$\bar{p}_{5/4} \cdot \bar{j} = -L_3 \sin(\delta_{dist}) \cos(\theta_{dist}) \quad (7b)$$

$$\bar{p}_{5/4} \cdot \bar{k} = L_3 \sin(\theta_{dist}), \quad (7c)$$

10 where:

$\bar{i}$ is a unit vector in the x direction;

$\bar{j}$ is a unit vector in the y direction; and

$\bar{k}$ is a unit vector in the z direction.

15 Once the vector from the fixed slave base position **128** to the third position **334** ($\bar{p}_{3/s}$) is known, the configuration variables, δ_{prox} and θ_{prox} , for the s-segment **130** can be found. The configuration variable δ_{prox} associated with the s-segment **130** is calculated by solving the following two equations for δ_{prox} :

$$\bar{p}_{3/s} \cdot \bar{i} = \frac{-L_1 \cos \delta_{prox} (\sin \theta_{prox} - 1)}{\frac{\pi}{2} - \theta_{prox}} \quad (8a)$$

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$$\bar{p}_{3/s} \cdot \bar{j} = \frac{L_1 \sin \delta_{prox} (\sin \theta_{prox} - 1)}{\frac{\pi}{2} - \theta_{prox}}. \quad (8b)$$

The ratio of (8b) and (8a) gives

$$\delta_{prox} = \text{atan2}(-\bar{p}_{3/s} \cdot \bar{j}, \bar{p}_{3/s} \cdot \bar{i}), \quad (9)$$

where $\bar{i}$ and $\bar{j}$ are unit vectors in the x and y directions respectively.

5

A closed form solution cannot be found for θ_{prox} , thus θ_{prox} must be found with a numerical equation solution to either of equations (8a) or (8b). A Newton-Raphson method, being a method for iteratively approximating successively better roots of a real-valued function, may be employed, for example. The Newton-Raphson method can be implemented using the following equations:

10

$$f(\theta_{prox}) = \frac{L_1}{\frac{\pi}{2} - \theta_{prox}} \cos \delta_{prox} (1 - \sin \theta_{prox}) - \bar{p}_{3/s} \cdot \bar{i} = 0, \quad (10)$$

where $\bar{i}$ is the unit vector in the x direction.

The equation (10) is equation (8a) rewritten in the form $f(\theta_{prox})=0$. The Newton-Raphson method tends to converge very quickly because in the range $0 < \theta_{prox} < \pi$, the function has a large radius of curvature and has no local stationary points. Following the Newton-Raphson method, successive improved estimates of θ_{prox} can be made iteratively to satisfy equation (10) using the following relationship:

15

$$\theta_{n+1} = \theta_n - \frac{f(\theta_n)}{f'(\theta_n)} \quad (11)$$

20

Finally, upon determination of θ_{prox} , the following equation can be used to find q_{ins} ,

$$q_{ins} = -\bar{p}_{3/s} \cdot \bar{k} - \frac{L_1 \cos \theta_{prox}}{\frac{\pi}{2} - \theta_{prox}}, \quad (12)$$

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where:

$\bar{k}$ is the unit vector in the z direction;

$\bar{p}_{3/s} \bullet \bar{k}$ is the dot product of the vector $\bar{p}_{3/s}$ and the unit vector $\bar{k}$.

5 The codes in the kinematics block **118** shown in Figure **6** direct the master apparatus **64** to calculate values for the above configuration variables in response to the end effector position and orientation signals $\bar{P}_{EE\text{NEW}}$ and $R_{EE\text{NEW}}$ produced by the end effector position and orientation calculation block **116** and these calculated configuration variables generally define a tool positioning device pose required to position the end
10 effector **73** at a desired location and at a desired orientation in the end effector workspace.

It will be appreciated that configuration variables are produced for each end effector **71** and **73** and therefore in the embodiment shown, two sets of configuration variables
15 which will be referred to as left and right configuration variables respectively are produced and forwarded or otherwise made available to the motion control block **120** and the feedback force control block **122**.

Referring to Figure **5**, the master apparatus **64** queries the control unit **92** for the handle
20 position vector $\bar{P}_{MC\text{CURR}}$ and handle rotation matrix $R_{MC\text{CURR}}$ periodically, at a sample rate of about 1 kHz. These values are stored by the master apparatus **64** in a first "current" buffer **140** having a first store **142** storing the three values representing the currently acquired handle position vector $\bar{P}_{MC\text{CURR}}$ and a second store **144** storing the nine values representing the acquired handle rotation matrix $R_{MC\text{CURR}}$.

25

Referring to Figures **2** and **5**, the master apparatus **64** also stores values x_{mb} , y_{mb} , z_{mb} representing a definable master base position represented by a base position vector $\bar{P}_{M\text{BASE}}$ in a third store **146** and stores values representing a definable master base rotation matrix $R_{M\text{BASE}}$ in a fourth store **148**. The master apparatus **64** initially causes

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the definable master base position vector $\bar{P}_{\text{MBASE}}$ to be set equal to the current handle position vector $\bar{P}_{\text{MCURR}}$ on startup of the system and causes the definable master base rotation matrix R_{MBASE} to define an orientation that is the same as the current orientation defined by the handle rotation matrix R_{MCURR} associated with the current handle rotation, on startup of the system.

Initially, therefore:

$$\bar{P}_{\text{MBASE}} = \bar{P}_{\text{MCURR}} ; \text{ and}$$

$$R_{\text{MBASE}} = R_{\text{MCURR}}$$

Thereafter, the master base position $\bar{P}_{\text{MBASE}}$ and the master base rotation matrix R_{MBASE} are maintained at the same values as on startup until the enablement signal is activated, such as by the footswitch (170 in Figures 1 and 3), which causes the enablement signal to transition from the inactive state to the active state. In response, the base setting block 216 in Figure 6 is executed to change the master base position vector $\bar{P}_{\text{MBASE}}$ and master base rotation matrix R_{MBASE} to the currently acquired master position $\bar{P}_{\text{MCURR}}$ and currently acquired master orientation R_{MCURR} respectively.

Referring to Figures 5 and 7, the master apparatus 64 further stores values $x_{\text{sb}}, y_{\text{sb}}, z_{\text{sb}}$ representing a definable slave base position $\bar{P}_{\text{EEBASE}}$ in a fifth store 152 and stores values representing a definable slave base rotation R_{EEBASE} in a sixth store 154. The master apparatus 64 initially causes the definable slave base position vector $\bar{P}_{\text{EEBASE}}$ to be set equal to the new end effector position vector $\bar{P}_{\text{EENEW}}$ and causes the definable slave base rotation matrix R_{EEBASE} to define an orientation that is the same as the orientation defined by the new end effector rotation matrix R_{EENEW} , on startup of the system.

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Initially, therefore:

$$\bar{P}_{EEBASE} = \bar{P}_{EE NEW} ; \text{ and}$$

$$R_{EEBASE} = R_{EE NEW}$$

In other words, the slave base reference frame and the end effector reference frame
5 coincide at startup.

The slave base position $\bar{P}_{EEBASE}$ and slave base rotation matrix R_{EEBASE} are maintained
at the same values as on startup until the enablement signal is activated such as by the
footswitch (170 in Figures 1 and 3), which causes the enablement signal to transition
10 from the inactive state to the active state. In response, the base setting block 216 in
Figure 6 changes the slave base position vector $\bar{P}_{EEBASE}$ and slave rotation matrix
 R_{EEBASE} to the newly calculated end effector position vector $\bar{P}_{EE NEW}$ and newly calculated
end effector rotation matrix $R_{EE NEW}$.

15 Referring to Figures 8A and 8B, the end effector position and orientation calculation
block 116 is executed each time a set of new values for $\bar{P}_{MCURR}$ and R_{MCURR} are
acquired from the control unit 92. The end effector position and orientation calculation
block 116 directs the master apparatus 64 to produce and store, in a seventh store 162
in Figure 5, values representing the new end effector position vector $\bar{P}_{EE NEW}$ and to
20 produce and store, in an eighth store 164 in Figure 5, values representing the desired
end effector rotation matrix $R_{EE NEW}$.

After new values for $\bar{P}_{MCURR}$ and R_{MCURR} are acquired from the control unit 92, block 160
in Figure 8A directs the master apparatus 64 to generate new end effector position
25 signals $\bar{P}_{EE NEW}$ and new end effector orientation signals $R_{EE NEW}$ representing a desired
end effector position 150 and desired end effector orientation, relative to the slave base
position 128 and the slave base orientation.

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The new end effector position signals $\bar{P}_{EENEW}$ and new end effector orientation signals R_{EENEW} are calculated according to the following relations:

$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}$$

5 and

$$R_{EENEW} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}$$

Where: $\bar{P}_{EENEW}$ is the new end effector position vector that represents the new
desired position of the end effector **73** in the end effector workspace,
10 relative to the slave base reference frame;

A is a scalar value representing a scaling factor in translational motion
between the master and the slave;

15 $\bar{P}_{MCURR}$ is the current representation of the handle position vector stored in
the first store **142**, the handle position vector being relative to the master
reference frame;

20 $\bar{P}_{MBASE}$ is the last-saved position vector $\bar{P}_{MCURR}$ for the handle that was
saved upon the last inactive to active state transition of the enablement
signal such as by release of the footswitch **170** or on system initialization
or by operation of a control interface by the user;

25 $\bar{P}_{EEBASE}$ is the last-saved position vector $\bar{P}_{EENEW}$ for the end effector **73** that
was saved upon the last inactive to active state transition of the
enablement signal;

R_{EENEW} is the new end effector rotation matrix representing the current
orientation of the end effector **73** relative to the slave reference frame;

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R_{EEBASE} is the rotation matrix representing the last-saved rotation of the end effector **73** saved upon the last inactive to active state transition of the enablement signal;

5

R_{MBASE}^{-1} is the inverse of rotation matrix R_{MBASE} , where R_{MBASE} is a rotation matrix representing the last-saved rotation of the handle **102** saved upon the last inactive to active state transition of the enablement signal;

10

R_{MCURR} is the currently acquired rotation matrix representing the orientation of the handle **102** relative to the master reference frame;

When the enablement signal is in the active state, as determined at block **161** in Figure **8A**, the master apparatus **64** is directed to the blocks shown generally at **200** in Figure **8B** to detect a rotational alignment difference, i.e. a difference, between the orientation of the handle **102** (R_{MCURR}) and the newly calculated end effector orientation (R_{EENEW}), the difference representing a difference in physical alignment of these entities.

A difference in alignment can comprise any single degree of freedom or combination of degrees of freedom of any representation of orientation. In the general case, the alignment error would be computed considering all three orientation degrees of freedom. This case would, therefore, require that to be aligned, the reference frames described by R_{EENEW} and R_{MCURR} be coincident.

In the general case, blocks **204** and **206** shown in Figure **8B** could be carried out to obtain the alignment error.

Block **204** directs the master apparatus **64** to compute a rotation matrix that carries the newly calculated end effector orientation into the current handle orientation ($R_{EE_TO_MASTER}$) by the relation:

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$$R_{EE_TO_MASTER} = R_{EE_NEW}^{-1} R_{MCURR}$$

Where: $R_{EE_NEW}^{-1}$ is the inverse matrix of the end effector rotation matrix R_{EE_NEW}
 5 represented by a **3x3** matrix stored in the eighth store **164**; and
 R_{MCURR} is the current handle rotation matrix represented by the **3x3** matrix
 stored in the second store **144**

Then, block **206** directs the master apparatus **64** to compute an angle of rotation
 10 associated with $R_{EE_TO_MASTER}$ ($\phi_{EE_TO_MASTER}$) by the relation:

$$\phi_{EE_TO_MASTER} = \arccos (0.5 \text{ trace}(R_{EE_TO_MASTER}) - 1)$$

This angle of rotation ($\phi_{EE_TO_MASTER}$) represents the alignment difference between the
 15 orientation of the handle **102** and the newly calculated end effector orientation.

In a special case, applicable to the embodiment described here, it is desirable that to be
 aligned, only the z-axes of the reference frames described by R_{EE_NEW} and R_{MCURR} be
 coincident. In this case the master handle and the slave end effector point in the same
 20 direction and the roll about their z-axis is not considered.

In this special case therefore, blocks **204** and **206** shown in Figure **8B** are replaced with
 block **205** shown in Figure **9** which involves the following computation

$$25 \quad \phi_{EE_TO_MASTER} = \arccos (R_{EE_NEW}(1,3)*R_{MCURR}(1,3) + R_{EE_NEW}(2,3)*R_{MCURR}(2,3) + R_{EE_NEW}(3,3)*R_{MCURR}(3,3))$$

This computation represents the angle obtained from the dot product of the z-axes of
 the master and slave reference frames.

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After determining the angle of rotation $\phi_{EE_TO_MASTER}$, using either the generic method shown in blocks **204** and **206** or the method that assumes the z axes of the master and slave reference frames are aligned, block **208** directs the master apparatus **64** to determine whether the alignment difference meets a criterion. A first criterion may be
 5 that the alignment difference is not less than a threshold value, and a second criterion may be that the alignment difference is less than the threshold value, for example.

If the alignment difference meets the second criterion (i.e. is less than the threshold value), block **214** directs the master apparatus **64** to release any previously produced
 10 translation lock signal locking the master input device **60** by setting the translation lock signal inactive, thereby signaling the feedback force control block **122** of Figure 3 to stop providing haptic feedback control signals that may have been preventing translational movement of the handle **102**.

Then block **215** directs the master apparatus **64** to signal the motion control block **120**
 15 of Figure 3 to indicate that motion control signals based on the newly calculated values for $\bar{P}_{EE_NEW}$ and R_{EE_NEW} are to be sent to the slave computer **74**. This causes the end effector **73** to assume a position and orientation determined by the current position and current orientation of the handle **102** when the alignment difference meets the second
 20 criterion.

Block **159** then directs the master apparatus **64** to copy the newly calculated end effector position vector $\bar{P}_{EE_NEW}$ and end effector rotation matrix R_{EE_NEW} into stores **147**
 and **149** of the previous buffer **141**. The newly calculated end effector position vector
 25 $\bar{P}_{EE_NEW}$ and newly calculated end effector rotation matrix R_{EE_NEW} are thus renamed as “previously calculated end effector position vector” $\bar{P}_{EE_PREV}$ and “previously calculated end effector rotation matrix” R_{EE_PREV} . By storing the newly calculated end effector position vector $\bar{P}_{EE_NEW}$ and newly calculated end effector rotation matrix R_{EE_NEW} , as previously calculated end effector position vector $\bar{P}_{EE_PREV}$ and previously calculated end

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effector rotation matrix R_{EEPREV} , a subsequently acquired new end effector position vector $\bar{P}_{EENEW}$ and subsequently acquired new end effector rotation matrix R_{EENEW} can be calculated from the next current handle position vector $\bar{P}_{MCURR}$ and next current handle position matrix R_{MCURR} .

5

If at block **208** the alignment difference meets the first criterion, i.e. alignment difference is not less than the threshold value but does not meet the second criterion, block **210** directs the master apparatus **64** to set the translation lock signal active to inform the feedback force control block (**122** in Figure **3**) that it should cause the master apparatus **64** to send haptic feedback control signals to the control unit **92** to cause it to provide haptic feedback that impedes translational movement of the handle **102** while at the same time permitting rotational movement of the handle **102**.

After executing block **210**, the master apparatus **64** may be directed by an optional block, block **212**, to start a program thread that directs the master apparatus **64** to produce annunciation signals for causing an annunciator to annunciate an indication of a relative alignment of the handle **102** and the end effector. The annunciator may include an audio producing device that changes a frequency of a signal in response to proximity of alignment and/or may include a display, possibly integrated into the viewer **62**, for example, to provide a visual indication of the relative alignment between the end effector **73** and the handle **102**. Such a visual presentation may be provided in the manner shown in Figure **10**, for example, for embodiments where alignment is defined as being when the z axes of the reference frames described by R_{EENEW} and R_{MCURR} are coincident. The visual representation includes a circular region **240**, with an end effector marker **242** shown in a center thereof and a circular boundary **244** shown around the end effector marker to mark a boundary set by the alignment threshold value. The radius of the circular boundary **244** is larger when the alignment threshold is greater and smaller when the alignment threshold is smaller. The visual representation further includes a handle position representation **246** shown in a position depicting a distance and direction of the handle **102** relative to the end effector marker **242**. The

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visual representation can be produced considering the z-axis of the end effector reference frame and the z-axis of the master handle reference frame. With the frame origins co-located at the center of the circular region **240** and the z-axis of the end effector pointing into the page normal to the page, a projection of the tip of the z axis of the master handle will appear as a dot in the circular region **240**, the dot representing the handle position **246** and depicting a distance and direction of the misalignment relative to the z-axis of the end effector as depicted by the end effector marker at the center of the circular region **240**. Other visual representations may alternatively be used. For example, referring to Figure **11**, in the case where alignment is defined as coincidence of the master reference frame and the end effector reference frame, two cubes **300** and **302** may be used to visually represent the orientation of the R_{MCURR} reference frame associated with the handle **102** and the reference frame R_{EENEW} associated with the end effector **73** respectively.

Referring back to Figures **8A-8B**, after executing block **210** and, optionally, after initiating execution of the visual or audio representation thread with block **212**, the master apparatus **64** is directed to block **163** causing it to set the “new” signal inactive to indicate to the motion control block **120** of Figure **3** that it should send the slave control signals based on $\bar{P}_{EEPREV}$ and R_{EEPREV} . Thus, it will be appreciated that in the embodiment described, while the alignment difference remains equal to or greater than the alignment threshold, the master apparatus **64** executes blocks **210**, **212**, and **163** whereby, the user cannot effect translational movement of the handle **102** and can only rotate the handle until the handle is rotated into a position in which the alignment difference is less than the threshold value, at which point block **208** directs the master apparatus **64** to blocks **214**, **215** and **159** which causes the master apparatus **64** to make the translation lock signal inactive, and to set the “new” signal active to indicate to the motion control block **120** that it should send the slave control signals based on $\bar{P}_{EENEW}$ and R_{EENEW} .

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Referring back to Figure 8A, at block 161, if the enablement signal is in the inactive state and while it remains in the inactive state, the master apparatus immediately executes block 163 of Figure 8B which directs the master apparatus 64 to set the “new” signal inactive to indicate to the motion control block 120 in Figure 3 that it should send the slave control signals based on the previously calculated values of $\bar{P}_{EEPREV}$ and R_{EEPREV} in the eleventh and twelfth stores 147 and 149, respectively. The wire length signals produced by the motion control block 120 thus represent wire length values derived from the last saved values of $\bar{P}_{EEPREV}$ and R_{EEPREV} , causing the end effector 73 to remain stationary because the same motion control signals as were previously determined are sent to the slave computer 74. The end effector position and orientation calculation block 116 is then ended. As long as the enablement signal is inactive, motion control signals based only on the previously calculated end effector position and orientation signals are produced.

Accordingly, when the enablement signal is in the inactive state, the handle 102 can be moved and rotated and the calculations of $\bar{P}_{EENEW}$ and R_{EENEW} will still be performed by block 160, but there will be no movement of the end effector 73, because the previous motion control signals are sent to the slave computer 74. This allows “clutching” or repositioning the handle 102 without corresponding movement of the end effector 73 and enables the end effector 73 to have increased range of movement when the end effector motion is constrained by the master controller workspace; for example, in the case where the scale factor “A” in the relation:

$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}$$

25

is such that the full range of motion in the master translational workspace does not cause the end effector to cover the full translational workspace of the slave instrument.

Referring back to Figure 3, the feedback force control block 122 is running in the background and, in response to an active translation lock signal produced by the master

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apparatus **64** at block **210** of Figure **8B**, the feedback control block **122** directs the master apparatus **64** to produce haptic feedback force control signals for receipt by the control unit **92** that cause the control unit **92** to present a haptic force to the arms **94**, **96**, **98**, to impede translational movement of the handle **102** and lock it in its current position in the handle translational workspace. In other words, the handle **102** is locked at its current position space by the haptic feedback produced by the control unit **92** in response to signals provided to it by the force control block **122**. Rotational movement of the handle **102**, can still be performed but translational movement cannot. The control unit **92** thus produces a constant handle position vector $\bar{P}_{MCURR}$ but produces a varying rotation matrix R_{MCURR} dependent on the orientation of the handle **102**.

When the translation lock signal is set inactive by block **214** of Figure **8B** by the end effector position and orientation calculation block **116**, the feedback force control block **122** directs the master apparatus **64** to send haptic feedback control signals to the control unit **92** to cause the control unit to cease providing haptic force and the user can resume translating and rotating the handle **102** to any position within the handle translational workspace.

The motion control block **120** uses the configuration values produced by the kinematics block **118** to produce wire length values by applying transfer functions to the calculated configuration variables to determine required wire lengths. Such transfer functions can be derived theoretically and/or empirically, for example, for the specific tools used. The motion control block **120** is responsive to the "new" signal controlled by blocks **215** and **163** of Figure **8B** and causes the current wire length values to be represented by the slave control signals when the enablement signal is active and the alignment difference is less than the threshold and causes the previous wire length values to be represented by the slave control signals when the enablement signal is not active and when the enablement signal is active but the alignment difference is not less than the threshold.

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Therefore, it can be seen that when the user releases the footswitch **170** such that the enablement signal transitions from inactive to active, the slave control signals produced in response to actuation of the handle represent $\bar{P}_{EE\text{NEW}}$ and $R_{EE\text{NEW}}$ only if the alignment difference is less than the alignment threshold. Otherwise, if, when the enablement signal transitions from inactive to active, the alignment difference is not less than the alignment threshold, the previous wire length values are represented by the slave control signals.

In addition, when the alignment difference is not less than the alignment threshold, the handle is locked against translational movement and, optionally, the user is provided with a visual display of the relative alignment between the end effector **73** and the handle **102**. In this state the user can only rotate the handle **102** until it is positioned into an orientation in which it is aligned with the end effector **73**, within the bounds of the alignment threshold, at which time the newly calculated $\bar{P}_{EE\text{NEW}}$ and $R_{EE\text{NEW}}$ values are again represented in the control signals sent from the master apparatus **64** to the slave computer **74** to again provide for normal operation where the end effector **73** is positioned and rotated in response to positioning and rotation of the handle **102**.

For example, referring to Figure **7**, the use could push the handle **102** in the Z_{mb} direction toward the control unit **92** while the enablement signal is active, whereby the end effector **73** is moved in the Z_{sb} direction corresponding to the movement of the handle **102**. Then, the user can actuate the footswitch **170** to set the enablement signal inactive and while the footswitch is actuated, withdraw the handle **102** along the Z_{mb} axis in the opposite direction, away from the control unit **92**. Since the motion control signals are produced based on the previously calculated end effector position $\bar{P}_{EE\text{PREV}}$ and the previously calculated end effector rotation $R_{EE\text{PREV}}$ when the footswitch is actuated, the end effector **73** remains stationary.

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Then, the user can release the footswitch **170** to set the enablement signal active and, in response to the enablement signal transitioning from the “not active” state to the “active” state, block **216** of Figure **6** directs the master apparatus **64** to store the current values of the handle position $\bar{P}_{MCURR}$ and handle orientation R_{MCURR} signals as new values of the master base position signals $\bar{P}_{MBASE}$ and new values of the master base orientation signals R_{MBASE} respectively, and stores the newly calculated values of the end effector position signals $\bar{P}_{EENEW}$ and newly calculated values of the end effector **73** rotation signals R_{EENEW} as new values of the end effector base position signals $\bar{P}_{EEBASE}$ and new values of the end effector base orientation signals R_{EEBASE} respectively.

Otherwise, upon release of the footswitch, the end effector **73** would “snap” to the absolute position directly determined by the position of the handle **102** and this could be dangerous if it were to occur inside a patient because the end effector **73** could tear into tissue or internal organs of the patient with possibly life-threatening effects. The user can then continue pushing the handle **102** in the z_{mb} direction toward the control unit **92** while the end effector **73** is further moved in the z_{sb} direction corresponding to the movement of the handle **102**.

This provides a clutching effect which is achieved by causing movements of the handle **102** and movements of the end effector **73** to be made relative to the last-saved master base position ($\bar{P}_{MBASE}$) and rotation (R_{MBASE}) and the last saved end effector base position ($\bar{P}_{EEBASE}$) and rotation (R_{EEBASE}) respectively.

While the above described clutching effect is desirable to match the range of translational movement of the end effector **73** with the range of movement of the handle **102** and for the user to reposition their hands to a comfortable position for operation, it is not desirable for clutching to occur in rotation because this would cause a misalignment in orientation between the master and the slave, making the teleoperated slave difficult to control. In the absence of a mechanical means to maintain the orientation of the handle **102** it would be difficult for the user to rotate the handle **102** to

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cause it to be exactly aligned with the end effector **73** on release of the footswitch **170** so that normal operation can be resumed.

5 By locking the handles against translational movement when the alignment difference is not less than the threshold and by representing the previously calculated $\bar{P}_{EEPREV}$ and R_{EEPREV} in the slave control signals, a safety feature is provided whereby translational movement of the handle is prevented and all movement of the end effector **73** is prevented until the handle **102** is generally rotationally aligned with the end effector **73**.

10 While specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of operating a robotic control system comprising a master apparatus in communication with an input device having a handle capable of translational and rotational movement and a slave system having a tool positioning device holding a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle, the method comprising:

producing a desired end effector position and a desired end effector orientation of the end effector, in response to a current position and a current orientation of the handle;

causing the input device to provide haptic feedback that impedes translational movement of the handle, while permitting rotational movement of the handle and while disabling translational and rotational movement of the end effector in response to movement of the handle, when a rotational alignment difference between the handle and the end effector meets a disablement criterion; and

enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion.

2. The method of claim 1 wherein producing said desired end effector position and said desired end effector orientation comprises:

causing the master apparatus to receive current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing said current position and said current orientation respectively of the handle of the input device; and

causing the master apparatus to produce new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining said desired end effector position and said desired end effector orientation, respectively of the end effector, in response to said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}).

3. The method of claim 2 wherein said causing the master apparatus to receive said current handle position signals and said current handle orientation signals comprises causing the master apparatus to periodically receive said current handle position signals and said current handle orientation signals.

4. The method of claim 2 or 3 further comprising causing the master apparatus to determine said rotational alignment difference between the handle and the end effector in response to said current handle orientation signals (R_{MCURR}) and said new end effector orientation signals (R_{EENEW}).

5. The method of claim 4 wherein causing the master apparatus to determine said rotational alignment difference between the handle and the end effector comprises causing the master apparatus to determine an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

6. The method of claim 5 further comprising causing the master apparatus to determine whether said angle of rotation is less than a threshold.

7. The method of any one of claims 3 to 6 wherein causing the input device to provide haptic feedback comprises causing the master apparatus to transmit a haptic feedback signal to the input device to cause the input device to provide said haptic feedback that impedes said translational movement of the handle.

8. The method of any one of claims 3 to 7 further comprising transmitting a slave control signal to the slave system and wherein:

5 enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion comprises transmitting said slave control signal to the slave system identifying said new end effector position and orientation signals based on said current position and orientation of the handle; and

10

disabling movement of the end effector in response to any movement of the handle comprises transmitting said slave control signal to the slave system identifying said new end effector position and orientation signals determined from a previous position and orientation of the handle.

15

9. The method of claim 8 further comprising causing the master apparatus to receive an enablement signal.

10. The method of claim 9 further comprising generating the enablement signal such
20 that the enablement signal selectively has an active state or an inactive state.

11. The method of claim 10 further comprising:

25

causing the master apparatus to detect a change of said enablement signal from the inactive state to the active state and when said change is detected:

30

causing the master apparatus to store said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base

orientation signals (R_{MBASE}) respectively, in response to said change of said enablement signal; and

5 causing the master apparatus to store said new end effector position signals ($\bar{P}_{EENEW}$) and said new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base orientation signals (R_{EEBASE}) respectively, in response to said change of said enablement signal.

10 **12.** The method of claim **11** wherein said causing the master apparatus to compute said new end effector position signals ($\bar{P}_{EENEW}$) and said new end effector orientation signals (R_{EENEW}) comprises causing the master apparatus to compute said new end effector position signals and said new end effector orientation signals according to the following relations:

15

$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}; \text{ and}$$

$$R_{EENEW} = R_{EEBASE}R_{MBASE}^{-1}R_{MCURR}.$$

20 **13.** The method of any one of claims **9** to **12** further comprising causing said slave control signal to be further dependent on the state of said enablement signal, such that:

25

said slave control signal identifies said new end effector position and orientation signals based on said current position and orientation of the handle when said alignment difference is less than the disablement criterion and said enablement signal is in the active state; and

said slave control signal identifies said new end effector position and orientation signals based on said previous position and orientation of the handle when said enablement signal is in the inactive state.

- 5 **14.** The method of any one of claims **1** to **13** further comprising causing the master apparatus to produce annunciation signals for causing an annunciator to annunciate an indication of a relative rotational alignment of said handle and said end effector.
- 10 **15.** The method of claim **14** wherein said causing the master apparatus to produce annunciation signals includes causing the master apparatus to produce display control signals for causing a display to depict said relative alignment.
- 15 **16.** A non-transitory computer readable medium encoded with codes for directing a processor to execute the method of any one of claims **1** to **15**.
- 20 **17.** An apparatus for use in a robotic control system, the apparatus in communication with an input device having a handle capable of translational and rotational movement and in communication with a slave system having a tool positioning device holding a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle, the apparatus comprising:
- 25 producing means for producing a desired end effector position and a desired end effector orientation of the end effector, in response to a current position and a current orientation of the handle;
- 30 causing means for causing the input device to provide haptic feedback that impedes translational movement of the handle, while causing rotational movement of the handle to be enabled and while causing

translational movement of the end effector in response to translational movement of the handle to be disabled, when a rotational alignment difference between the handle and the end effector meets a disablement criterion; and

5

enabling means for enabling translational movement of the handle when the rotational alignment difference meets an enablement criterion.

18. The apparatus of claim **17** wherein said producing means comprises:

10

means for receiving current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing said current position and said current orientation respectively of the handle of the input device; and

15

means for producing new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining said desired end effector position and said desired end effector orientation, respectively of the end effector, in response to said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}).

20

19. The apparatus of claim **18** wherein said means for receiving said current handle position signals and said current handle orientation signals comprises means for periodically receiving said current handle position signals and said current handle orientation signals.

25

20. The apparatus of claim **18** or **19** further comprising means for determining said rotational alignment difference between the handle and the end effector in response to said current handle orientation signals (R_{MCURR}) and said new end effector orientation signals (R_{EENEW}).

30

21. The apparatus of claim **20** wherein said means for determining said rotational alignment difference between the handle and the end effector comprises means for determining an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

5

22. The apparatus of claim **21** further comprising means for determining whether said angle of rotation is less than a threshold.

10

23. The apparatus of any one of claims **17** to **21** wherein said causing means comprises means for transmitting a haptic feedback signal to the input device to cause the input device to provide said haptic feedback that impedes said translational movement of the handle.

15

24. The apparatus of any one of claims **19** to **23** wherein said enabling means comprises means for transmitting a slave control signal to the slave system, and wherein:

20

said means for transmitting transmits said slave control signal identifying said new end effector position and orientation signals based on said current position and orientation of the handle when the rotational alignment difference meets said enablement criterion; and

25

said means for transmitting transmits said slave control signal identifying said new end effector position and orientation signals determined from a previous position and orientation of the handle when the rotational alignment difference meets said disablement criterion.

30

25. The apparatus of claim **24** further comprising means for receiving an enablement signal.

26. The apparatus of claim 25 further comprising means for generating the enablement signal such that the enablement signal selectively has an active state or an inactive state.

5 27. The apparatus of claim 26 further comprising:

means for detecting a change of said enablement signal from the inactive state to the active state;

10 means for storing said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base orientation signals (R_{MBASE}) respectively, in response to said change of said enablement signal; and

15 means for storing said new end effector position signals ($\bar{P}_{EENEW}$) and said new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base orientation signals (R_{EEBASE}) respectively, in response to said change of said enablement signal.

20 28. The apparatus of claim 27 wherein said means for producing said new end effector position signals ($\bar{P}_{EENEW}$) and said new end effector orientation signals (R_{EENEW}) comprises means for computing said new end effector position signals and said new end effector orientation signals according to the following relations:

25
$$\bar{P}_{EENEW} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}; \text{ and}$$
$$R_{EENEW} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}.$$

29. The apparatus of any one of claims **25** to **28** further comprising means for causing said slave control signal to be further dependent on the state of said enablement signal, such that:

5 said slave control signal identifies said new end effector position and orientation signals based on said current position and orientation of the handle when said alignment difference is less than the disablement criterion and said enablement signal is in the active state; and

10 said slave control signal identifies said new end effector position and orientation based on said previous position and orientation of the handle when said enablement signal is in the inactive state.

30. The apparatus of any one of claims **17** to **29** further comprising annunciation
15 signal means for producing annunciation signals for causing an annunciator to annunciate an indication of a relative rotational alignment of said handle and said end effector.

31. The apparatus of claim **30** wherein said annunciation signal causing means
20 includes means for producing display control signals for causing a display to depict said relative alignment.

32. An apparatus for use in a robotic control system, the apparatus in communication
25 with an input device having a handle capable of translational and rotational movement and in communication with a slave system having a tool positioning device holding a tool having an end effector whose position and orientation is determined in response to a position and orientation of the handle, the apparatus comprising:

30 at least one processor circuit configured to:

produce a desired end effector position and a desired end effector orientation of the end effector, in response to a current position and a current orientation of the handle;

5

cause the input device to provide haptic feedback that impedes translational movement of the handle, while causing rotational movement of the handle to be enabled and while causing translational movement of the end effector in response to translational movement of the handle to be disabled, when a rotational alignment difference between the handle and the end effector meets a disablement criterion; and

10

enable translational movement of the handle when the rotational alignment difference meets an enablement criterion.

15

33. The apparatus of claim **32** wherein said at least one processor circuit is configured to produce said desired end effector position and said desired end effector orientation by:

20

receiving current handle position signals ($\bar{P}_{MCURR}$) and current handle orientation signals (R_{MCURR}) representing said current position and said current orientation respectively of the handle of the input device; and

25

producing new end effector position signals ($\bar{P}_{EENEW}$) and new end effector orientation signals (R_{EENEW}) defining said desired end effector position and said desired end effector orientation, respectively of the end effector, in response to said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}).

30

34. The apparatus of claim **33** wherein said at least one processor circuit is configured to receive said current handle position signals and said current handle orientation signals by periodically receiving said current handle position signals and said current handle orientation signals.

5

35. The apparatus of claim **33** or **34** wherein said at least one processor circuit is further configured to determine said rotational alignment difference between the handle and the end effector in response to said current handle orientation signals (R_{MCURR}) and said new end effector orientation signals (R_{EENEW}).

10

36. The apparatus of claim **35** wherein said at least one processor circuit is configured to determine said rotational alignment difference between the handle and the end effector by determining an angle of rotation through which the end effector would have to be rotated to align it with the current handle orientation.

15

37. The apparatus of claim **36** wherein said at least one processor circuit is further configured to determine whether said angle of rotation is less than a threshold.

20

38. The apparatus of any one of claims **32** to **37** wherein said at least one processor circuit is configured to cause the input device to provide haptic feedback by transmitting a haptic feedback signal to the input device to cause the input device to provide said haptic feedback that impedes said translational movement of the handle.

25

39. The apparatus of any one of claims **34** to **38** wherein said at least one processor circuit is configured to transmit a slave control signal to the slave system and wherein:

30

said slave control signal identifies said new end effector position and orientation signals based on said current position and orientation of the

handle when the rotational alignment difference meets an enablement criterion; and

5 said slave control signal identifies said new end effector position and orientation signals determined from a previous position and orientation of the handle when the rotational alignment difference meets said disablement criterion.

10 **40.** The apparatus of claim **39** wherein said at least one processor circuit is further configured to receive an enablement signal.

41. The apparatus of claim **40** wherein said at least one processor circuit is further configured to generate the enablement signal such that the enablement signal selectively has an active state or an inactive state.

15 **42.** The apparatus of claim **41** wherein said at least one processor circuit is further configured to:

20 detect a change of said enablement signal from the inactive state to the active state and when said change is detected:

25 store said current handle position signals ($\bar{P}_{MCURR}$) and said current handle orientation signals (R_{MCURR}) as master base position signals ($\bar{P}_{MBASE}$) and master base orientation signals (R_{MBASE}) respectively, in response to said change of said enablement signal; and

 store said new end effector position signals ($\bar{P}_{EENEW}$) and said new end effector orientation signals (R_{EENEW}) as end effector base position signals ($\bar{P}_{EEBASE}$) and end effector base orientation signals

(R_{EEBASE}) respectively, in response to said change of said enablement signal.

- 5 **43.** The apparatus of claim **42** wherein said at least one processor circuit is configured to compute said new end effector position signals ($\bar{P}_{EE_{NEW}}$) and said new end effector orientation signals ($R_{EE_{NEW}}$) by computing said new end effector position signals and said new end effector orientation signals according to the following relations:

10 $\bar{P}_{EE_{NEW}} = A(\bar{P}_{MCURR} - \bar{P}_{MBASE}) + \bar{P}_{EEBASE}$; and

$$R_{EE_{NEW}} = R_{EEBASE} R_{MBASE}^{-1} R_{MCURR}.$$

- 15 **44.** The apparatus of any one of claims **40** to **43** wherein said at least one processor circuit is further configured to cause said slave control signal to be further dependent on the state of said enablement signal, such that

20 said slave control signal identifies said new end effector position and orientation signals based on said current position and orientation of the handle when said alignment difference is less than the disablement criterion and said enablement signal is in the active state; and

25 said slave control signal identifies said new end effector position and orientation based on said previous position and orientation of the handle when said enablement signal is in the inactive state.

- 30 **45.** The apparatus of any one of claims **32** to **44** wherein said at least one processor circuit is further configured to produce annunciation signals for causing an annunciator to annunciate an indication of a relative rotational alignment of said handle and said end effector.

- 46.** The apparatus of claim **45** wherein said at least one processor circuit is configured to produce said annunciation signals by producing display control signals for causing a display to depict said relative alignment.

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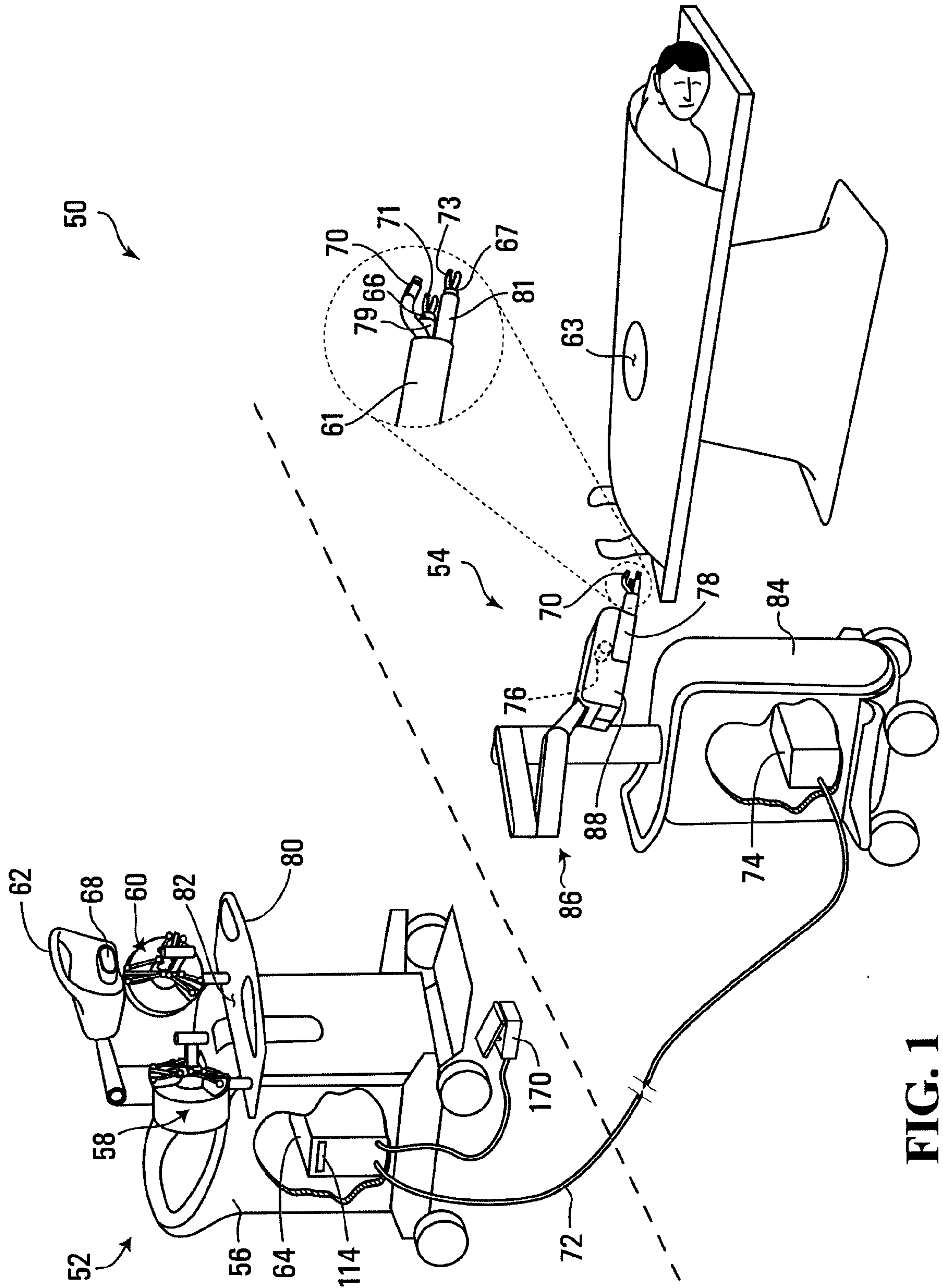
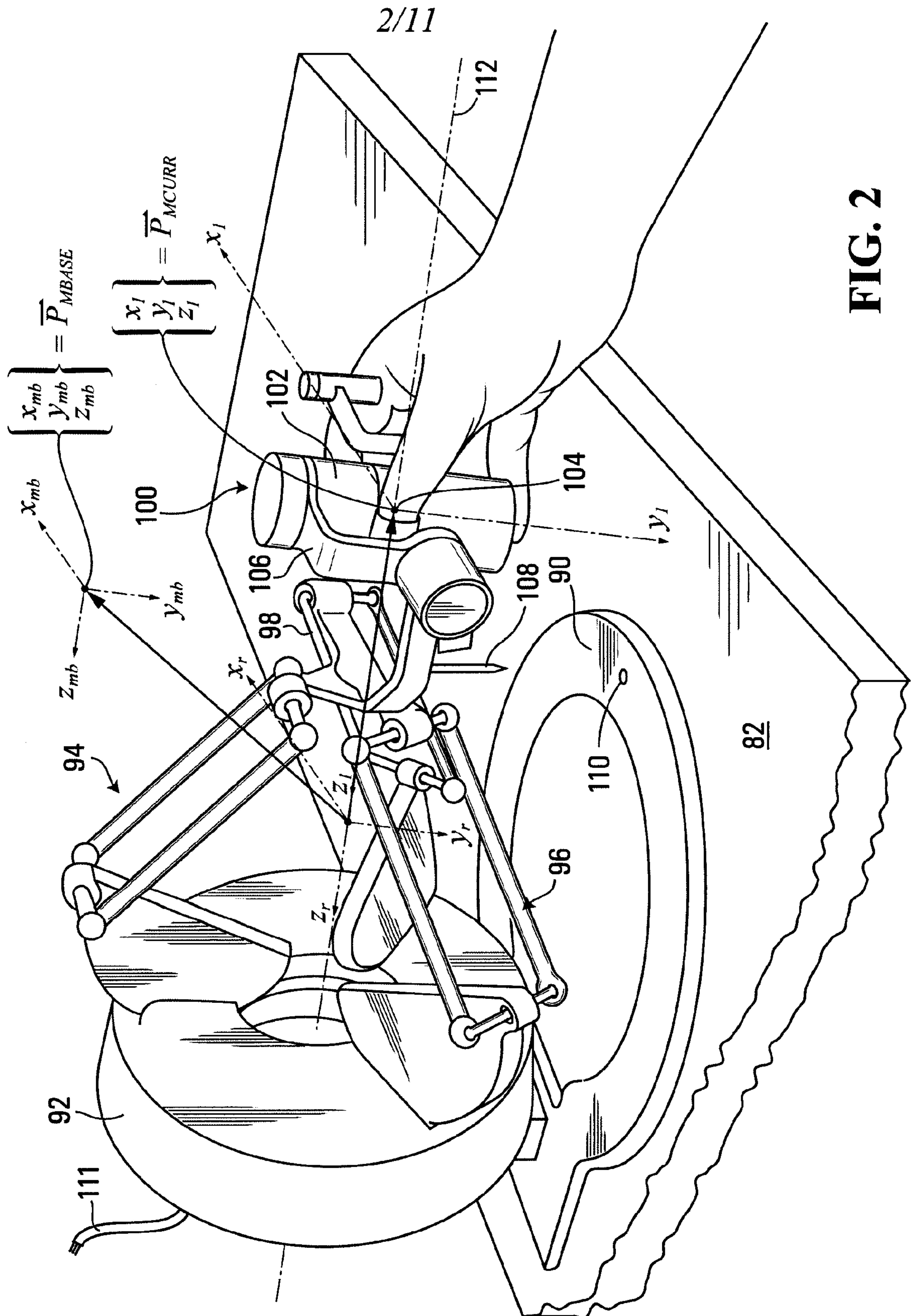


FIG. 1



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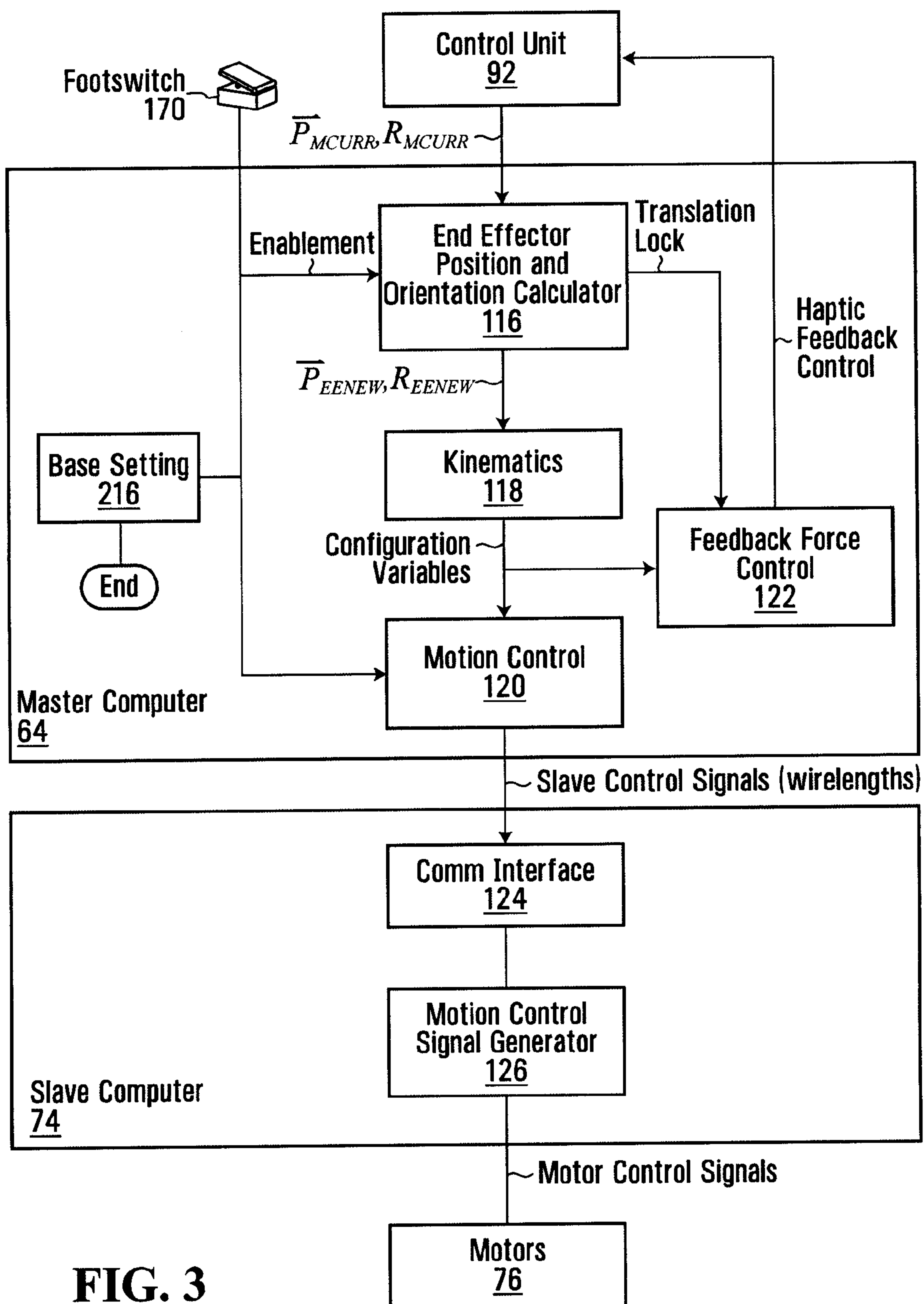


FIG. 3

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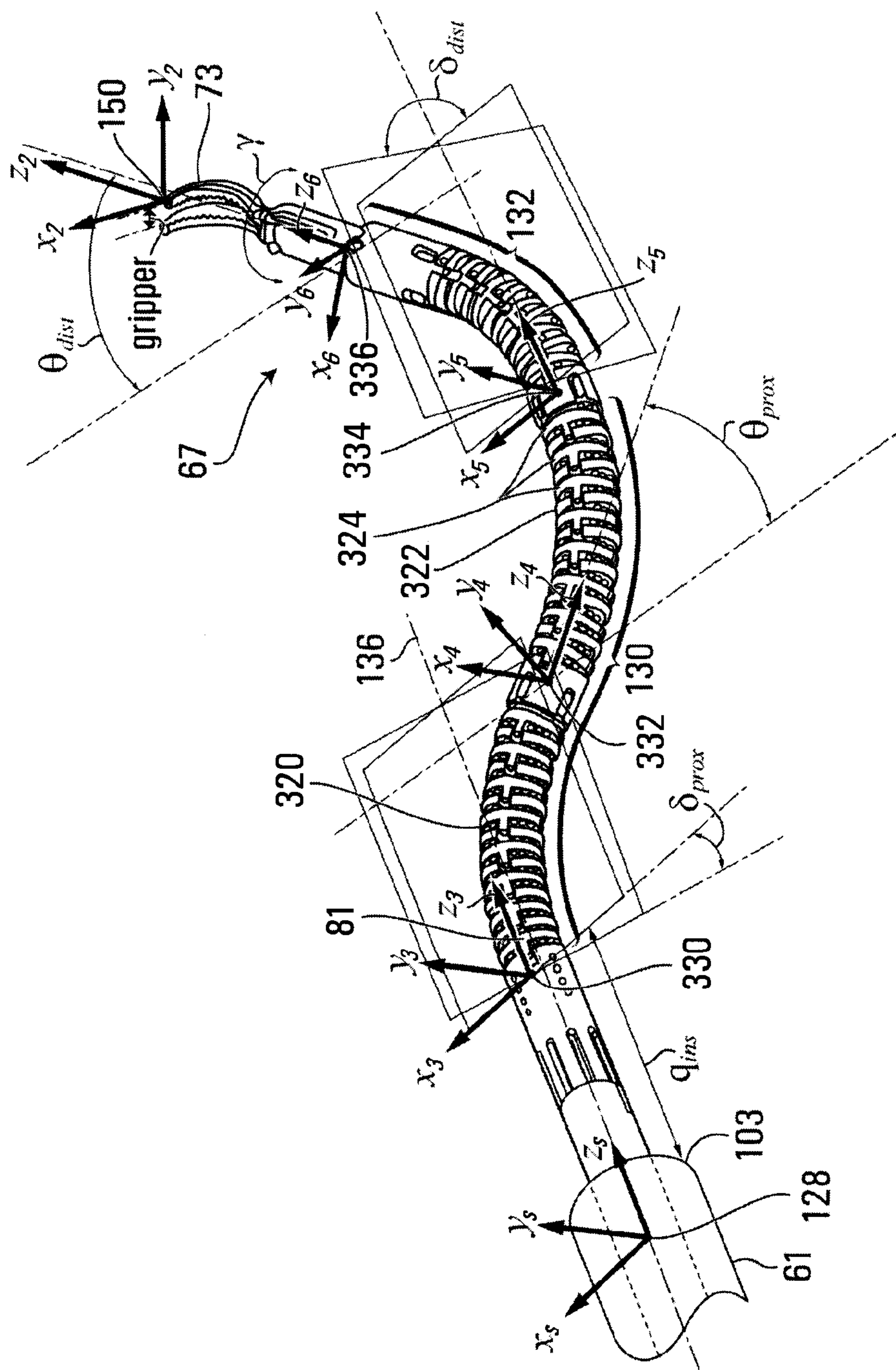


FIG. 4

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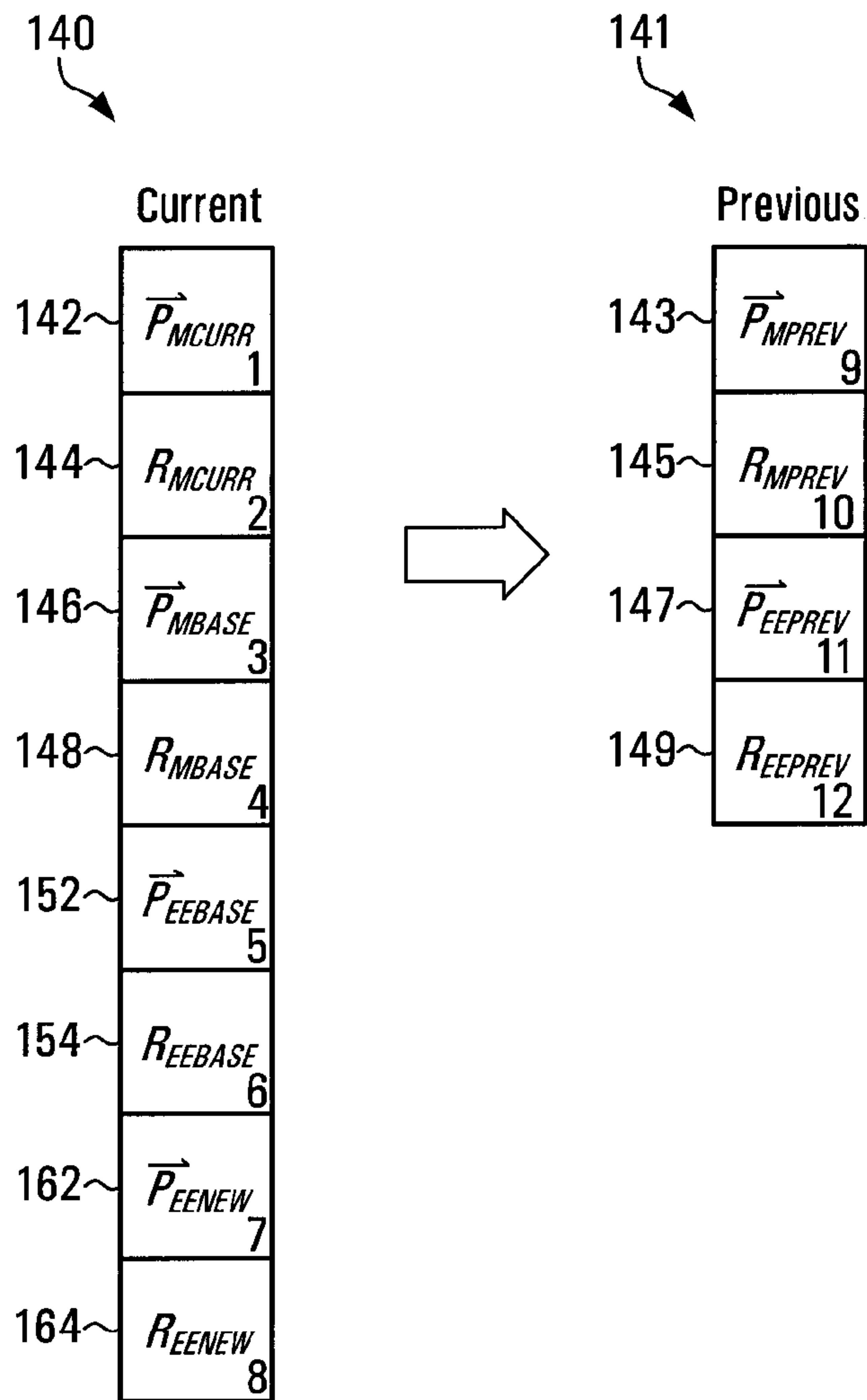


FIG. 5

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Enablement Signal Transition Inactive→Active

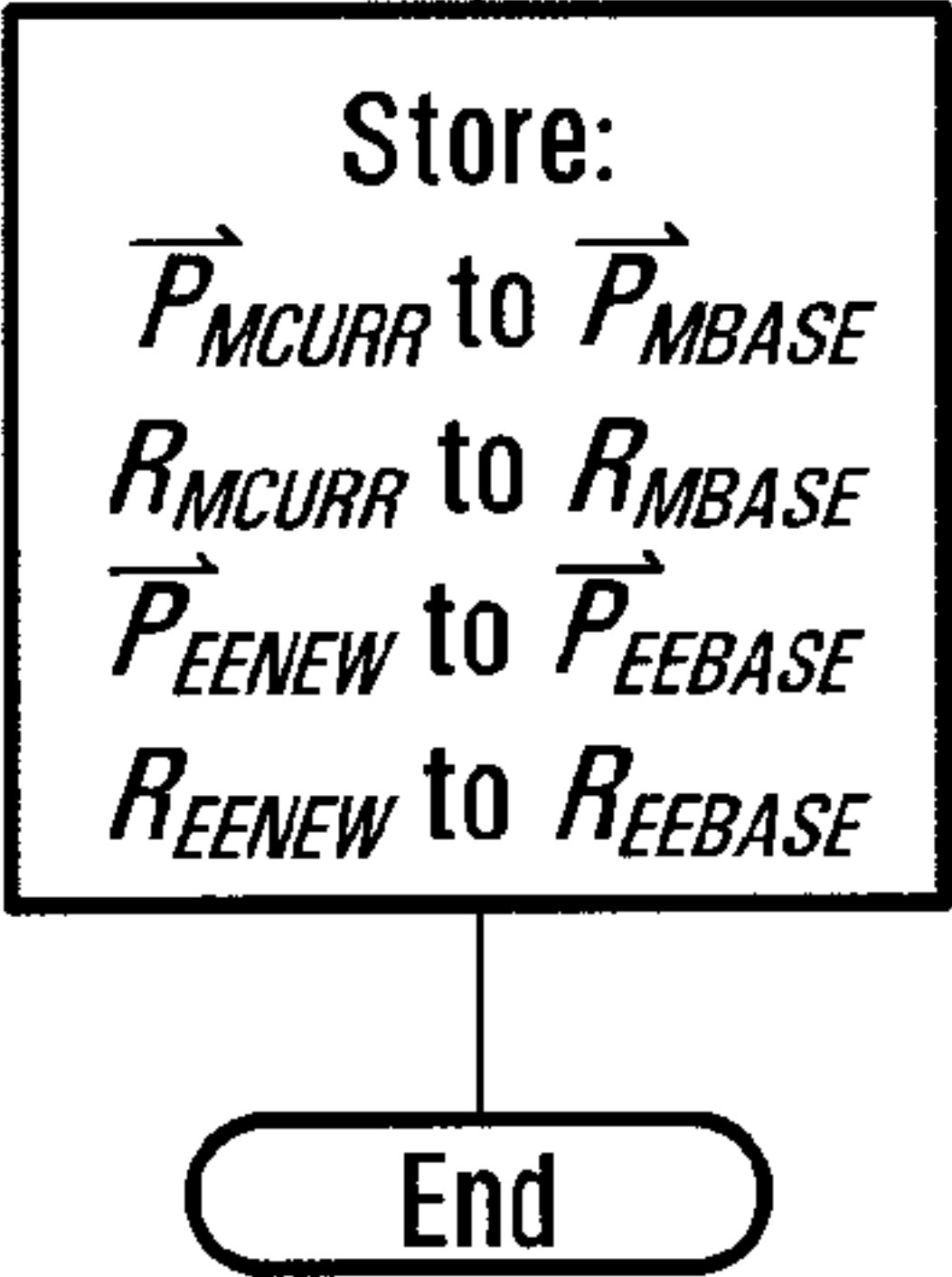
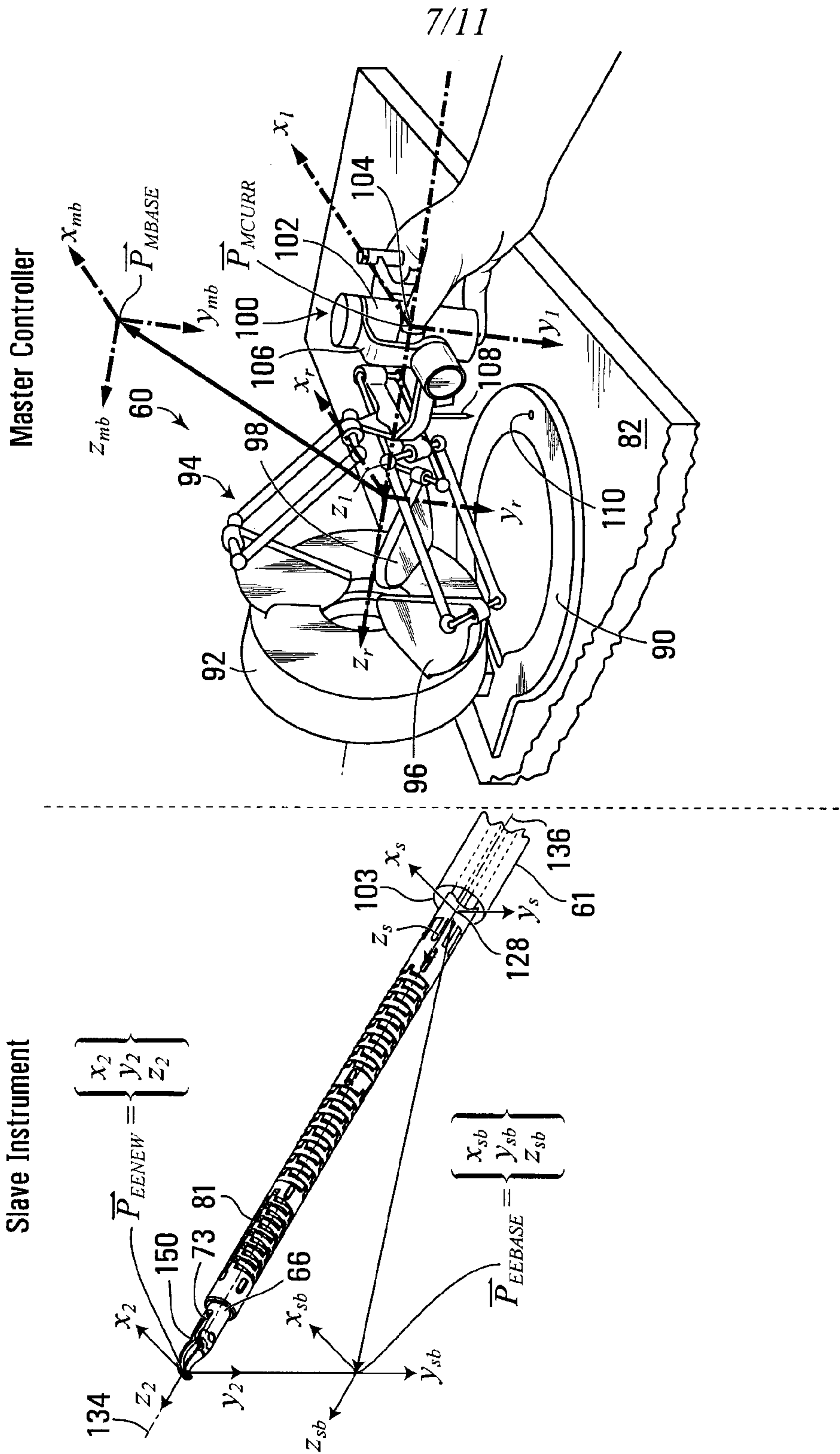


FIG. 6

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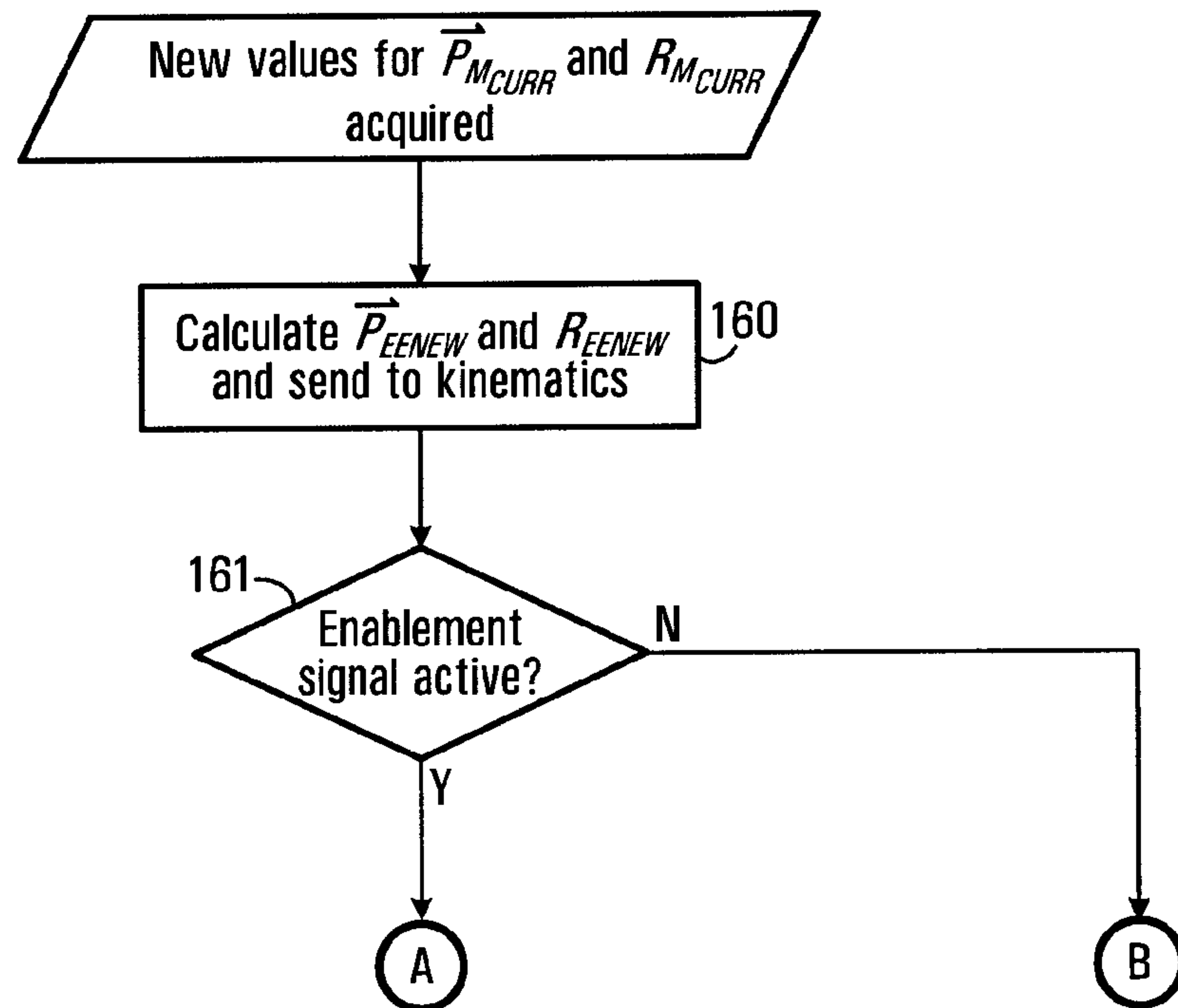


FIG. 8A

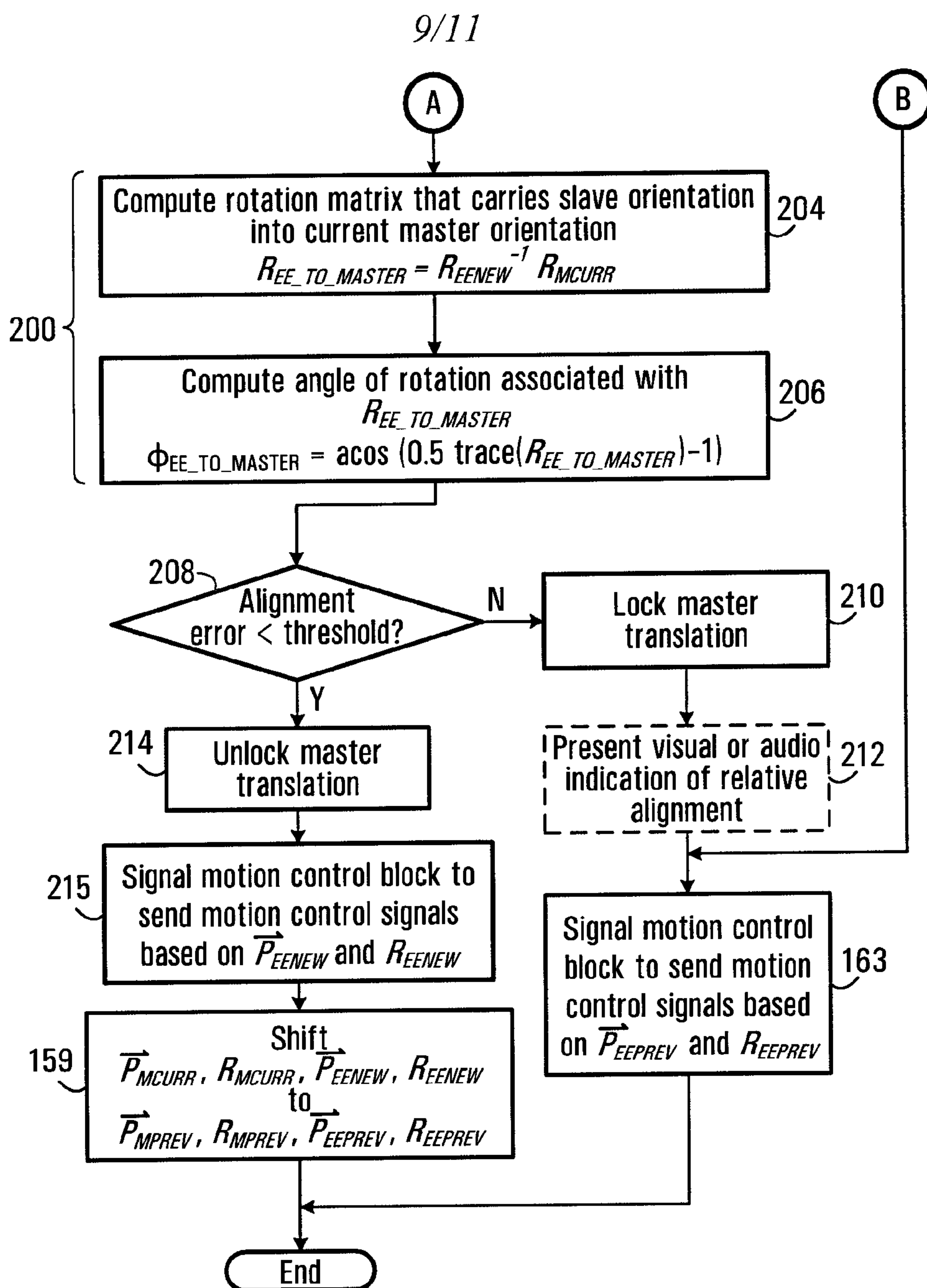


FIG. 8B

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Compute the offset angle between the master and
the slave z-axes

$$\Phi_{EE_TO_MASTER} = \arccos \left(\begin{aligned} &R_{EENEW}(1,3) * R_{MCURR}(1,3) + \\ &R_{EENEW}(2,3) * R_{MCURR}(2,3) + \\ &R_{EENEW}(3,3) * R_{MCURR}(3,3) \end{aligned} \right)$$

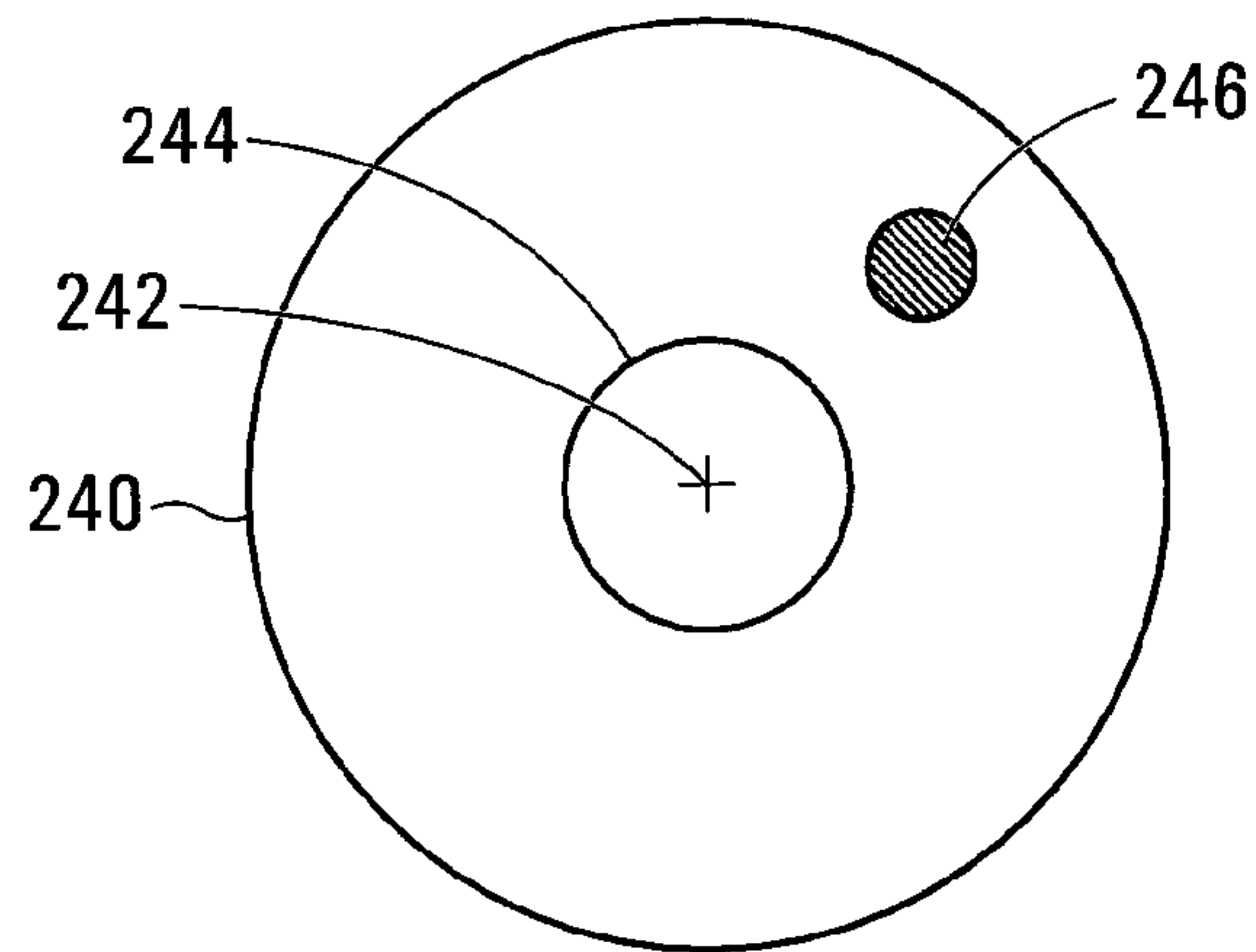
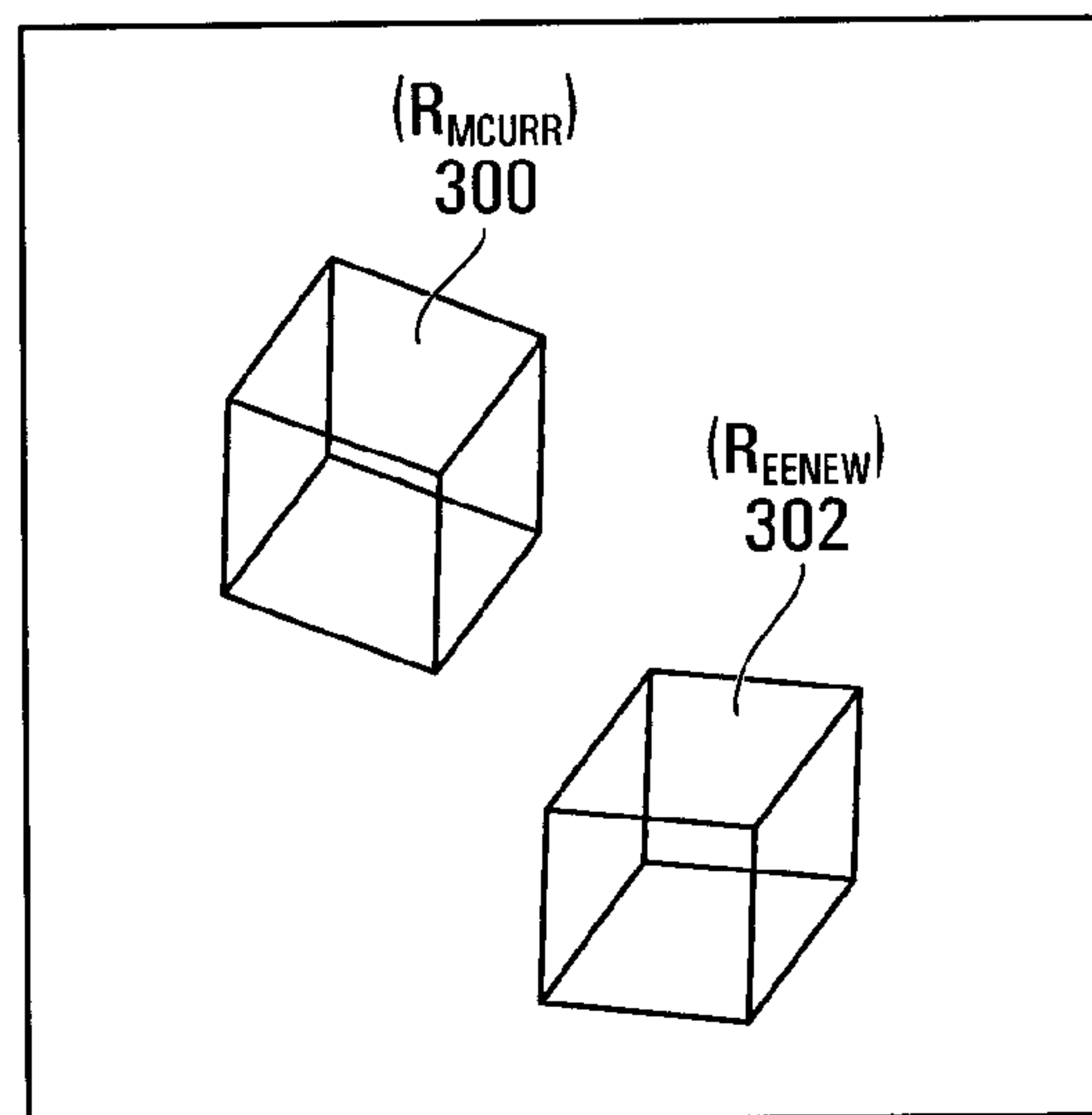
205

FIG. 9

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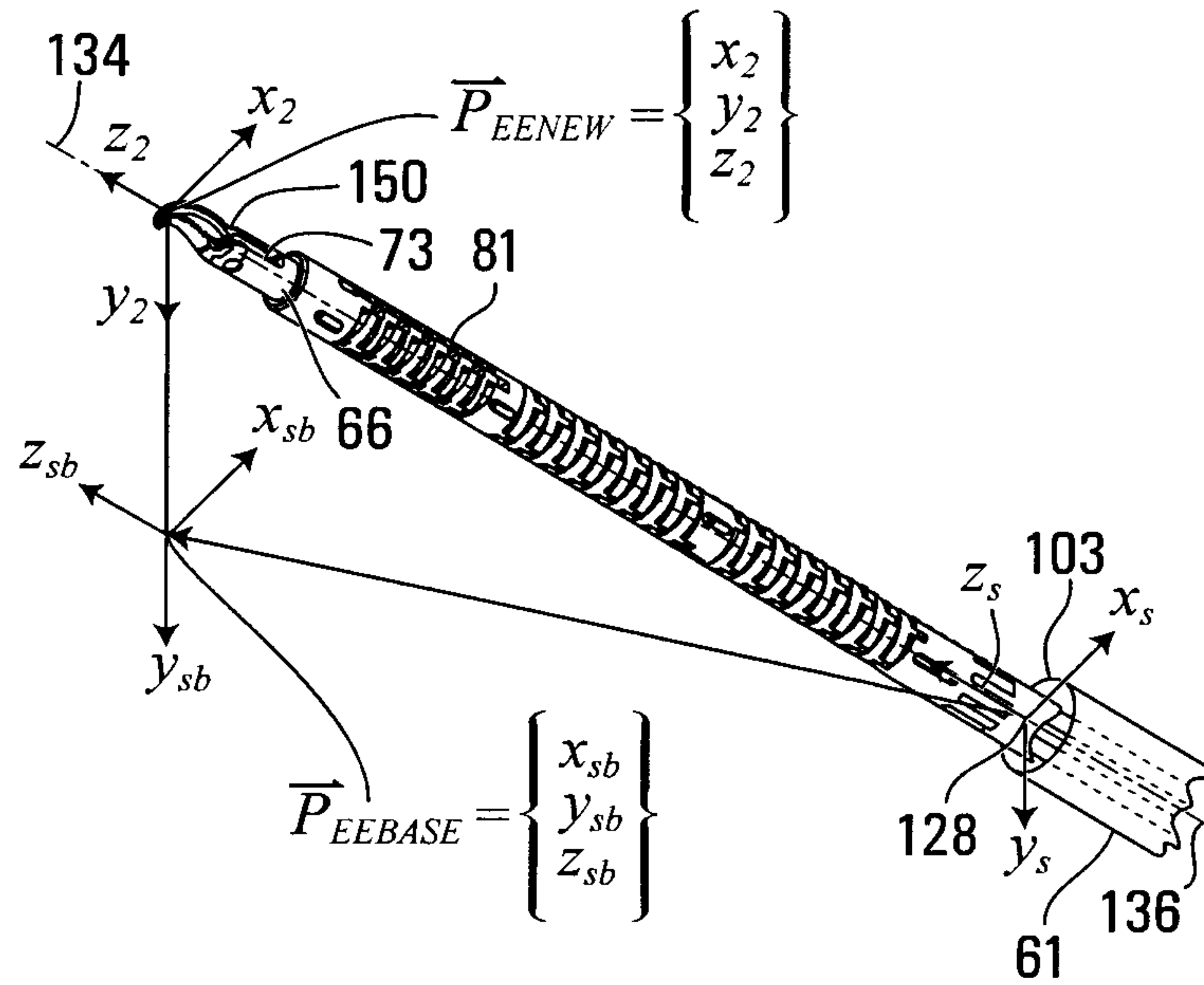
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**FIG. 10****FIG. 11**

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Slave Instrument



Master Controller

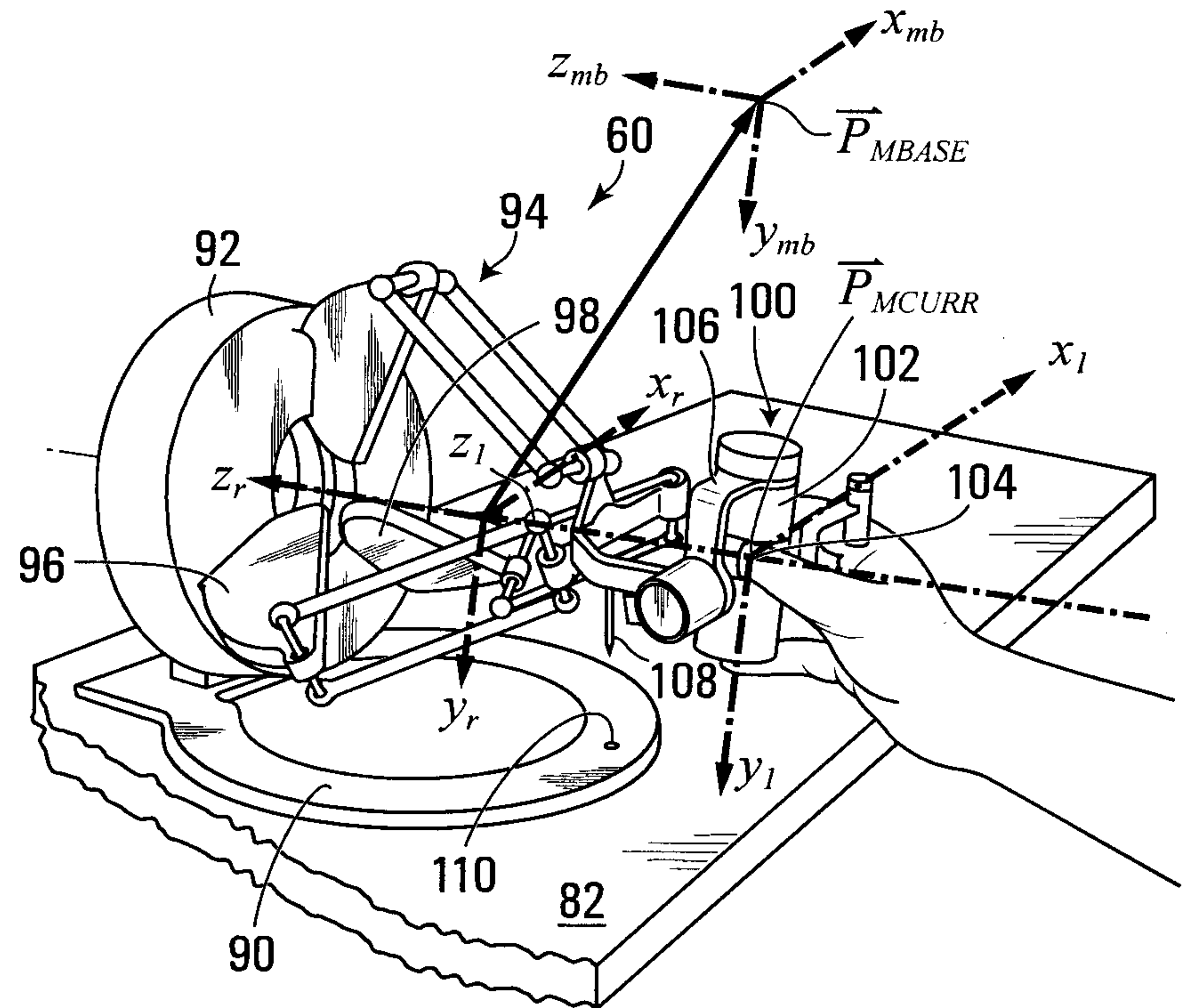


FIG. 7