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(71) **Applicant: COVIDIEN LP** [US/US]; 15 Hampshire Street, Mansfield, Massachusetts 02048 (US).

(72) **Inventors: PEINE, William**; 24 Holly Lane, Ashland, Massachusetts 01721 (US). **LIVIANU, Mathew**; 72 Hawthorne Street, Malden, Massachusetts 02148 (US). **YILMAZ, Burak**; 58 East St, Upton, Massachusetts 01568 (US).

(74) **Agent: HUGHES, Thomas** et al.; Medtronic, 60 Middletown Avenue, c/o Legal Mailstop MS 54, North Haven, Connecticut 06473 (US).

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(54) **Title:** BOUNDARY SCALING OF SURGICAL ROBOTS

(57) **Abstract:** A method of scaling a desired velocity of a tool of a surgical robot with a processing unit includes receiving an input signal, determining a position of the tool relative to a boundary of a surgical site, and scaling a desired velocity of movement of the tool when the tool is within a predetermined distance of the boundary of the surgical site. The input signal includes the desired velocity of movement of the tool.

BOUNDARY SCALING OF SURGICAL ROBOTS

BACKGROUND

[0001] Robotic surgical systems have been used in minimally invasive medical procedures. During a medical procedure, the robotic surgical system is controlled by a surgeon interfacing with a user interface. The user interface allows the surgeon to manipulate an end effector that acts on a patient. The user interface includes an input controller or handle that is moveable by the surgeon to control the robotic surgical system.

[0002] Robotic surgical systems typically use a scaling factor to scale down the motions of the surgeon's hands to determine the desired position of the end effector within the patient so that the surgeon can more precisely move the end effector inside the patient. As the surgeon moves the input handle, a surgical robot moves the end effector within the patient. As the end surgical robot moves the end effector, an arm of the surgical robot and/or the end effector may approach a boundary of movement. This boundary of movement may be artificial, e.g., a virtual wall, or may be an actual boundary, e.g., a joint limit of the surgical robot, a physical edge of a surgical space, or a collision with another object. Typically as the end effector or surgical robot reaches the boundary, the end effector or robot arm abruptly stops. This deceleration may be accentuated when the end effector or surgical robot is moving at a high velocity towards the boundary. This sudden deceleration of the end effector or surgical robot may damage the surgical robot and/or result in unintended movement of the surgical robot.

SUMMARY

[0003] This disclosure generally relates to velocity scaling of movement of the end effector or surgical robot as the end effector or surgical robot approaches a boundary. The velocity scaling reduces a velocity of the end effector or surgical robot as it approaches the boundary to a desired impact velocity. The velocity scaling reduces the velocity towards the boundary at a controlled deceleration rate to the desired impact velocity. The desired impact velocity may be a velocity at which a sudden stop results in no damage to the surgical robot or the desired impact velocity may be zero.

[0004] In an aspect of the present disclosure, a method of scaling a desired velocity of a tool of a surgical robot with a processing unit includes receiving an input signal, determining a position of the tool relative to a boundary of a surgical site, and scaling a desired velocity of movement of the tool when the tool is within a predetermined distance of the boundary of the surgical site. The input signal may include the desired velocity of movement of the tool.

[0005] In aspects, scaling the desired velocity of movement includes reducing the desired velocity of movement of the tool. The boundary may be a virtual boundary of the surgical site.

[0006] In some aspects, the method includes determining a direction of movement of the tool relative to the boundary. Scaling the desired velocity of movement of the tool may only occur when the direction of movement of the tool is towards the boundary.

[0007] In certain aspects, scaling the desired velocity of movement of the tool includes applying a velocity scaling factor to the desired velocity of movement. The method may include determining the velocity scaling factor as a function of the determined position of the tool relative to the boundary. Determining the velocity scaling factor may include the velocity scaling factor being one (1) when the determined position of the tool relative to the boundary is beyond a predetermined distance. Determining the velocity scaling factor as the function of the determined position of the tool may include reducing the scaling factor from one towards a minimum value when the determined position of the tool relative to the boundary is below a predetermined distance. The minimum value of the velocity scaling factor may be non-zero.

[0008] In particular aspects, the method includes generating control signals after scaling the desired velocity of movement of the tool. The method may include transmitting the control signals to a surgical robot. The method may include transmitting feedback control signals to a user console when the scaling the desired velocity of movement of the tool.

[0009] Further details and aspects of exemplary embodiments of the present disclosure are described in more detail below with reference to the appended figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Various aspects of the present disclosure are described herein below with reference to the drawings, which are incorporated in and constitute a part of this specification, wherein:

[0011] FIG. 1 is a schematic illustration of an user console and a robotic system in accordance with the present disclosure;

[0012] FIG. 2 is a perspective view of a tool of the surgical robot of FIG. 1 within a surgical site of a patient;

[0013] FIG. 3 is graph illustrating a maximum velocity as a function of the distance of a tool from a boundary;

[0014] FIG. 4 is another graph illustrating a maximum velocity as a function of the distance of a tool from a boundary; and

[0015] FIG. 5 is a flowchart of a method of scaling a velocity of a tool in accordance with the present disclosure.

DETAILED DESCRIPTION

[0016] Embodiments of the present robotic surgical systems are now described in detail with reference to the drawings in which like reference numerals designate identical or corresponding elements in each of the several views. As used herein, the term “clinician” refers to a doctor, a nurse, or any other care provider and may include support personnel. Throughout this description, the term “proximal” refers to the portion of the device or component thereof that is closest to the clinician and the term “distal” refers to the portion of the device or component thereof that is farthest from the clinician. In addition, as used herein the term “neutral” is understood to mean non-scaled.

[0017] This disclosure generally relates to the scaling of a velocity of a component of a surgical robot based on a distance between the component and a boundary. The component of the surgical robot may be, for example, a joint, arm, or tool. The scaling of the velocity may be a function of the distance between the component of the surgical instrument from the boundary such that as the component approaches the boundary, the velocity of the component is scaled down.

[0018] Referring to FIG. 1, a robotic surgical system 1 in accordance with the present disclosure is shown generally as a surgical robot 10, a processing unit 30, and a user console 40. The surgical robot 10 generally includes linkages 12 and a robot base 18. The linkages 12 moveably support an end effector or tool 20 which is configured to act on tissue. The linkages 12 may be in the form of arms each having an end 14 that supports the end effector or tool 20 which is configured to act on tissue. In addition, the ends 14 of the linkages 12 may include an imaging device 16 for imaging a surgical site “S”. The user console 40 is in communication with robot base 18 through the processing unit 30.

[0019] The user console 40 includes a display device 44 which is configured to display three-dimensional images. The display device 44 displays three-dimensional images of the surgical site “S” which may include data captured by imaging devices 16 positioned on the ends 14 of the linkages 12 and/or include data captured by imaging devices that are positioned about the surgical theater (e.g., an imaging device positioned within the surgical site “S”, an imaging device positioned adjacent the patient “P”, imaging device 56 positioned at a distal end of an imaging arm 52). The imaging devices (e.g., imaging devices 16, 56) may capture visual images, infra-red images, ultrasound images, X-ray images, thermal images, and/or any other known real-time images of the surgical site “S”. The imaging devices transmit captured imaging data to the processing unit 30 which creates three-dimensional images of the surgical site “S” in real-time from the imaging data and transmits the three-dimensional images to the display device 44 for display.

[0020] The user console 40 also includes input handles 42 which are supported on control arms 43 which allow a clinician to manipulate the surgical robot 10 (e.g., move the linkages 12, the ends 14 of the linkages 12, and/or the tools 20). Each of the input handles 42 is in communication with the processing unit 30 to transmit control signals thereto and to receive feedback signals therefrom. Additionally or alternatively, each of the input handles 42 may include input devices (not explicitly shown) which allow the surgeon to manipulate (e.g., clamp, grasp, fire, open, close, rotate, thrust, slice, etc.) the tools 20 supported at the ends 14 of the linkages 12.

[0021] Each of the input handles 42 is moveable through a predefined workspace to move the ends 14 of the linkages 12, e.g., tools 20, within a surgical site “S”. The three-dimensional images on the display device 44 are orientated such that the movement of the input handles 42 moves the ends 14 of the linkages 12 as viewed on the display device 44. The three-dimensional images remain stationary while movement of the input handles 42 is scaled to movement of the ends 14 of the linkages 12 within the three-dimensional images. To maintain an orientation of the three-dimensional images, kinematic mapping of the input handles 42 is based on a camera orientation relative to an orientation of the ends 14 of the linkages 12. The orientation of the three-dimensional images on the display device 44 may be mirrored or rotated relative to the view captured by the imaging devices 16, 56. In addition, the size of the three-dimensional images on the display device 44 may be scaled to be larger or smaller than the actual structures of the surgical site permitting a clinician to have a better view of structures within the surgical site “S”. As the input handles 42 are moved, the tools 20 are moved within the surgical site “S” as detailed below. Movement of the tools 20 may also include movement of the ends 14 of the linkages 12 which support the tools 20.

[0022] For a detailed discussion of the construction and operation of a robotic surgical system 1, reference may be made to U.S. Patent No. 8,828,023, the entire contents of which are incorporated herein by reference.

[0023] The movement of the tools 20 is scaled relative to the movement of the input handles 42. When the input handles 42 are moved within a predefined workspace, the input handles 42 send control signals to the processing unit 30. The processing unit 30 analyzes the control signals to move the tools 20 in response to the control signals. The processing unit 30 transmits scaled control signals to the robot base 18 to move the tools 20 in response to the movement of the input handles 42. The processing unit 30 scales the control signals by dividing an $\text{Input}_{\text{distance}}$ (e.g., the distance moved by one of the input handles 42) by a scaling factor S_F to arrive at a scaled $\text{Output}_{\text{distance}}$ (e.g., the distance that one of the ends 14 is moved). The scaling factor S_F is in a range between about one and about ten (e.g., three). This scaling is represented by the following equation:

$$\text{Output}_{\text{distance}} = \text{Input}_{\text{distance}} / S_F$$

It will be appreciated that the larger the scaling factor S_F the smaller the movement of the tools 20 relative to the movement of the input handles 42.

[0024] For a detailed description of scaling movement of the input handle 42 along the X, Y, and Z coordinate axes to movement of the tool 20, reference may be made to commonly owned International Patent Application Serial No. PCT/US2015/051130, filed on September 21, 2015, and entitled “Dynamic Input Scaling for Controls of Robotic Surgical System,” and International Patent Application No. PCT/US2016/14031, filed January 20, 2016, the entire contents of each of these disclosures are herein incorporated by reference.

[0025] Referring to FIG. 2, the tool 20 is movable within the surgical site “S” towards and away from a boundary “B”. The boundary “B” may be a position of the tool 20 or a part of the linkage 12. For example, the tool 20 may be approaching a wall defining the surgical site “S” or a portion of the linkage 12 may be approaching another linkage of the surgical robot 10. In addition, the boundary “B” may be a position of a joint of the linkage 12. For example, a boundary “B” may be defined at a singularity of a joint of the linkage 12.

[0026] As the tool 20 is moved towards the boundary “B”, in a direction of arrow “M”, the velocity of the tool 20 towards the boundary “B”, e.g., in the direction of arrow “M”, is analyzed by the processing unit 30 (FIG. 1). When the velocity towards the boundary “B” is greater than a velocity that can be safely decelerated to a predetermined boundary velocity before reaching the boundary “B”, the processing unit 30 reduces or scales down the velocity of the tool 20 in the direction of arrow “M” by a velocity scaling factor “α” to reduce the velocity of the tool 20 in the direction of arrow “M” as the tool 20 approaches the boundary “B”.

[0027] With additional reference to FIG. 3, the velocity scaling factor “α” varies as a function of a distance “d” that the tool 20 is from the boundary “B”. The velocity scaling factor “α” scales down a velocity of the tool 20 in the direction “M” based on a deceleration of the maximum velocity “V_{max}” that the tool 20 can have in the direction “M” to be reduced to the predetermined boundary velocity when the tool 20 reaches the boundary “B” such that the distance “d” is zero. As shown in FIG. 3, when the tool 20 is a distance greater than a predetermined distance “D” from the boundary “B”, the velocity scaling factor “α” is one (1) such that a velocity of the tool 20 is unaffected by the velocity scaling factor “α.” As the tool 20 is moved such that the tool 20 is within the predetermined distance “d” from the boundary “B”, the velocity scaling factor “α” scales down a velocity of the tool 20. The velocity scaling factor “α” may be applied to all movement of the tool 20 when the tool 20 is within the predetermined distance “d” or the velocity scaling factor “α” may be applied only to movement of the tool 20 towards the boundary “B”. In addition, the velocity scaling factor “α” may be utilized as a limit to the velocity of the tool 20 such that movement below the maximum velocity “V_{max}” line is unaffected by the velocity scaling factor “α.” As shown in FIG. 3, the velocity scaling factor “α” is reduced to zero when the distance “d” is zero.

[0028] With reference to FIG. 4, the function of the velocity scaling factor "α" may have a non-zero minimum value. The non-zero minimum value is between zero and one and corresponds to a velocity scaling factor "α" equal to a scaling down of the maximum velocity "V_{max}" of the tool 20 to abruptly stop at the boundary "B" without causing damage to the tool 20, the surgical robot 1 (FIG. 1), or the boundary "B".

[0029] Referring to FIG. 5, a method 100 of scaling the velocity of a tool 20 with a processing unit 30 is disclosed in accordance with the present disclosure with reference to the robotic surgical system 1 of FIGS. 1 and 2 and the function of FIG. 4. Initially, the input handle 42 is moved in a direction to move the tool 20. In response to movement of the input handle 42, the user console 40 transmits an input signal to the processing unit 30. The processing unit 30 receives the input signal and generates control signals which are transmitted to the surgical robot 10 to move the tool 20 to a desired position (Step 110).

[0030] To generate the control signals (Step 150), the processing unit 30 may determine a direction of movement of the tool 20 towards the desired position (Step 120). In some embodiments, when the movement of the tool 20 towards the desired position is towards the boundary "B" (Step 124), the processing unit 30 applies the velocity scaling factor "α" to the desired velocity of movement of the tool (Step 130) and when the movement of the tool 20 towards the desired position is away from the boundary "B" the processing unit 20 does not apply the velocity scaling factor "α" to the desired velocity of movement (Step 122). In other embodiments, the processing unit 30 applies the velocity scaling factor "α" to the desired velocity of movement regardless of the direction of movement of the tool 20 towards the desired position by skipping directly to Step 130.

[0031] To apply the velocity scaling factor "α" to a desired velocity of movement of the tool 20 (Step 130), the processing unit 30 determines the position of the tool 20 and the desired position of the tool 20 relative to the boundary "B" (Step 132). If the position of the tool 20 and/or the desired position of the tool 20 are both greater than or equal to the predetermined distance "D" from the boundary "B", the velocity scaling factor "α" is equal to one such that the desired velocity of movement of the tool 20 is unaffected by application of the velocity scaling factor "α". If the position of the tool 20 or the desired position of the tool 20 is less than the predetermined distance "D", application of the velocity scaling factor "α" may scale down the velocity of movement of the tool 20 towards the desired position. Specifically, in some embodiments, the velocity scaling factor "α" is applied directly to the desired velocity of movement of the tool 20 towards the desired position such that the desired velocity is reduced by the velocity scaling factor as shown in FIG. 4 (Step 134). In other embodiments, the maximum velocity "V_{max}" is reduced such that any desired velocity below the maximum velocity "V_{max}" for a given distance "d" is unchanged and only desired velocities above the maximum velocity "V_{max}" is reduced (Step 140).

[0032] After the velocity scaling factor "α" is applied to the desired velocity of movement of the tool 20, the processing unit 30 generates control signals (Step 150) and transmits the control signals to the surgical robot 10 to move the tool 20 to the desired position at the scaled desired velocity (Step 160).

[0033] In some embodiments, when the velocity scaling factor "α" is less than one, the processing unit 30 transmits a feedback control signal to the user console 40 to provide feedback to the clinician that the velocity of the tool 20 is being scaled. For example, the user console 40 may provide force feedback against movements of the input handle 42 in a direction that would move the tool 20 towards the boundary “B”.

[0034] As detailed with respect to the illustrative embodiments herein, the velocity scaling factor “α” is scaled down as a linear function of the distance “d” away from the boundary “B”. However, the velocity scaling factor “α” may be scaled down exponentially, in a step-wise manner, or other suitable functions based on the distance “d” away from the boundary “B”.

[0035] While several embodiments of the disclosure have been shown in the drawings, it is not intended that the disclosure be limited thereto, as it is intended that the disclosure be as broad in scope as the art will allow and that the specification be read likewise. Any combination of the above embodiments is also envisioned and is within the scope of the appended claims. Therefore, the above description should not be construed as limiting, but merely as exemplifications of particular embodiments. Those skilled in the art will envision other modifications within the scope of the claims appended hereto.

WHAT IS CLAIMED IS:

1. A method of scaling a desired velocity of a tool of a surgical robot with a processing unit, the method comprising:

receiving an input signal including a desired velocity of movement of a tool;

determining a position of the tool relative to a boundary of a surgical site; and

scaling the desired velocity of movement of the tool when the tool is within a predetermined distance of the boundary of the surgical site.

2. The method according to claim 1, wherein scaling the desired velocity of movement includes reducing the desired velocity of movement of the tool.

3. The method according to claim 1, wherein the boundary is a virtual boundary of the surgical site.

4. The method according to claim 1, further comprising determining a direction of movement of the tool relative to the boundary.

5. The method according to claim 0, wherein scaling the desired velocity of movement of the tool only occurs when the direction of movement of the tool is towards the boundary.

6. The method according to claim 1, wherein scaling the desired velocity of movement of the tool includes applying a velocity scaling factor to the desired velocity of movement.

7. The method according to claim 0, further comprising determining the velocity scaling factor as a function of the determined position of the tool relative to the boundary.

8. The method according to claim 0, wherein determining the velocity scaling factor includes the velocity scaling factor being one when the determined position of the tool relative to the boundary is beyond a predetermined distance.

9. The method according to claim 0, wherein determining the velocity scaling factor as the function of the determined position of the tool includes reducing the scaling factor from one towards a minimum value when the determined position of the tool relative to the boundary is below a predetermined distance.

10. The method according to claim 0, wherein the minimum value of the velocity scaling factor is non-zero.

11. The method according to claim 1, further comprising generating control signals after scaling the desired velocity of movement of the tool.

12. The method according to claim 0, further comprising transmitting the control signals to a surgical robot.

13. The method according to claim 1, further comprising transmitting feedback control signals to a user console when scaling the desired velocity of movement of the tool.

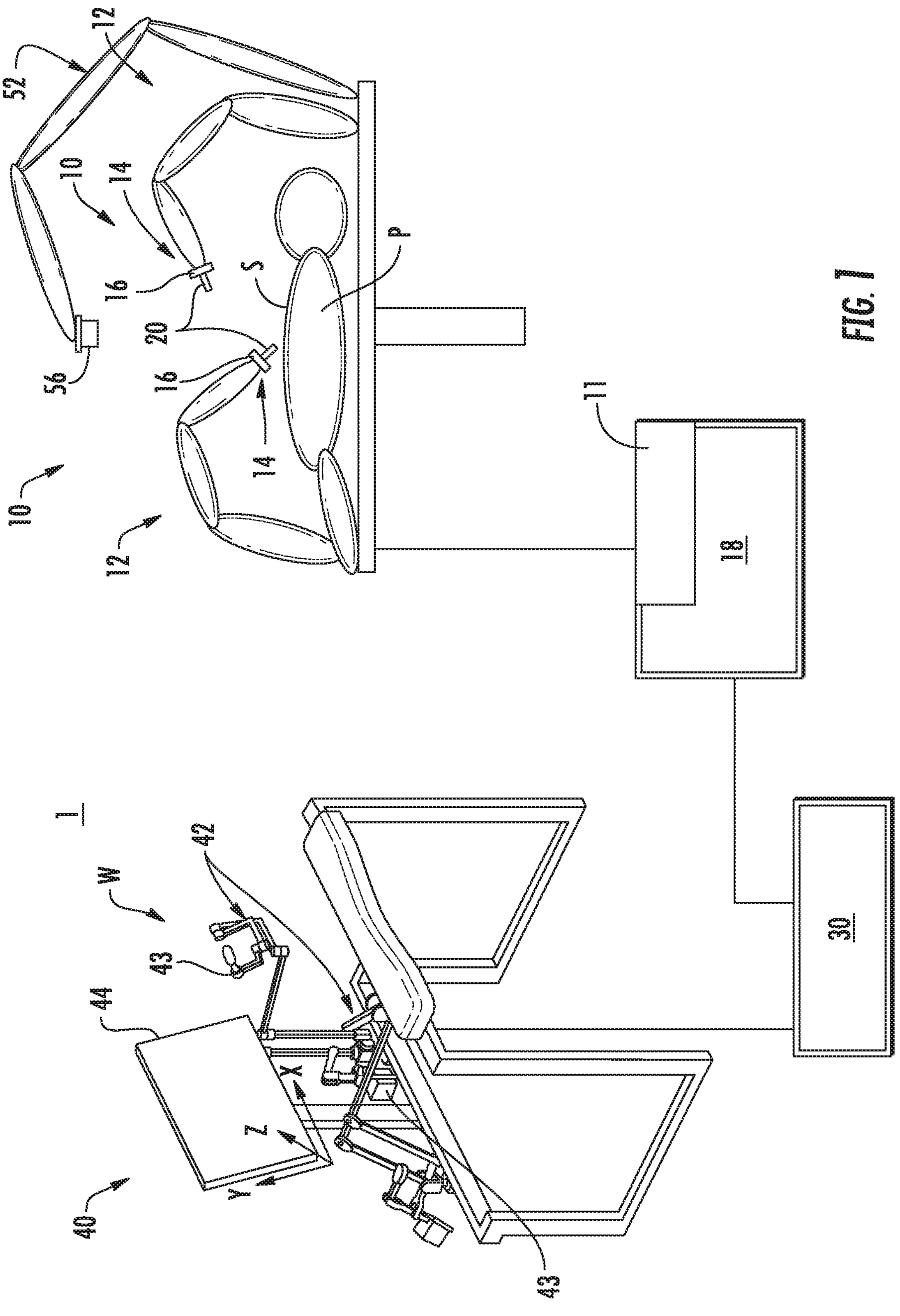

FIG. 1

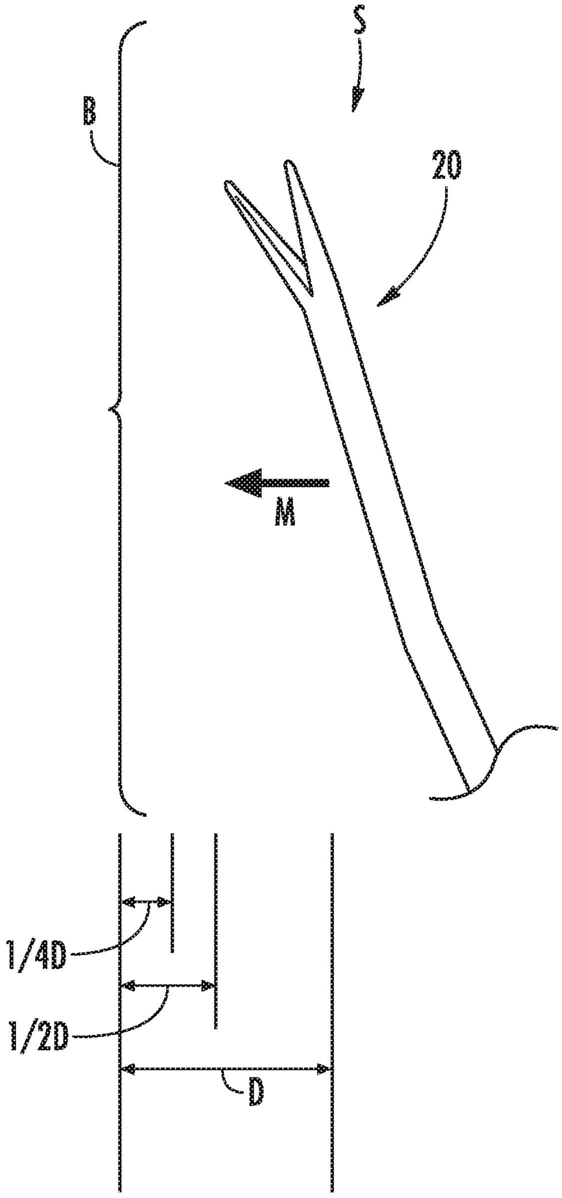

FIG. 2

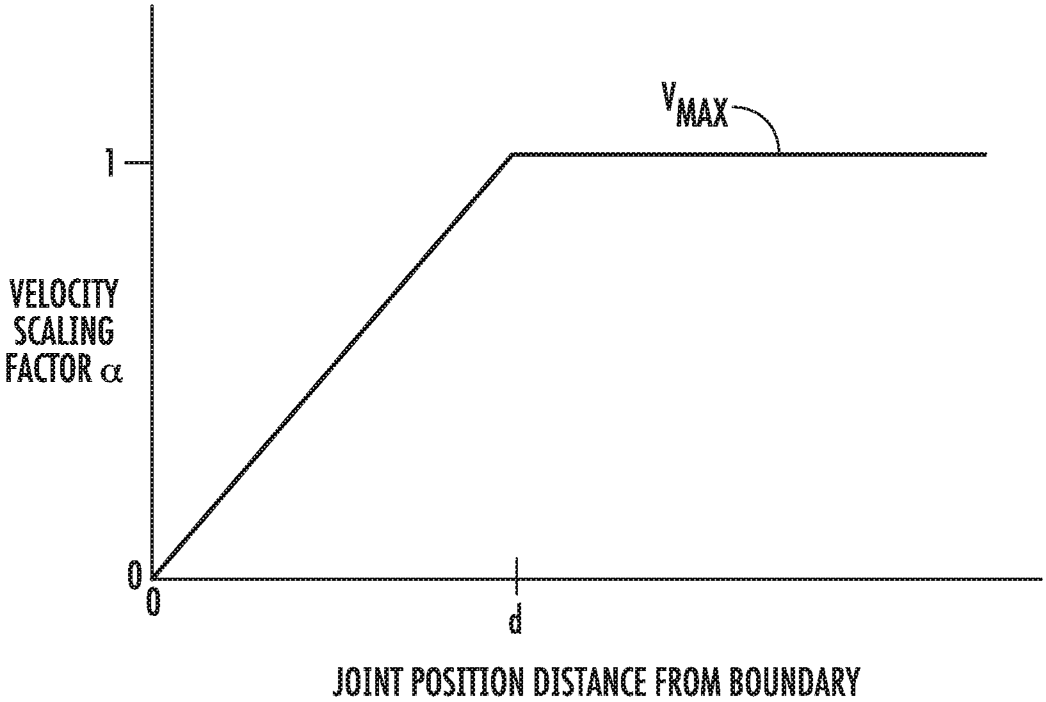
VMAX
1
VELOCITY
SCALING
FACTOR α
0
0
d
JOINT POSITION DISTANCE FROM BOUNDARY

FIG. 3

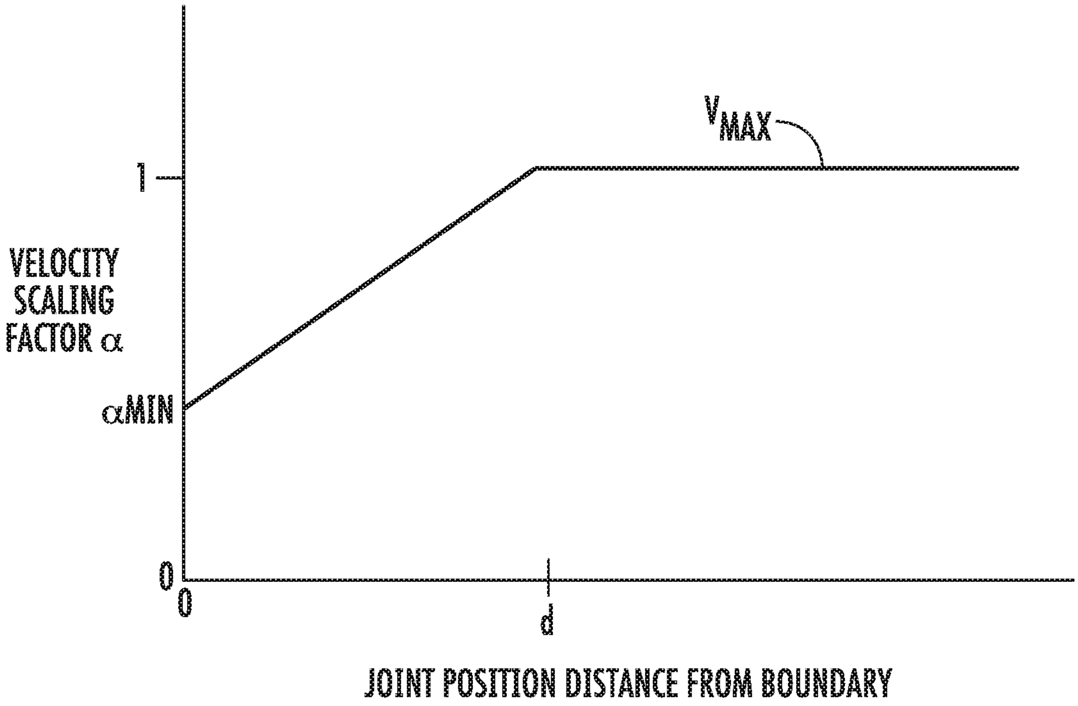
VMAX
1
VELOCITY
SCALING
FACTOR α
αMIN
0
0
d
JOINT POSITION DISTANCE FROM BOUNDARY

FIG. 4

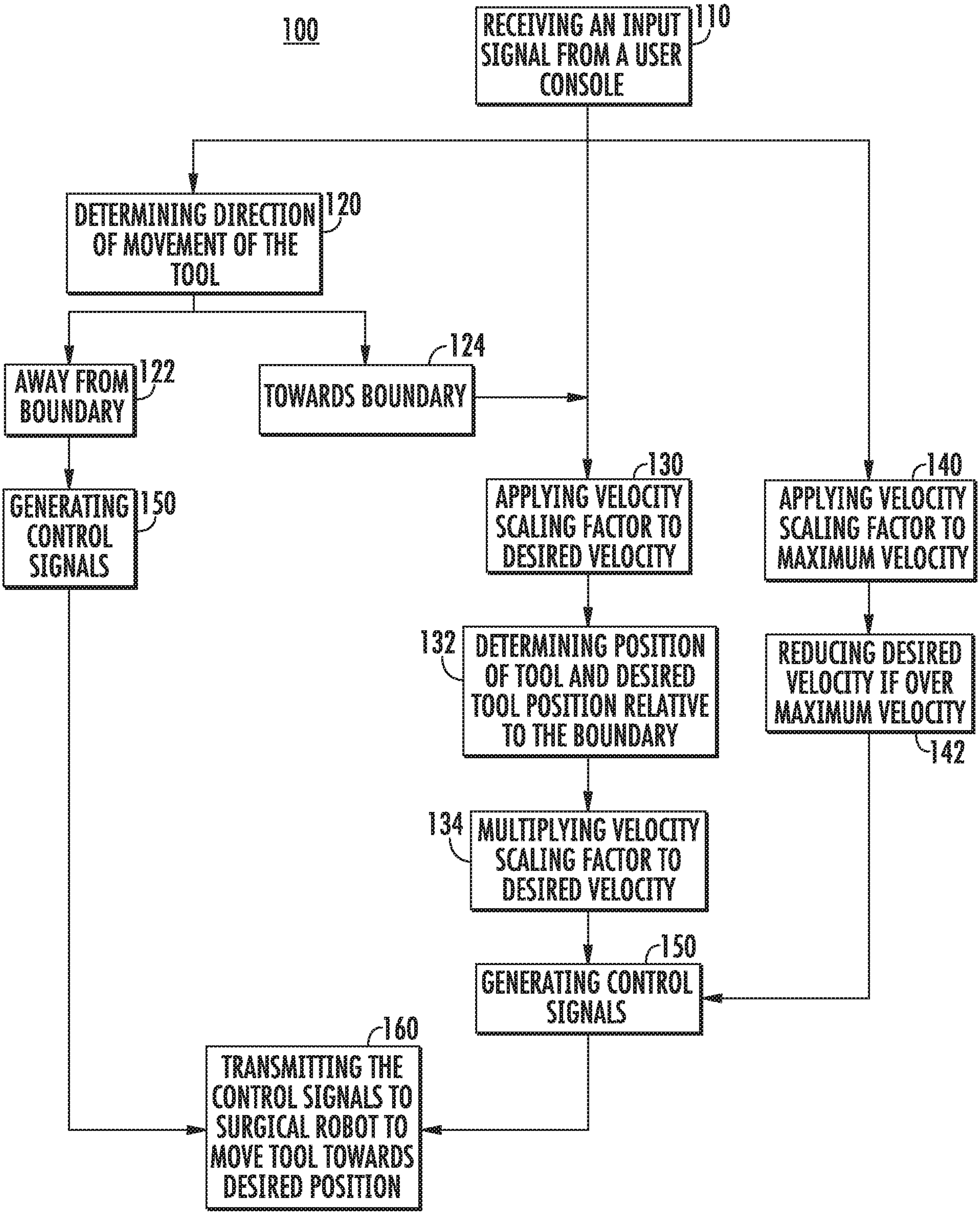
100
RECEIVING AN INPUT SIGNAL FROM A USER CONSOLE
110
DETERMINING DIRECTION OF MOVEMENT OF THE TOOL
120
AWAY FROM BOUNDARY
122
TOWARDS BOUNDARY
124
GENERATING CONTROL SIGNALS
150
APPLYING VELOCITY SCALING FACTOR TO DESIRED VELOCITY
130
APPLYING VELOCITY SCALING FACTOR TO MAXIMUM VELOCITY
140
132
DETERMINING POSITION OF TOOL AND DESIRED TOOL POSITION RELATIVE TO THE BOUNDARY
REDUCING DESIRED VELOCITY IF OVER MAXIMUM VELOCITY
142
134
MULTIPLYING VELOCITY SCALING FACTOR TO DESIRED VELOCITY
150
GENERATING CONTROL SIGNALS
160
TRANSMITTING THE CONTROL SIGNALS TO SURGICAL ROBOT TO MOVE TOOL TOWARDS DESIRED POSITION

FIG. 5