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(71) **Applicant: ACTIV SURGICAL, INC.** [US/US]; 840 Summer Street, Boston, MA 02127 (US).

(72) **Inventor: DEGHANI, Hossein**; c/o Activ Surgical, Inc., 840 Summer Street, Boston, MA 02127 (US).

(74) **Agent: HESLIN, Jim** et al.; Wilson Sonsini Goodrich & Rosati, P.C., 650 Page Mill Road, Palo Alto, CA 94304-1050 (US).

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(54) **Title:** SYSTEMS AND METHODS TO OPTIMIZE REACHABILITY, WORKSPACE, AND DEXTERITY IN MINIMALLY INVASIVE SURGERY

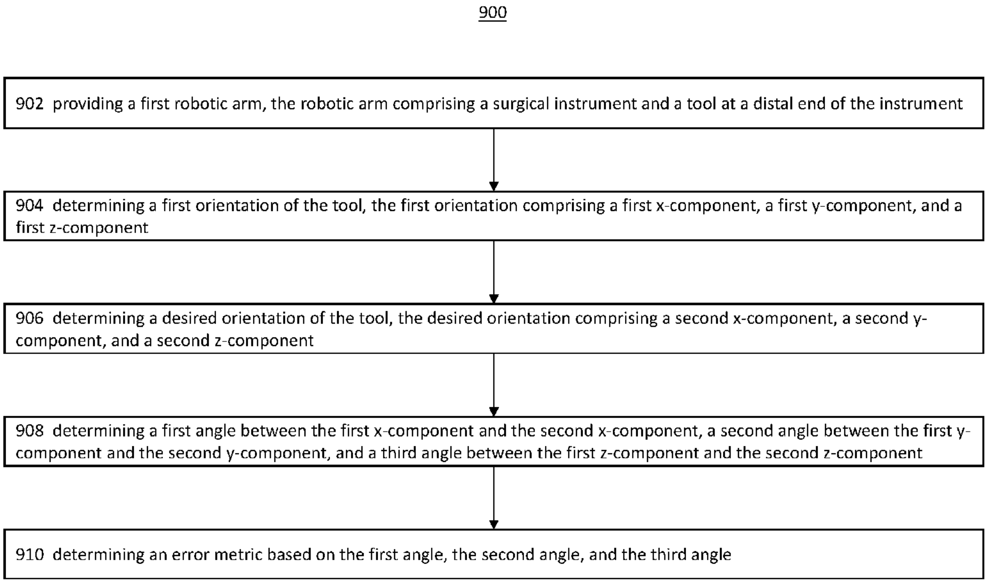

Fig. 9

(57) **Abstract:** Systems, methods, and computer program products for quantification of error in tool orientation of a surgical robotic are disclosed. A first robotic arm is provided where the robotic arm includes a surgical instrument and a tool disposed at the distal end of the surgical instrument. A first orientation of the tool is determined including a first x-component, a first y-component, and a first z-component. A desired orientation of the tool is determined including a second x-component, a second y-component, and a second z-component. A first angle between the first x-component and the second x-component is determined, a second angle between the first y-component and the second y-component is determined, and a third angle between the first z-component and the second z-component is determined. An error metric based on the first angle, the second angle, and the third angle is determined.

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SYSTEMS AND METHODS TO OPTIMIZE REACHABILITY, WORKSPACE, AND DEXTERITY IN MINIMALLY INVASIVE SURGERY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/785,957, filed on December 28, 2018, which is incorporated by reference herein in its entirety.

BACKGROUND

[0002] Embodiments of the present disclosure generally relate to optimization of reachability, workspace, and dexterity of a minimally invasive surgical robot. In particular, the present disclosure describes a method of determining an error-minimizing incision placement to optimize the reachability, workspace, and dexterity of the surgical robot.

BRIEF SUMMARY

[0003] According to embodiments of the present disclosure, systems for, methods for, and computer program products for determining an error-minimizing workspace for a surgical robot are provided. In various embodiments, the system includes a first robotic arm having a proximal end and a distal end. The proximal end is fixed to a base. The system further includes a surgical instrument disposed at the distal end of the robotic arm and the surgical instrument has a proximal end and a distal end. The system further includes a tool coupled to the distal end of the surgical instrument and a computing node including a computer readable storage medium having program instructions embodied therewith. The program instructions are executable by a processor of the computing node to cause the processor to perform a method where an error-minimizing incision site is determined in a patient. A tool orientation error for the tool is determined based on one or more locations of anatomical structures and the error-minimizing incision site. The surgical robot is adjusted based on the tool orientation error thereby minimizing the tool orientation error.

[0004] In various embodiments, a surgical trajectory to the one or more locations of anatomical structures may be determined. In various embodiments, the surgical trajectory is discretized with a plurality of points defined along the surgical trajectory. In various embodiments, the tool orientation error is determined for each of the plurality of points along the surgical trajectory. In various embodiments, the tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool. In various embodiments, determining an error-minimizing incision site in a patient includes discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface. In various embodiments, determining the error-minimizing incision site in a patient includes determining tool orientation error for each of the plurality of candidate incision sites. In various embodiments, one of the plurality of candidate incision sites having a smallest error metric is selected. In various embodiments, an error-minimizing position of a base of the surgical robot is determined and the error-minimizing position is based on the selected incision site. In various embodiments, determining the error-minimizing position of the base includes discretizing a space exterior to the patient into a plurality of candidate base locations. In various embodiments, a second tool orientation error based on the discretized surgical trajectory is determined for each of the plurality of candidate base locations. In various embodiments, the second tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

[0005] In various embodiments, a method is provided for determining an error-minimizing workspace for a surgical robot having a proximal end and a distal end and a surgical instrument at the distal end having a tool, where an error-minimizing incision site in a patient is determined. A tool orientation error for the tool is determined based on one or more locations of anatomical structures and the error-minimizing incision site. The surgical robot is adjusted based on the tool orientation error thereby minimizing the tool orientation error.

[0006] In various embodiments, a surgical trajectory to the one or more locations of anatomical structures may be determined. In various embodiments, the surgical trajectory is discretized with a plurality of points defined along the surgical trajectory. In various embodiments, the tool orientation error is determined for each of the plurality of points along the surgical trajectory. In various embodiments, the tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool. In various embodiments, determining an error-minimizing incision site in a patient includes discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface. In various embodiments, determining the error-minimizing incision site in a patient includes determining tool orientation error for each of the plurality of candidate incision sites. In various embodiments, one of the plurality of candidate incision sites having a smallest error metric is selected. In various embodiments, an error-minimizing position of a base of the surgical robot is determined and the error-minimizing position is based on the selected incision site. In various embodiments, determining the error-minimizing position of the base includes discretizing a space exterior to the patient into a plurality of candidate base locations. In various embodiments, a second tool orientation error based on the discretized surgical trajectory is determined for each of the plurality of candidate base locations. In various embodiments, the second tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

[0007] In various embodiments, computer program products for determining an error-minimizing workspace for a surgical robot having a proximal end and a distal end and a surgical instrument at the distal end having a tool are provided. The computer program product includes a computer readable storage medium having program instructions embodied therewith. The program instructions are executable by a processor of the computing node to cause the processor to perform a method where an error-minimizing incision site is determined in a patient. A tool orientation error for the tool is determined based on one or more locations of anatomical structures and the error-minimizing incision site. The surgical robot is adjusted based on the tool orientation error thereby minimizing the tool orientation error.

[0008] In various embodiments, a surgical trajectory to the one or more locations of anatomical structures may be determined. In various embodiments, the surgical trajectory is discretized with a plurality of points defined along the surgical trajectory. In various embodiments, the tool orientation error is determined for each of the plurality of points along the surgical trajectory. In various embodiments, the tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool. In various embodiments, determining an error-minimizing incision site in a patient includes discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface. In various embodiments, determining the error-minimizing incision site in a patient includes determining tool orientation error for each of the plurality of candidate incision sites. In various embodiments, one of the plurality of candidate incision sites having a smallest error metric is selected. In various embodiments, an error-minimizing position of a base of the surgical robot is determined and the error-minimizing position is based on the selected incision site. In various embodiments, determining the error-minimizing position of the base includes discretizing a space exterior to the patient into a plurality of candidate base locations. In various embodiments, a second tool orientation error based on the discretized surgical trajectory is determined for each of the plurality of candidate base locations. In various embodiments, the second tool orientation error is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

[0009] According to embodiments of the present disclosure, systems for, methods for, and computer program products for determining error in tool orientation at a distal end of a surgical instrument of a surgical robot are provided. In various embodiments, a system includes a first robotic arm having a proximal end and a distal end. The proximal end is fixed to a base. A surgical instrument is disposed at the distal end of the robotic arm and the surgical instrument has a proximal end and a distal end. A tool is coupled to the distal end of the surgical instrument. The system further includes a computing node including computer readable storage medium having program instructions embodied therewith. The program instructions are executable by a processor of the computing node to cause the processor to perform a method where a first orientation of the end effector is determined. The first orientation includes a first x-component, a first y-component, and a first z-component. A desired orientation of the end effector is determined. The desired orientation includes a second x-component, a second y-component, and a second z-component. A first angle between the first x-component and the second x-component is determined, a second angle between the first y-component and the second y-component is determined, and a third angle between the first z-component and the second z-component is determined An error metric based on the first angle, the second angle, and the third angle is determined.

[0010] In various embodiments, the error metric is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is the first angle, β is the second angle, and γ is the third angle. In various embodiments, an anatomical model of a patient is determined. In various embodiments, a first incision site on the anatomical model is selected and the error metric corresponds to the first incision site. In various embodiments, the anatomical model includes an anatomical atlas. In various embodiments, the anatomical model includes a three-dimensional reconstruction of patient anatomy based on imaging of the patient. In various embodiments, determining the error metric includes maintaining a fixed three-dimensional position at a proximal location along the surgical instrument. In various embodiments, the proximal location corresponds to the incision site on the anatomical model. In various embodiments, the anatomical model comprises a target anatomical structure. In various embodiments, one or more additional error metrics are determined such that each of the additional error metrics corresponds to a different location of a plurality of locations within the anatomical model. In various embodiments, the different locations correspond to a 2D Cartesian grid. In various embodiments, a graph of error metrics for each of the plurality of locations within the anatomical model is displayed. In various embodiments, the method further includes selecting a one or more additional incision sites on the anatomical model and, for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model. In various embodiments, one of the incision sites having the smallest error metric is selected.

[0011] In various embodiments, a method for determining error in the orientation of an end effector is provided where a first orientation of the end effector is determined. The first orientation includes a first x-component, a first y-component, and a first z-component. A desired orientation of the end effector is determined. The desired orientation includes a second x-component, a second y-component, and a second z-component. A first angle between the first x-component and the second x-component is determined, a second angle between the first y-component and the second y-component is determined, and a third angle between the first z-component and the second z-component is determined An error metric based on the first angle, the second angle, and the third angle is determined.

[0012] In various embodiments, the error metric is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is the first angle, β is the second angle, and γ is the third angle. In various embodiments, an anatomical model of a patient is determined. In various embodiments, a first incision site on the anatomical model is selected and the error metric corresponds to the first incision site. In various embodiments, the anatomical model includes an anatomical atlas. In various embodiments, the anatomical model includes a three-dimensional reconstruction of patient anatomy based on imaging of the patient. In various embodiments, determining the error metric includes maintaining a fixed three-dimensional position at a proximal location along the surgical instrument. In various embodiments, the proximal location corresponds to the incision site on the anatomical model. In various embodiments, the anatomical model comprises a target anatomical structure. In various embodiments, one or more additional error metrics are determined such that each of the additional error metrics corresponds to a different location of a plurality of locations within the anatomical model. In various embodiments, the different locations correspond to a 2D Cartesian grid. In various embodiments, a graph of error metrics for each of the plurality of locations within the anatomical model is displayed. In various embodiments, the method further includes selecting a one or more additional incision sites on the anatomical model and, for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model. In various embodiments, one of the incision sites having the smallest error metric is selected.

[0013] In various embodiments, a computer program product for determining error in the orientation of an end effector is provided in the form of a computer readable storage medium having program instructions embodied therewith. The program instructions are executable by a processor to cause the processor to perform a method where a first orientation of the end effector is determined. The first orientation includes a first x-component, a first y-component, and a first z-component. A desired orientation of the end effector is determined. The desired orientation includes a second x-component, a second y-component, and a second z-component. A first angle between the first x-component and the second x-component is determined, a second angle between the first y-component and the second y-component is determined, and a third angle between the first z-component and the second z-component is determined An error metric based on the first angle, the second angle, and the third angle is determined..

[0014] In various embodiments, the error metric is determined by: $error = \alpha^2 + \beta^2 + \gamma^2$ where α is the first angle, β is the second angle, and γ is the third angle. In various embodiments, an anatomical model of a patient is determined. In various embodiments, a first incision site on the anatomical model is selected and the error metric corresponds to the first incision site. In various embodiments, the anatomical model includes an anatomical atlas. In various embodiments, the anatomical model includes a three-dimensional reconstruction of patient anatomy based on imaging of the patient. In various embodiments, determining the error metric includes maintaining a fixed three-dimensional position at a proximal location along the surgical instrument. In various embodiments, the proximal location corresponds to the incision site on the anatomical model. In various embodiments, the anatomical model comprises a target anatomical structure. In various embodiments, one or more additional error metrics are determined such that each of the additional error metrics corresponds to a different location of a plurality of locations within the anatomical model. In various embodiments, the different locations correspond to a 2D Cartesian grid. In various embodiments, a graph of error metrics for each of the plurality of locations within the anatomical model is displayed. In various embodiments, the method further includes selecting a one or more additional incision sites on the anatomical model and, for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model. In various embodiments, one of the incision sites having the smallest error metric is selected.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] **Fig. 1** illustrates a robotic arm system for performing laparoscopic surgery according to an embodiment of the present disclosure.

[0016] **Figs. 2A-2B** illustrate a robotic arm system for performing laparoscopic surgery according to an embodiment of the present disclosure.

[0017] **Fig. 2C** illustrates a top view of a robotic arm system for performing laparoscopic surgery according to an embodiment of the present disclosure.

[0018] **Fig. 3A** illustrates two orientations of a surgical instrument and tool within an abdomen according to an embodiment of the present disclosure. **Fig. 3B** illustrates various orientations of a surgical instrument and tool within an abdomen according to an embodiment of the present disclosure.

[0019] **Figs. 4A-4B** illustrate a tool orientation according to an embodiment of the present disclosure.

[0020] **Fig. 5A** illustrates a discretized anatomical model according to an embodiment of the present disclosure. **Fig. 5B** illustrates a discretized anatomical model according to an embodiment of the present disclosure.

[0021] **Figs. 6A-6B** illustrate graphical representations of tool orientation error according to an embodiment of the present disclosure.

[0022] **Fig. 7** illustrates a graphical representation of tool orientation error according to an embodiment of the present disclosure.

[0023] **Fig. 8** illustrates a diagram of a robotic surgical system according to an embodiment of the present disclosure.

[0024] **Fig. 9** illustrates a flowchart of a method for computing tool error according to an embodiment of the present disclosure.

[0025] **Fig. 10** depicts an exemplary computing node according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0026] Many surgical maneuvers (*e.g.*, suturing, cutting, and/or folding) require highly dexterous and highly accurate motion of surgical tools to achieve a satisfactory surgical outcome. In fully automated robotic surgical procedures, surgical robots generally include a surgical instrument attached thereto having a tool that is inserted through a trocar placed in a small, keyhole incision in the abdomen of a patient. A keyhole incision, as used herein, may refer to a minimally invasive incision that is about 0.25 inch to 1 inch in size. The tool may include any suitable medical tool, such as, for example, a camera, a cutting tool, a gripping tool, a crimping tool, an electrocautery tool, or any other suitable tool as is known in the art. When the surgical instrument is inserted through the trocar (and into a body cavity, *e.g.*, abdomen, of the patient), the range of motion and/or possible orientations of the tool may be limited based on the position of the trocar in the patient. If the trocar position is not optimized based on the range of motion and/or possible orientations, the tool may not be capable of reaching certain regions of or objects (*e.g.*, a major artery) within a workspace (*e.g.*, a body cavity) and, thus, may not be able to perform the surgical task (*e.g.*, cutting, gripping, *etc.*) for which it is intended. For example, if the base of a robotic arm is placed too far away from the patient, an anatomical object (*e.g.*, a kidney) which is a target object of a surgical procedure may be out of the working range of the tool, thus complicating the surgical process.

[0027] Accordingly, a need exists for a system and method to determine an error-minimizing incision placement to thereby enable accurate surgical maneuvers and improve robotic-assisted surgery.

[0028] **Fig. 1** illustrates a robotic arm system **100** for performing laparoscopic surgery according to an embodiment of the present disclosure. The robotic arm system **100** includes a robotic arm **102** affixed to a base **101** at a proximal end. The robotic arm **102** further includes a surgical instrument **104** at the distal end and the surgical instrument **104** includes a tool (not shown), such as, for example, a grasper, electrocautery tool, a cutting tool, *etc.*. A trocar **105** is inserted into an incision **106** in the abdomen **108** to thereby provide access to a body cavity (*e.g.*, abdominal cavity) in which a surgical procedure will take place. In various embodiments, a surgeon **110** overseeing the robotic surgery may insert the surgical instrument **104** (and the tool) through the trocar **105** and into the body cavity.

[0029] **Figs. 2A-2B** illustrate a robotic arm system **200** for performing laparoscopic surgery according to an embodiment of the present disclosure. Similar to the robotic arm system of **Fig. 1**, the robotic arm system **200** includes a robotic arm **202** positioned over an abdomen **208** (modeled as a rectangular box having dimensions of 40cm x 40cm x 20cm). In various embodiments, the dimensions of the abdomen **208** may vary based on the particular patient. **Fig. 2B** shows an abdomen **208** including a first incision **206a** corresponding to a first case and a second keyhole incision **206b** corresponding to a second case. The tool at the end of the surgical instrument may have a different orientation error depending on the location of the incision for a given surgical process. The variability of end effector orientation error will be discussed in more detail with respect to **Figs. 6A, 6B** and 7.

[0030] **Fig. 2C** illustrates a top view of a robotic arm system **200** for performing laparoscopic surgery according to an embodiment of the present disclosure. As shown in **Fig. 2C**, the second keyhole incision **206b** in the abdomen **208** (approximately in the center of the abdomen) is positioned approximately 30cm from the base in either direction. In various embodiments, an optimization algorithm may be applied to each potential incision **206a, 206b** to determine the maximum error in the tool based on a particular surgical procedure.

[0031] **Fig. 3A** illustrates two orientations of a surgical instrument **304a, 304b** and tool **307a, 307b** within an abdomen **308** according to an embodiment of the present disclosure. As shown in **Fig. 3A**, a surgical instrument **304a** and a tool **307a** are placed in a first orientation within the incision **306** in the abdomen **308**. Due to one or more constraints created by the incision **306** and/or sensitive tissues (*e.g.*, nerves and/or blood vessels), the tool **307a** may not be capable of a desired orientation, such as the orientation shown by surgical instrument **304b** with the tool **307b** having a different orientation than the orientation of the tool **307a**. In various embodiments, cone **350a** represents all possible orientations of the tool **307a** when surgical instrument **304a** is in that particular location. In various embodiments, cone **350b** represents all possible orientations of the tool **307b** when surgical instrument **304b** is in that particular location. As shown in Fig. 3A, cone **350b** does not collide with object **320** and can access anatomical structure **322**.

[0032] In various embodiments, the surgical instrument (and tool) may have a limited workspace within a particular body cavity. In various embodiments, one or more objects **320** (*e.g.*, a bone or blood vessel) may prevent the surgical instrument from being capable of adopting a particular desired orientation to access an anatomical structure **322** (*e.g.*, a kidney). In the first orientation, the tool **307a**, may not be capable of performing a surgical maneuver on the anatomical structure **322** in certain portions of the abdomen **308**, whereas, in the desired orientation, the surgical instrument **304b** is capable of performing the surgical maneuver on the anatomical structure **322**.

[0033] In various embodiments, the surgical instrument (and tool) may have a limited workspace within a particular body cavity based on placement of the base of the robotic arm. In various embodiments, if the base of the robotic arm is incorrectly positioned (*e.g.*, placed too far away from the patient), the surgical instrument may not be capable of adopting a particular, desired orientation (such as the orientation shown by tool **307b** of surgical instrument **304b**) to access an anatomical structure **322** (*e.g.*, a kidney).

[0034] **Fig. 3B** illustrates various orientations of a surgical instrument **304a, 304b, 304c, 304d** and tool **307a, 307b, 307c, 307d** within an abdomen **308** according to an embodiment of the present disclosure. In various embodiments, in a first orientation of the surgical instrument **304a**, the desired orientation for the tool is not achievable due to the presence of an object **320** (*e.g.*, a nerve and/or vascular structure) blocking the tool. In various embodiments, in a second orientation of the surgical instrument **304b**, the desired orientation for the tool is not achievable due to the incision site **306** and/or trocar as only orientations that fall inside the cone **350** are achievable. In various embodiments, tools **307b** and **307c** may have the least tool orientation error with respect to the desired tool orientation **307a**. In this example, **307b** is not achievable due to the incision site **306** and, thus, tool **307c** orientation would be selected.

[0035] In various embodiments, the location if the incision (and subsequent trocar placement) imposes a kinematics constraint on a surgical robot. In various embodiments, one constraint is that the instrument should not move laterally at the incision site (*e.g.*, to avoid damaging the incision). In various embodiments, the maneuverability at the tool may be significantly reduced when a procedure is performed laparoscopically (because of this constraint at the incision/trocar). In various embodiments, if the instrument does not have an articulated distal tool, proper placement of the incision site is important to preserve maneuverability of the instrument given a surgical target (*e.g.*, an organ). In various embodiments, even with a dexterous tool (*e.g.*, a grasper) having one or more articulated joints, the tool may encounter issues when attempting to reach a target from a certain angle because, for example, the incision site restricts the motion of the instrument and/or tool.

[0036] **Figs. 4A-4B** illustrate a tool **407** orientation according to an embodiment of the present disclosure. As shown in **Fig. 4A**, the tool **407** has an orientation based on a distal most point **412**. The orientation of the tool **407** includes three vectors: an x-component **414a**, a y-component **414b**, and a z-component **414c** that together define the orientation of the tool **407** in 3D space.

[0037] **Fig. 4B** illustrates the distal point **412** without the tool **407** illustrated in **Fig. 4A**. As shown in **Fig. 4B**, the tool **407** includes an actual orientation including the x-component **414a**, the y-component **414b**, and the z-component **414c**. In this case, the actual orientation is different than the desired orientation, which is represented by a x'-component **416a**, a y'-component **416b**, and a z'-component **416c** that together define the desired orientation of the tool **407**.

[0038] In various embodiments, angles may be measured between the particular axes and their desired configurations. For example, an angle $\boldsymbol{\alpha}$ is measured between the x-component **414a** and the x'-component **416a**, an angle $\boldsymbol{\beta}$ is measured between the y-component **414b** and the y'-component **416b**, and an angle γ is measured between the z-component **414c** and the z'-component **416c**. An error metric may be determined using the equation below:

$$\alpha^2 + \beta^2 + \gamma^2 = error \quad \text{(Eqn. 1)}$$

[0039] In various embodiments, a surgical target may be identified. In various embodiments, the surgical target may be a tissue, organ, structure, and/or any other suitable target of a surgical procedure.

[0040] In various embodiments, a surgical task (*e.g.*, suturing a tissue) may be specified. In various embodiments, the surgical task may be specified with respect to a trajectory of the distal-most end of the tool. In various embodiments, the trajectory may include one or more lines. In various embodiments, the trajectory may include one or more curves. In various embodiments, the trajectory may include a spline.

[0041] In various embodiments, the trajectory may be discretized into a finite set of discrete points. In various embodiments, the discretized trajectory may include a set of discrete points having a pre-determined distance between each point. In various embodiments, the pre-determined distance between each point may be different. For example, points along a straight line may have a larger distance between each point while points on a curve may have a smaller distance between each point. In various embodiments, the trajectory may be discretized using any suitable known discretization algorithm.

[0042] In various embodiments, for each point along the discretized trajectory, a desired orientation of the tool is determined. In various embodiments, the desired orientation is compared to one or more possible orientations. In various embodiments, the one or more possible orientations may be the actual orientation of the tool. In various embodiments, the actual orientation is compared to the desired orientation at each discretized point using equation 1 above to determine error for each discretized point along the trajectory. In various embodiments, the error for a trajectory performed from a given incision location may be visualized as shown in **Figs. 6A, 6B, and** 7.

[0043] In various embodiments, a tool orientation is selected from the one or more possible orientations having the lowest error when compared to the desired orientation. In various embodiments when one of the possible orientations includes the desired orientation, that orientation is selected. In various embodiments, when the desired orientation is included among the possible orientations, the error may be zero.

[0044] In various embodiments, the determined error at each discretized point may be summed to determine a total error metric for the entire trajectory given a particular candidate incision location. In various embodiments, the total error metric may be computed for each of a plurality of candidate incision locations.

[0045] In various embodiments, the trajectory and/or total error metric may depend on the type of surgical subtasks (*e.g.*, suturing), type of surgery, design of surgery, dimension of the instrument and/or tool (*e.g.*, 4 DOF, 5 DOF, 6 DOF), surgical complexity, and/or circumstances (*e.g.*, surrounding nerves that should be avoided).

[0046] In various embodiments, the plurality of candidate incision locations may collectively define a mesh. In various embodiments, the mesh may include discretized points along a surface of an anatomical model as described in more detail below with respect to **Figs. 5A** and **5B**.

[0047] In various embodiments, one incision point having the smallest total error metric is selected among the candidate incision points. In various embodiments, the selected incision point is presented to the user (*e.g.*, a surgeon). In various embodiments, two or more incision points may be highlighted when the two or more incision points have the same, smallest total error metric. In various embodiments, the two or more highlighted incision points may be displayed to a user (*e.g.*, a surgeon). In various embodiments, the user (*e.g.*, surgeon) may determine which of the two or more highlighted incision points the surgery will ultimately use. In various embodiments, the system may receive user input selecting one of the two or more highlighted incision sites that will be used for the surgical procedure.

[0048] In various embodiments, the process described herein may be a two-phase optimization which includes incision placement and robotic base placement. In various embodiments, a user (*e.g.*, a surgeon) may select from a finite set of incision options (*e.g.*, informed/guided decision making). In various embodiments, the process may determine a location for the base of the robot such that the instrument tool tip is capable of reaching the surgical target. In various embodiments, the process of determining the placement of the robot base is independent from the incision placement. **[0049]** In various embodiments, the process may include intraoperative optimization. In various embodiments, the incision site has already been selected and created on the patient's body. In various embodiments, a trocar has been inserted into the incision site. In various embodiments, the robot base has been locked into place. In various embodiments, an algorithm intraoperatively minimizes the error between any actual and desired orientation of the surgical instrument and/or tool. **[0050]** **Fig. 5A** illustrates a discretized anatomical model **508** according to an embodiment of the present disclosure. In various embodiments, the anatomical model may include any portion of anatomy (*e.g.*, a complete anatomical model or only a portion of an anatomical model). In various embodiments, the anatomical model **508** is a portion of a full model and includes the human torso. In various embodiments, the anatomical model **508** may be retrieved from a generic 3D anatomical atlas. In various embodiments, the anatomical model **508** may be retrieved from patient pre-surgical imaging. In various embodiments, the anatomical model may include a three-dimensional reconstruction of the patient based on prior imaging (*e.g.*, pre-surgical imaging). In various embodiments, one or more surfaces of the anatomical model **508** may be discretized using any suitable discretization algorithm. For example, the top surface of the anatomical model **508** may be discretized using a polygonal mesh **509** (*e.g.*, surface mesh). In various embodiments, the mesh **509** may include a plurality of vertices **511**. A vertex (or vertices), as used herein, may be any intersection point of two edges in a grid used to discretize a surface into a plurality of discrete segments (*i.e.*, a mesh). In various embodiments, each vertex **511** may represent a potential incision site for a minimally invasive surgical procedure. In various embodiments, one or more computations may be carried out at each vertex. In various embodiments, the computation(s) may be iterated based on the results of adjacent vertices. In various embodiments, the computation(s) may be iterated until the results converge to a result (*e.g.*, the result does not change by more than a predetermined percent from iteration to iteration). In various embodiments, an incision (and trocar) placement algorithm to optimize a surgical robot workspace may be computed at each of the vertices **511**. In various embodiments, one or more error-minimizing incision site **513** may be displayed on the 3D anatomical model **508**. In various embodiments, one or more error-minimizing incision site **513** may be projected onto the patient (*e.g.*, while on the surgical table) via a projector.

[0051] In various embodiments, each vertex comprises a three-dimensional point. In various embodiments, each vertex may be located on any suitable surface of the body where a candidate incision may be placed. In various embodiments, predetermined areas of the body may be excluded from the mesh, for example, where no suitable incision can be made.

[0052] In various embodiments, the mesh **509** may be projected onto the patient via a projector. In various embodiments, the projected mesh may be, for example, a Cartesian grid. In various embodiments, a camera may record an image of the patient and the projected mesh **509**. In various embodiments, the system may register the image of the patient with 3D anatomy (*e.g.*, an anatomical atlas). In various embodiments, the system may determine the available workspace and/or tool orientation error at each of the vertices **511** of the mesh **509** for the tool to reach a particular location and/or anatomical structure within the 3D anatomy.

[0053] **Fig. 5B** illustrates a discretized anatomical model **508** according to an embodiment of the present disclosure. In various embodiments, an anatomical region of a patient having a complex shape may be represented by a simpler shape. In various embodiments, the anatomical model **508** is a simple three-dimensional shape, *e.g.*, a rectangular box, a cube, a sphere, an ellipsoid, a cylinder, *etc*. For example, an abdomen of a patient may be represented as a box having a length (L), a width (W), and a depth (D). In various embodiments, one or more surfaces of the box may be discretized using any suitable discretization algorithm. For example, the top surface of the box may be discretized using a polygonal (*e.g.*, rectangular, square, triangular, *etc.*) mesh **509** (*e.g.*, surface mesh). In various embodiments, the mesh **509** may include a plurality of vertices **511**. In various embodiments, each vertex **511** may represent a potential incision site for a minimally invasive surgical procedure. In various embodiments, one or more computations may be carried out at each vertex **511**. In various embodiments, the computation(s) may be iterated based on the results of adjacent vertices **511**. In various embodiments, the computation(s) may be iterated until the results converge to a result (*e.g.*, the result does not change by more than a predetermined percent from iteration to iteration). In various embodiments, an incision (and trocar) placement algorithm to optimize a surgical robot workspace may be computed at each of the vertices **511**. In various embodiments, although the surface of the box is 2D, an incision may be 3D. In various embodiments, all points along the incision may have the same depth (*e.g.*, z-value) if the box is aligned with the base of the robot.

[0054] In various embodiments, a surgical path may be determined for each vertex **511** in the mesh **509**. In various embodiments, an error metric may be determined for each vertex in the mesh **509**. In various embodiments, a plot (*e.g.*, surface plot) of the error metric may be displayed to a user (*e.g.*, a surgeon) separately from the model **508**. In various embodiments, a plot (*e.g.*, surface plot) may be overlaid on the model **508**. In various embodiments, the plot may be color coded with a range of colors such that one color (*e.g.*, blue) represents the lowest or negligible determined error while another color (*e.g.*, red) represents the highest determined error. In various embodiments, the system may provide an indication to the user (*e.g.*, surgeon) of the error-minimizing incision point(s) for a particular surgery. In various embodiments, more than one incision point may be returned as error-minimizing for performing a particular surgery.

[0055] Similar to **Fig. 5A**, an error-minimizing incision site **513** (to access target anatomical structure **522** within the volume of the anatomical model **508**) may be selected after tool orientation error has been determined at each vertex **511** of the mesh **509**. In various embodiments, the target anatomical structure **522** may be represented by one or more point in three-dimensional space (x, y, z). In various embodiments, the point in three-dimensional space may correspond to any suitable part of the anatomical structure **522**. For example the point may correspond to a centroid. In another example, the one or more point may correspond to any discrete point along the surface of the anatomical structure **522**. In various embodiments, the one or more point may correspond to any discrete point within the volume of the anatomical structure **522**. In various embodiments, the target anatomical structure **522** may be modeled (*i.e.*, shape and/or position within the anatomical model **508**) from a generic 3D anatomical atlas. In various embodiments, the target anatomical structure **522** may be modeled (*i.e.*, shape and/or position within the anatomical model **508**) as a 3D reconstruction of patient imaging (*e.g.*, pre-surgical imaging). In various embodiments, the target anatomical structure may be represented as a simplified shape (*e.g.*, a rectangular box, a cube, a sphere, an ellipsoid, a cylinder, *etc.*). For example, target anatomical structure **508** may be a kidney represented as an ellipsoid. In some embodiments, iterative optimization techniques are applied to select the error-minimizing incision site.

[0056] **Figs. 6A-6B** illustrate graphical representations of tool orientation error according to an embodiment of the present disclosure. To generate the graphs, a desired orientation for the tool distal-most tip is provided and X and Y values for the tool were incremented by a predetermined value. For each increment, the algorithm described above was performed to compute tool orientation error. The error-minimizing orientation has the smallest amount of error between the given orientation and desired orientation. The computed errors may be visualized in graphical form. **Fig. 6A** represents a first incision position using the first keyhole incision as described above and shows that tool orientation error is the highest in the center of the abdomen model. **Fig. 6B** shows the error calculation of **Fig. 6A** with a refined (*i.e.*, higher resolution) mesh.

[0057] In various embodiments, a surgeon may be provided with a map of tool error. In various embodiments, the visualized error is representative of error caused by kinematic constraints of performing a task. In various embodiments, the surgeon may be provided with two or more recommended incision sites along with the map of tool error for a particular procedure (*i.e.*, trajectory). In various embodiments, the recommended incision sites may include those with the lowest error. In various embodiments, the recommended incision sites may include the incision site with the absolute lowest error. In various embodiments, the recommended incision sites may include the incision sites having the lowest 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, *etc.* of error.

[0058] In various embodiments, if an incision site is pre-selected, the pre-operative algorithm where robot base location is pre-selected and incision site is pre-selected may not be needed. In various embodiments, the intraoperative algorithm may minimize the error at the tool tip based on the pre-selected kinematic constraints,

[0059] **Fig.** 7 illustrates a graphical representation of tool orientation error according to an embodiment of the present disclosure. **Fig. 7** represents a second incision position using the second keyhole incision as described above and shows that tool orientation error is the highest in the top-right corner of the abdomen model.

[0060] Based on the above graphs shown in **Figs. 6A, 6B** and 7, the error distribution varies depending on the incision location. While these experiments were performed with a single orientation, certain surgical maneuvers (*e.g.*, suturing) require multiple orientations through any combination of, *e.g.*, rotations and/or translations of the surgical instrument and/or tool. Therefore, the error-minimizing incision placement requires knowledge about the procedure (how many points and in which directions). For a suturing example, if a suitable suturing procedure is known, error-minimizing incision placement may be determined from the known motions for performing the particular suture procedure.

[0061] **Fig. 8** illustrates a diagram of a robotic surgical system **800** according to an embodiment of the present disclosure. The robotic surgical system **800** is similar to the systems described above in that the system **800** includes a robotic arm **802** affixed to a base **801**. The robotic arm **802** includes a surgical instrument **804** disposed at a distal end of the robotic arm **802**. The surgical instrument **804** is inserted through a trocar **805** placed within an incision **806** and includes a tool at a distal-most end **812**.

[0062] In some embodiments, iterative optimization techniques are applied to select an error-minimizing incision point, an error-minimizing trocar position, and an error-minimizing base position such that tool orientation error is minimized. In some such embodiments, an exhaustive search is performed of one or more position variable. For example, for a given base position, error may be computed for every point on a predetermined grid of potential incision points. Once the computation has been performed for each potential position for a given variable, the lowest error configuration is selected. In some embodiments, mathematical optimization methods are used, thereby avoiding an exhaustive search. For example, gradient descent may be applied to arrive at an error minimizing selection of positional variables. It will be appreciated that a variety of mathematical optimization methods are useful for minimizing error based on placement variables, *e.g.*, differential evolution, local search, gradient descent, or simulated annealing.

[0063] In various embodiments, in a first step, an error-minimizing incision position may be selected on the patient to provide the error-minimizing amount of workspace to access one or more target anatomical structures **822** within a body cavity (*e.g.*, abdominal cavity) of an anatomical model **808**.

[0064] In various embodiments, in a second step, a position of a base **801** of the robotic arm **802** is determined. In various embodiments, the position of the base **801** is determined based on the selected error-minimizing incision site **806** from the first step. In various embodiments, the position of the base may include two or more potential error-minimizing positions that allow for optimal laparoscopic workspace for a particular surgical procedure.

[0065] In various embodiments, to determine a location of a base of a surgical robot, the surgical trajectory, surgical target (*e.g.*, target anatomy), and instrument type are given. In various embodiments, an incision site may be selected prior to determining the location of the base.

[0066] In various embodiments, to determine the location of the base, a pre-determined space outside the patient may discretized into a grid of points, where each point is candidate location for the base. For a candidate location of a base **801** and the incision site **806**, reachability of the robot arm and/or tool may be determined. In various embodiments, the reachability may be constrained to a region defined by an arc, as shown in **Fig. 8**. In various embodiments, moving the base changes the shape and/or volume of the workspace. For a candidate base **801** (and pre-selected incision site **806**), an error metric may be determined. In various embodiments, the error metric may be based on the trajectory of the tool, similar to the error determination described above. In various embodiments, the trajectory of the tool is discretized and an error is determined for the candidate base location. In various embodiments, as an example, one or more locations of the base may have the similar (*e.g.*, same) error as computed for the tool by itself where the robot workspace is capable of performing the trajectory (*e.g.*, with minimal error between the actual and desired orientation). In various embodiments, if the robot base is located too far away from the patient, for example, the tool orientation may significantly differ from the desired tool orientation because the robot is not capable of assuming an error-minimizing tool orientation given the constraint of the incision site (and trocar).

[0067] In various embodiments, one or more of the discretized locations may be excluded. In various embodiments, the excluded location(s) may correspond to location(s) that are unavailable for positioning the robotic base. For example, required healthcare equipment (*e.g.*, an anesthesia monitor/delivery device) may be located near the patient.

[0068] In various embodiments, the candidate base location(s) with the least error are recommended for the robot placement. In various embodiments, a map of error may be provided to the user with recommended base location(s) for the surgical robot.

[0069] In various embodiments, in a third step, tool orientation error is determined as described above. In various embodiments, tool orientation error may be minimized to avoid one or more objects within the laparoscopic workspace (*e.g.*, critical nerves and/or blood vessels). In various embodiments, for example, a tool has a desired orientation and a cone extending therefrom representing possible orientations. In various embodiments, one orientation in the cone will minimize the error as defined in equation 1. In various embodiments, if the cone of possible orientations includes the desired orientation, the error is zero.

[0070] In various embodiments, the tool orientation error may be determined as the difference between an actual trajectory and a desired trajectory of pathing of the distal-most end of the tool.

[0071] **Fig. 9** illustrates a flowchart of a method **900** for computing end effector error according to an embodiment of the present disclosure. At **902**, a first robotic arm is provided where the robotic arm includes a trocar and an end effector. At **904**, a first orientation of the end effector is determined. The first orientation includes a first x-component, a first y-component, and a first z-component. At **906**, a desired orientation of the end effector is determined, the desired orientation comprising a second x-component, a second y-component, and a second z-component. At **908**, a first angle between the first x-component and the second x-component is determined, a second angle between the first y-component and the second y-component is determined, and a third angle between the first z-component and the second z-component is determined. At **910**, an error metric based on the first angle, the second angle, and the third angle is determined.

[0072] In various embodiments, determining an error metric may include summing the squares of each of the first angle, the second angle, and the third angle. In various embodiments, two or more error metrics may be determined, such that each error metric corresponds to a different trocar position. In various embodiments, the determined error metrics for each trocar position may be compared to determine an error-minimizing trocar position for a particular surgical procedure.

[0073] In various embodiments, the algorithm inputs for determining end effector orientation error may include, for example, trocar position, abdominal cavity size and position, and desired end effector tip orientation. In various embodiments, error in the end effector orientation may be determined for two or more potential incision sites and the errors may be compared to determine an error-minimizing incision site for a particular surgical procedure.

[0074] Referring now to **Fig. 10**, a schematic of an exemplary computing node is shown that may be used with the computer vision systems described herein. Computing node **10** is only one example of a suitable computing node and is not intended to suggest any limitation as to the scope of use or functionality of embodiments described herein. Regardless, computing node **10** is capable of being implemented and/or performing any of the functionality set forth hereinabove.

[0075] In computing node **10** there is a computer system/server **12**, which is operational with numerous other general purpose or special purpose computing system environments or configurations. Examples of well-known computing systems, environments, and/or configurations that may be suitable for use with computer system/server **12** include, but are not limited to, personal computer systems, server computer systems, thin clients, thick clients, handheld or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputer systems, mainframe computer systems, and distributed cloud computing environments that include any of the above systems or devices, and the like.

[0076] Computer system/server **12** may be described in the general context of computer system-executable instructions, such as program modules, being executed by a computer system. Generally, program modules may include routines, programs, objects, components, logic, data structures, and so on that perform particular tasks or implement particular abstract data types. Computer system/server **12** may be practiced in distributed cloud computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed cloud computing environment, program modules may be located in both local and remote computer system storage media including memory storage devices.

[0077] As shown in **Fig. 10**, computer system/server **12** in computing node **10** is shown in the form of a general-purpose computing device. The components of computer system/server **12** may include, but are not limited to, one or more processors or processing units **16**, a system memory **28**, and a bus **18** coupling various system components including system memory **28** to processor **16**.

[0078] Bus **18** represents one or more of any of several types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port, and a processor or local bus using any of a variety of bus architectures. By way of example, and not limitation, such architectures include Industry Standard Architecture (ISA) bus, Micro Channel Architecture (MCA) bus, Enhanced ISA (EISA) bus, Video Electronics Standards Association (VESA) local bus, and Peripheral Component Interconnect (PCI) bus.

[0079] Computer system/server **12** typically includes a variety of computer system readable media. Such media may be any available media that is accessible by computer system/server **12**, and it includes both volatile and non-volatile media, removable and non-removable media.

[0080] System memory **28** can include computer system readable media in the form of volatile memory, such as random access memory (RAM) **30** and/or cache memory **32**. Computer system/server **12** may further include other removable/non-removable, volatile/non-volatile computer system storage media. By way of example only, storage system **34** can be provided for reading from and writing to a non-removable, non-volatile magnetic media (not shown and typically called a "hard drive"). Although not shown, a magnetic disk drive for reading from and writing to a removable, non-volatile magnetic disk (e.g., a "floppy disk"), and an optical disk drive for reading from or writing to a removable, non-volatile optical disk such as a CD-ROM, DVD-ROM or other optical media can be provided. In such instances, each can be connected to bus **18** by one or more data media interfaces. As will be further depicted and described below, memory **28** may include at least one program product having a set (e.g., at least one) of program modules that are configured to carry out the functions of embodiments of the disclosure.

[0081] Program/utility **40**, having a set (at least one) of program modules **42**, may be stored in memory **28** by way of example, and not limitation, as well as an operating system, one or more application programs, other program modules, and program data. Each of the operating system, one or more application programs, other program modules, and program data or some combination thereof, may include an implementation of a networking environment. Program modules **42** generally carry out the functions and/or methodologies of embodiments described herein.

[0082] Computer system/server **12** may also communicate with one or more external devices **14** such as a keyboard, a pointing device, a display **24**, etc.; one or more devices that enable a user to interact with computer system/server **12**; and/or any devices (e.g., network card, modem, etc.) that enable computer system/server **12** to communicate with one or more other computing devices. Such communication can occur via Input/Output (I/O) interfaces **22**. Still yet, computer system/server **12** can communicate with one or more networks such as a local area network (LAN), a general wide area network (WAN), and/or a public network (e.g., the Internet) via network adapter **20**. As depicted, network adapter **20** communicates with the other components of computer system/server **12** via bus **18**. It should be understood that although not shown, other hardware and/or software components could be used in conjunction with computer system/server **12**. Examples, include, but are not limited to: microcode, device drivers, redundant processing units, external disk drive arrays, RAID systems, tape drives, and data archival storage systems, etc.

[0083] In other embodiments, the computer system/server may be connected to one or more cameras (*e.g.*, digital cameras, light-field cameras) or other imaging/sensing devices (*e.g.*, infrared cameras or sensors).

[0084] The present disclosure includes a system, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present disclosure.

[0085] The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (*e.g.*, light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

[0086] Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

[0087] Computer readable program instructions for carrying out operations of the present disclosure may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Smalltalk, C++ or the like, and conventional procedural programming languages, such as the “C” programming language or similar programming languages. The computer readable program instructions may execute entirely on the user’s computer, partly on the user’s computer, as a stand-alone software package, partly on the user’s computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user’s computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In various embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present disclosure.

[0088] Aspects of the present disclosure are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

[0089] These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

[0090] The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0091] The flowchart and block diagrams in the figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present disclosure. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In various alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0092] The descriptions of the various embodiments of the present disclosure have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

CLAIMS

What is claimed is:

1. A system for determining an error-minimizing workspace for a surgical robot, the system comprising:

a first robotic arm having a proximal end and a distal end, the proximal end fixed to a base;

a surgical instrument disposed at the distal end of the robotic arm, the surgical instrument having a proximal end and a distal end;

a tool coupled to the distal end of the surgical instrument; and

a computing node comprising a computer readable storage medium having program instructions embodied therewith, the program instructions executable by a processor of the computing node to cause the processor to perform a method comprising:

determining an error-minimizing incision site in a patient;

determining a tool orientation error for the tool based on one or more locations of anatomical structures and the error-minimizing incision site; and

adjusting the surgical robot based on the tool orientation error thereby minimizing the tool orientation error.

2. The system of claim 1, wherein the method further comprises determining a surgical trajectory to the one or more locations of anatomical structures.

3. The system of claim 2, wherein the method further comprises discretizing the surgical trajectory with a plurality of points defined along the surgical trajectory.

4. The system of claim 3, wherein the tool orientation error is determined for each of the plurality of points along the surgical trajectory.

5. The system of claim 4, wherein the tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

6. The system of claim 5, wherein determining an error-minimizing incision site in a patient comprises discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface.

7. The system of claim 1, wherein determining the error-minimizing incision site in a patient comprises determining tool orientation error for each of the plurality of candidate incision sites.

8. The system of claim 1, wherein the method further comprises selecting one of the plurality of candidate incision sites having a smallest error metric.

9. The system of claim 8, wherein the method further comprises determining an error-minimizing position of a base of the surgical robot, wherein the error-minimizing position is based on the selected incision site.

10. The system of claim 9, wherein determining the error-minimizing position of the base comprises discretizing a space exterior to the patient into a plurality of candidate base locations.

11. The system of claim 10, wherein the method further comprises, for each of the plurality of candidate base locations, determining a second tool orientation error based on the discretized surgical trajectory.

12. The system of claim 11, wherein the second tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

13. A method for determining an error-minimizing workspace for a surgical robot having a proximal end and a distal end and a surgical instrument at the distal end having a tool, the method comprising:

determining an error-minimizing incision site in a patient;

determining a tool orientation error for the tool based on one or more locations of anatomical structures and the error-minimizing incision site; and

adjusting the surgical robot based on the tool orientation error thereby minimizing the tool orientation error.

14. The method of claim 13, further comprising determining a surgical trajectory to the one or more locations of anatomical structures.

15. The system of claim 14, further comprising discretizing the surgical trajectory with a plurality of points defined along the surgical trajectory.

16. The method of claim 15, wherein the tool orientation error is determined for each of the plurality of points along the surgical trajectory.

17. The method of claim 13, wherein the tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

18. The method of claim 17, wherein determining an error-minimizing incision site in a patient comprises discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface.

19. The method of claim 1, wherein determining the error-minimizing incision site in a patient comprises determining tool orientation error for each of the plurality of candidate incision sites.

20. The method of claim 13, further comprising selecting one of the plurality of candidate incision sites having a smallest error metric.

21. The method of claim 20, further comprising determining an error-minimizing position of a base of the surgical robot, wherein the error-minimizing position is based on the selected incision site.

22. The method of claim 21, wherein determining the error-minimizing position of the base comprises discretizing a space exterior to the patient into a plurality of candidate base locations.

23. The method of claim 22, further comprising, for each of the plurality of candidate base locations, determining a second tool orientation error based on the discretized surgical trajectory.

24. The method of claim 23, wherein the second tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

25. A computer program product for determining an error-minimizing workspace for a surgical robot having a proximal end and a distal end and a surgical instrument at the distal end having a tool, the computer program product comprising a computer readable storage medium

having program instructions embodied therewith, the program instructions executable by a processor to cause the processor to perform a method comprising:

determining an error-minimizing incision site in a patient;

determining a tool orientation error for the tool based on one or more locations of anatomical structures and the error-minimizing incision site; and

adjusting the surgical robot based on the tool orientation error thereby minimizing the tool orientation error.

26. The computer program product of claim 25, further comprising determining a surgical trajectory to the one or more locations of anatomical structures.

27. The computer program product of claim 26, further comprising discretizing the surgical trajectory with a plurality of points defined along the surgical trajectory.

28. The computer program product of claim 27, wherein the tool orientation error is determined for each of the plurality of points along the surgical trajectory.

29. The computer program product of claim 25, wherein the tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

30. The computer program product of claim 29, wherein determining an error-minimizing incision site in a patient comprises discretizing a surface of an anatomical model of the patient thereby generating a plurality of candidate incision sites on the surface.

31. The computer program product of claim 25, wherein determining the error-minimizing incision site in a patient comprises determining tool orientation error for each of the plurality of candidate incision sites.

32. The computer program product of claim 25, further comprising selecting one of the plurality of candidate incision sites having a smallest error metric.

33. The computer program product of claim 32, further comprising determining an error-minimizing position of a base of the surgical robot, wherein the error-minimizing position is based on the selected incision site.

34. The computer program product of claim 33, wherein determining the error-minimizing position of the base comprises discretizing a space exterior to the patient into a plurality of candidate base locations.

35. The computer program product of claim 34, further comprising, for each of the plurality of candidate base locations, determining a second tool orientation error based on the discretized surgical trajectory.

36. The computer program product of claim 35, wherein the second tool orientation error is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is an angle between a desired x-component and actual x-component of the tool, β is an angle between a desired y-component and actual y-component of the tool, and γ is an angle between a desired z-component and actual z-component of the tool.

37. A system comprising:

a first robotic arm having a proximal end and a distal end, the proximal end fixed to a base;

a surgical instrument disposed at the distal end of the robotic arm, the surgical instrument having a proximal end and a distal end;

a tool coupled to the distal end of the surgical instrument; and

a computing node comprising a computer readable storage medium having program instructions embodied therewith, the program instructions executable by a processor of the computing node to cause the processor to perform a method comprising:

determining a first orientation of the tool, the first orientation comprising a first x-component, a first y-component, and a first z-component;

determining a desired orientation of the tool, the desired orientation comprising a second x-component, a second y-component, and a second z-component;

determining a first angle between the first x-component and the second x-component, a second angle between the first y-component and the second y-component, and a third angle between the first z-component and the second z-component; and

determining an error metric based on the first angle, the second angle, and the third angle.

38. The system of claim 37, wherein the error metric is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is the first angle, β is the second angle, and γ is the third angle.

39. The system of claim 37, wherein the method further comprises determining an anatomical model of a patient.

40. The system of claim 39, wherein the method further comprises selecting a first incision site on the anatomical model, the error metric corresponding to the first incision site.

41. The system of claim 39, wherein the anatomical model comprises an anatomical atlas.

42. The system of claim 39, wherein the anatomical model comprises a three-dimensional reconstruction of patient anatomy based on imaging of the patient.

43. The system of claim 40, wherein determining the error metric comprises maintaining a fixed three-dimensional position at a proximal location along the surgical instrument.

44. The system of claim 43, wherein the proximal location corresponds to the incision site on the anatomical model.

45. The system of claim 39, wherein the anatomical model comprises a target anatomical structure.

46. The system of claim 39, wherein the method further comprises determining one or more additional error metrics, each of the additional error metrics corresponding to a different location of a plurality of locations within the anatomical model.

47. The system of claim 46, wherein the different locations correspond to a 2D Cartesian grid.

48. The system of claim 46, wherein the method further comprises displaying a graph of error metrics for each of the plurality of locations within the anatomical model.

49. The system of claim 40, wherein the method further comprises:

selecting a one or more additional incision sites on the anatomical model;

for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model.

50. The system of claim 49, wherein the method further comprises selecting one of the incision sites having the smallest error metric.

51. A method for determining error in an orientation of a tool at a distal end of a surgical instrument of a surgical robot, the method comprising:

providing a first robotic arm, the robotic arm comprising a surgical instrument and a tool disposed at a distal end of the surgical instrument;

determining a first orientation of the tool, the first orientation comprising a first x-component, a first y-component, and a first z-component;

determining a desired orientation of the tool, the desired orientation comprising a second x-component, a second y-component, and a second z-component;

determining a first angle between the first x-component and the second x-component, a second angle between the first y-component and the second y-component, and a third angle between the first z-component and the second z-component; and

determining an error metric based on the first angle, the second angle, and the third angle.

52. The method of claim 51, wherein the error metric is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is the first angle, β is the second angle, and γ is the third angle.

53. The method of claim 51, further comprising determining an anatomical model of a patient.

54. The method of claim 53, further comprising selecting a first incision site on the anatomical model, the error metric corresponding to the first incision site.

55. The method of claim 53, wherein the anatomical model comprises an anatomical atlas.

56. The method of claim 53, wherein the anatomical model comprises a three-dimensional reconstruction of patient anatomy based on imaging of the patient.

57. The method of claim 54, wherein determining the error metric comprises maintaining a fixed three-dimensional position at a proximal location along the surgical instrument.

58. The method of claim 57, wherein the proximal location corresponds to an incision site on the anatomical model.

59. The method of claim 53, wherein the anatomical model comprises a target anatomical structure.

60. The method of claim 53, further comprising determining one or more additional error metrics, each of the additional error metrics corresponding to a different location of a plurality of locations within the anatomical model.

61. The method of claim 60, wherein the different locations correspond to a 2D Cartesian grid.

62. The method of claim 60, further comprising displaying a map of error metrics for each of the plurality of locations within the anatomical model.

63. The method of claim 54, further comprising:

selecting a one or more additional incision sites on the anatomical model;

for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model.

64. The method of claim 63, further comprising selecting one of the incision sites having the smallest error metric.

65. A computer program product for determining error in an orientation of a tool at a distal end of a surgical instrument of a surgical robot comprising a computer readable storage medium having program instructions embodied therewith, the program instructions executable by a processor to cause the processor to perform a method comprising:

determining a first orientation of the tool, the first orientation comprising a first x-component, a first y-component, and a first z-component;

determining a desired orientation of the tool, the desired orientation comprising a second x-component, a second y-component, and a second z-component;

determining a first angle between the first x-component and the second x-component, a second angle between the first y-component and the second y-component, and a third angle between the first z-component and the second z-component; and

determining an error metric based on the first angle, the second angle, and the third angle.

66. The computer program product of claim 65, wherein the error metric is determined by:

$$error = \alpha^2 + \beta^2 + \gamma^2$$

where α is the first angle, β is the second angle, and γ is the third angle.

67. The computer program product of claim 65, further comprising determining an anatomical model of a patient.

68. The computer program product of claim 67, further comprising selecting a first incision site on the anatomical model, the error metric corresponding to the first incision site.

69. The computer program product of claim 67, wherein the anatomical model comprises an anatomical atlas.

70. The computer program product of claim 67, wherein the anatomical model comprises a three-dimensional reconstruction of patient anatomy based on imaging of the patient.

71. The computer program product of claim 68, wherein determining the error metric comprises maintaining a fixed three-dimensional position at a proximal location along the surgical instrument.

72. The computer program product of claim 71, wherein the proximal location corresponds to an incision site on the anatomical model.

73. The computer program product of claim 67, wherein the anatomical model comprises a target anatomical structure.

74. The computer program product of claim 67, further comprising determining one or more additional error metrics, each of the additional error metrics corresponding to a different location of a plurality of locations within the anatomical model.

75. The computer program product of claim 74, wherein the different locations correspond to a 2D Cartesian grid.

76. The computer program product of claim 74, further comprising displaying a graph of error metrics for each of the plurality of locations within the anatomical model.

77. The computer program product of claim 68, further comprising:

selecting a one or more additional incision sites on the anatomical model;

for each additional incision site, determining a map of error metrics for each of a plurality of locations within the anatomical model.

78. The computer program product of claim 77, further comprising selecting one of the incision sites having the smallest error metric.

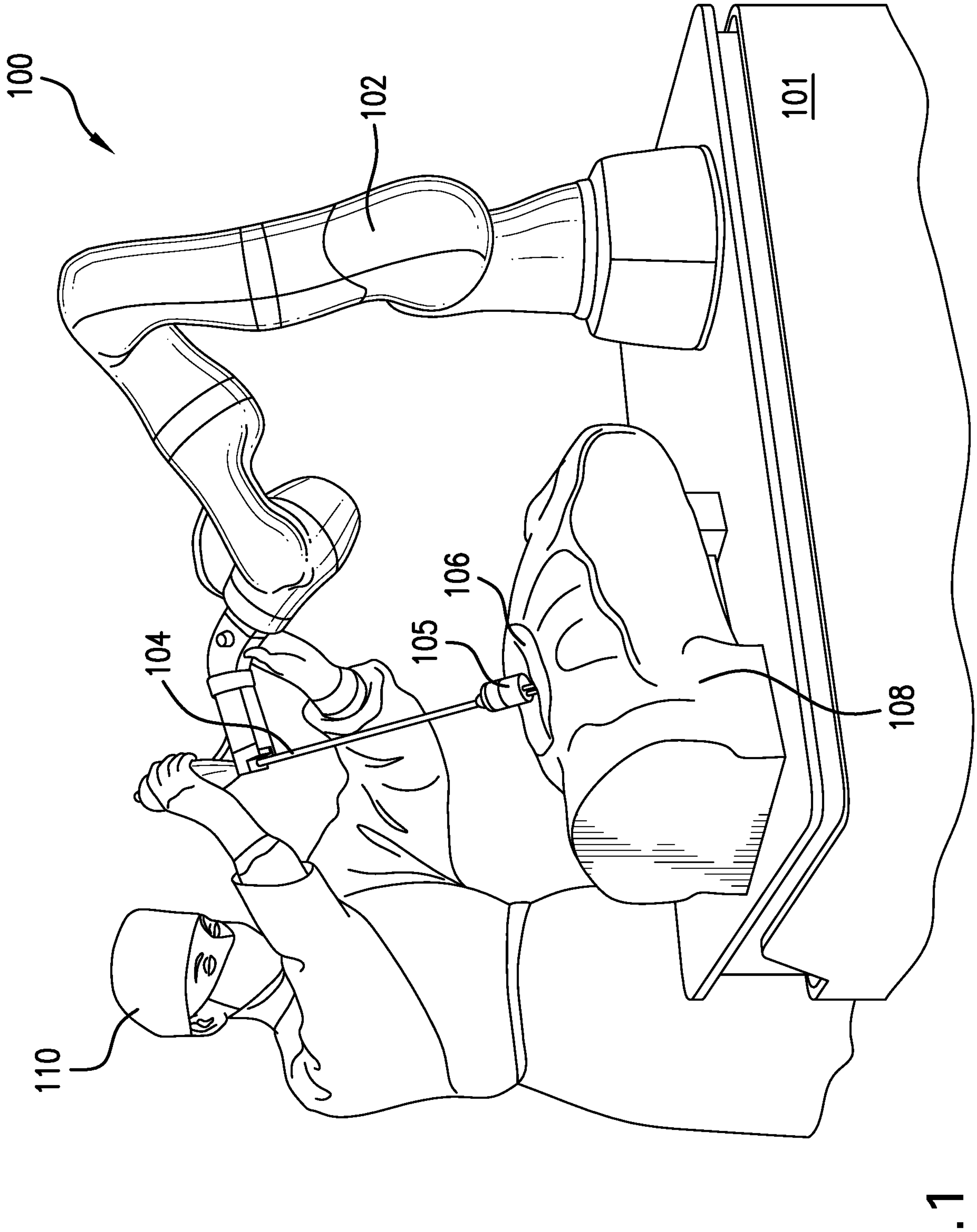

FIG.1

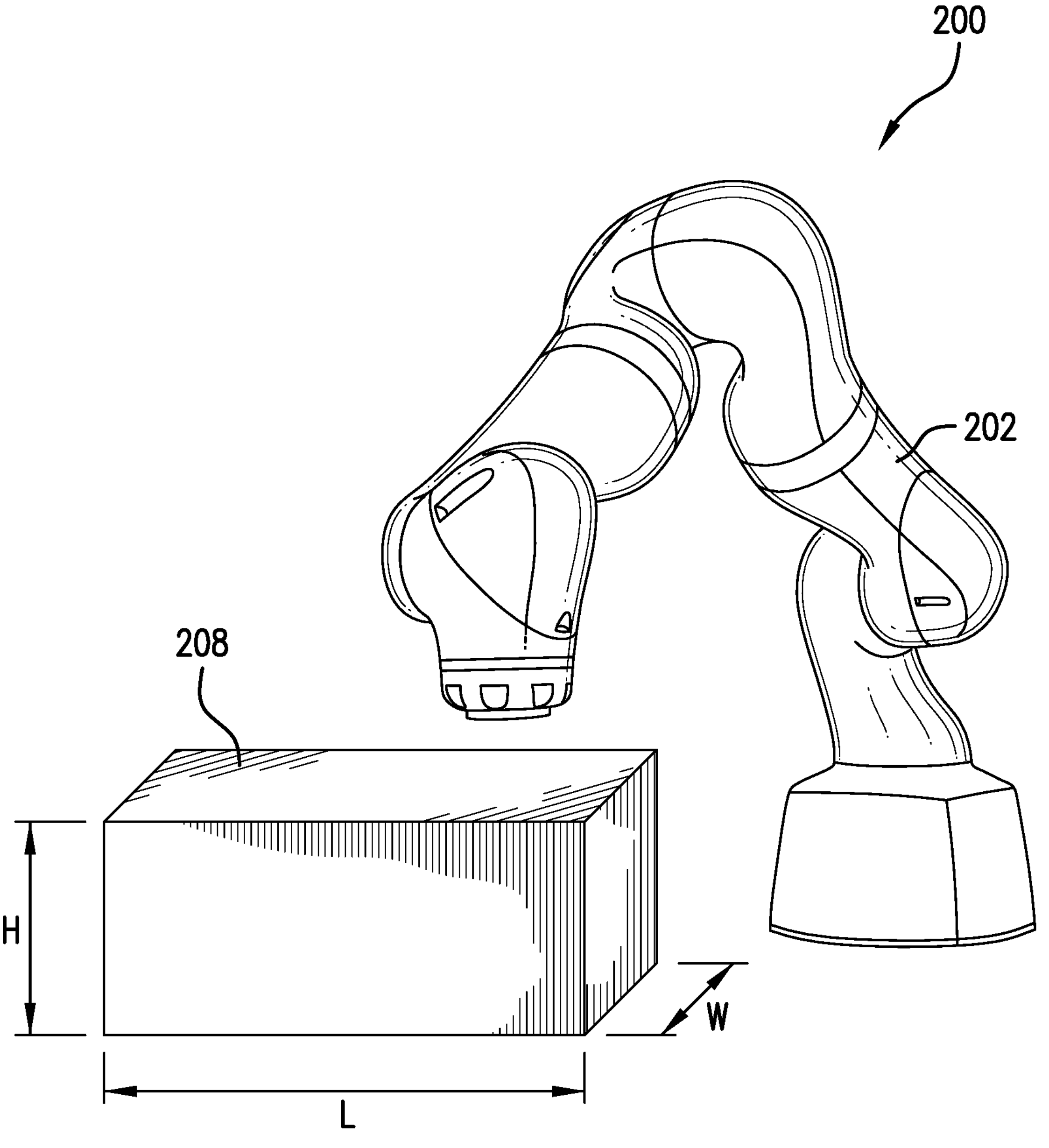

FIG.2A

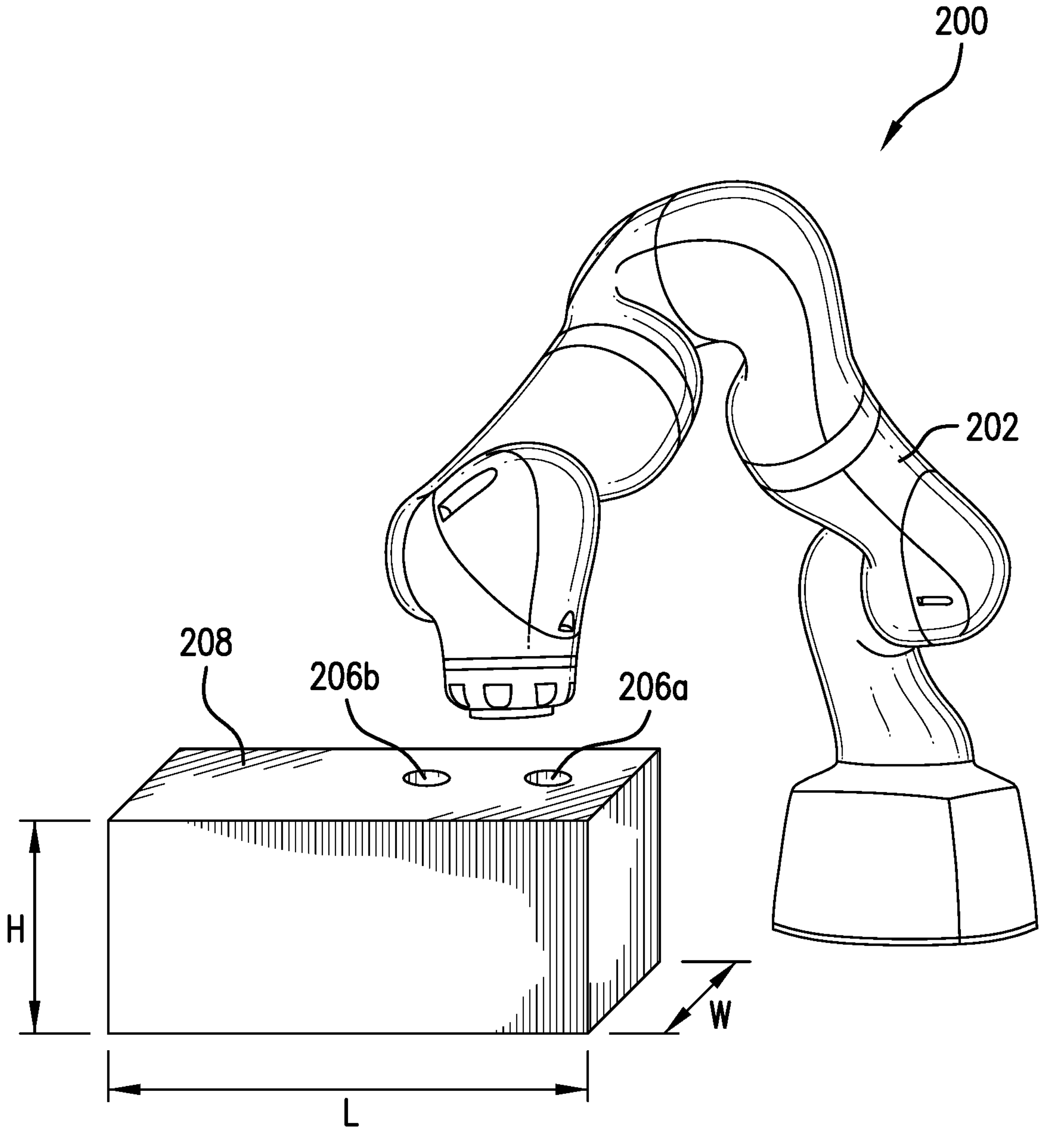

FIG.2B

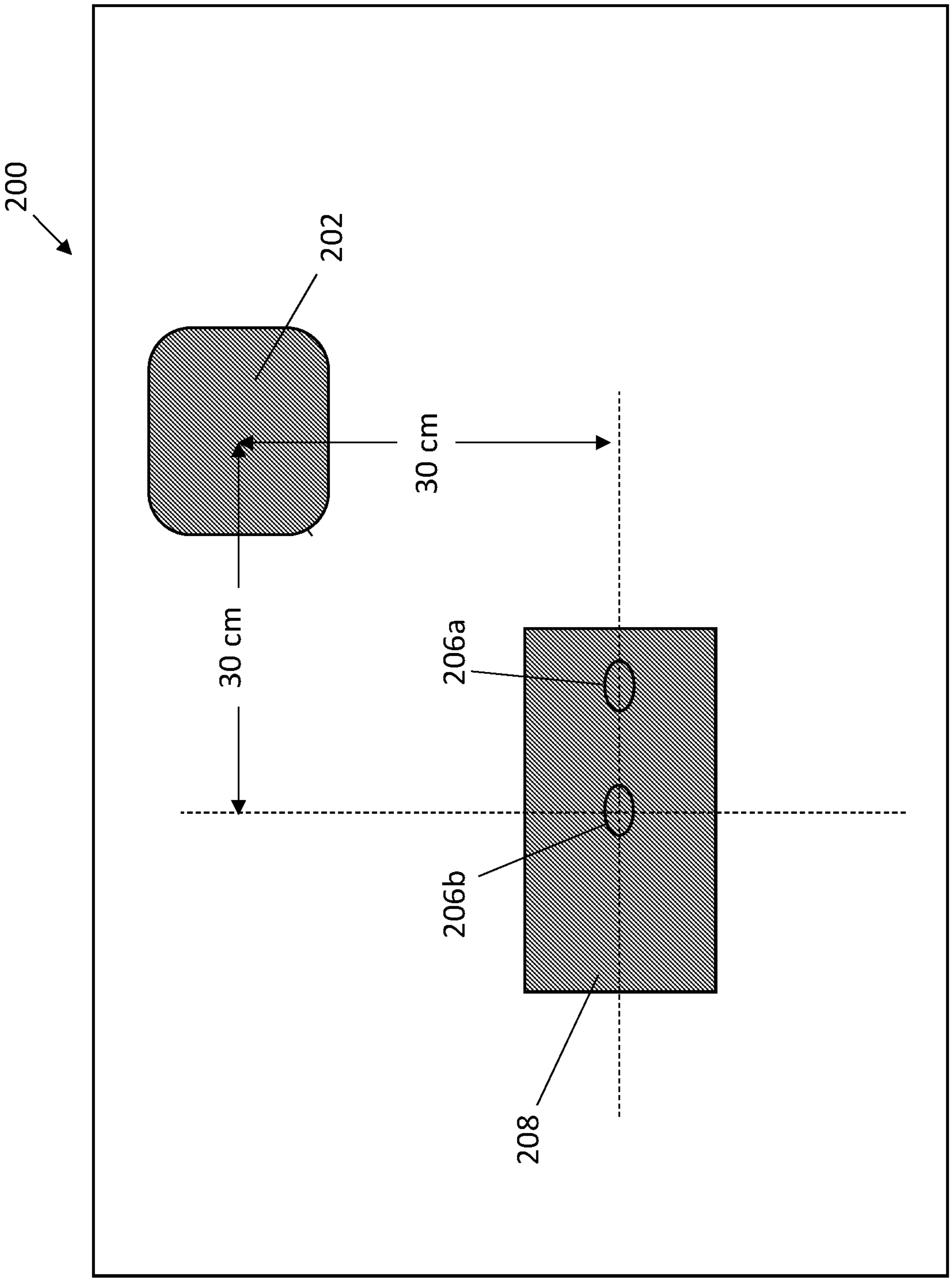

Fig. 2C

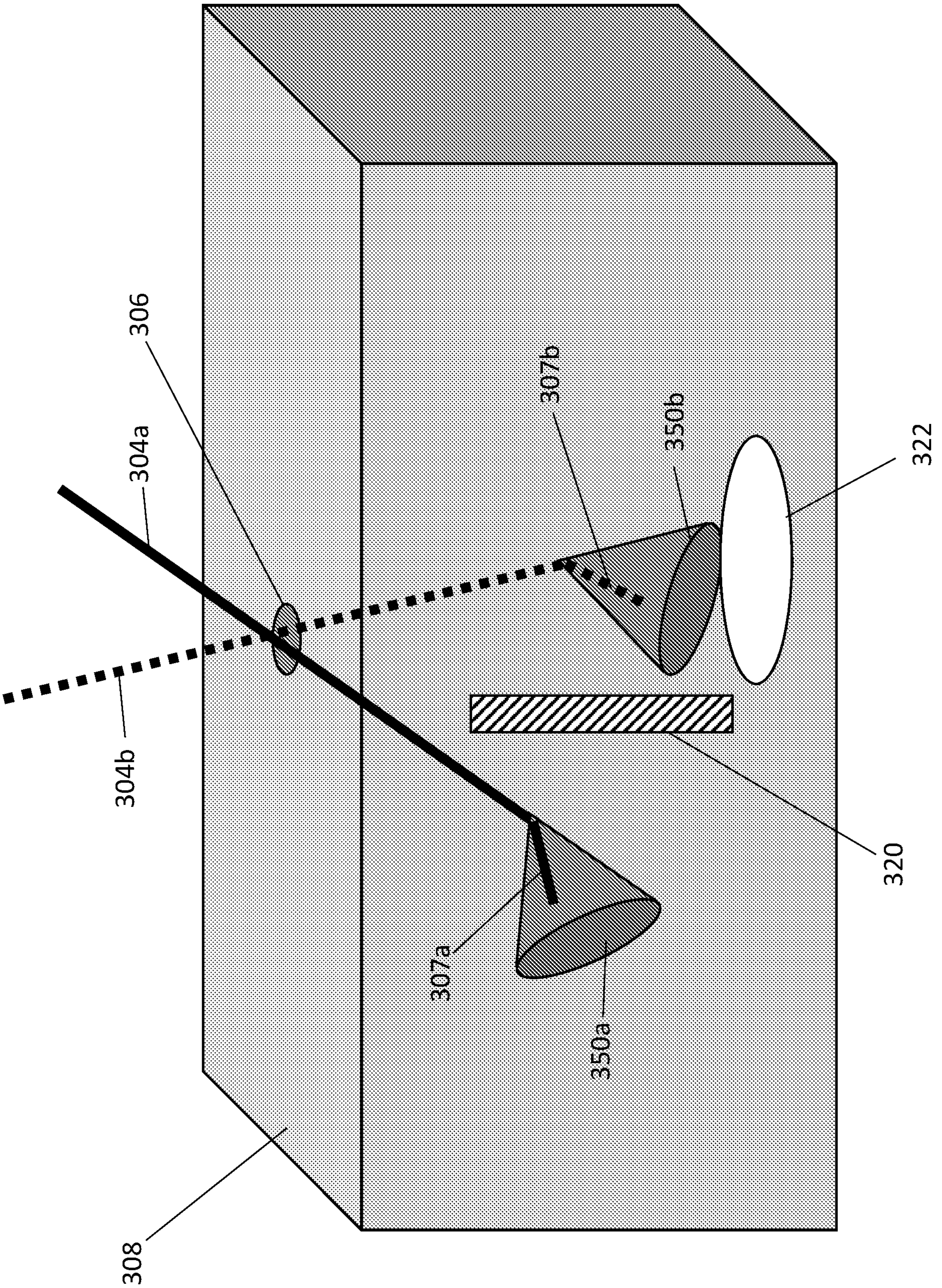

Fig. 3A

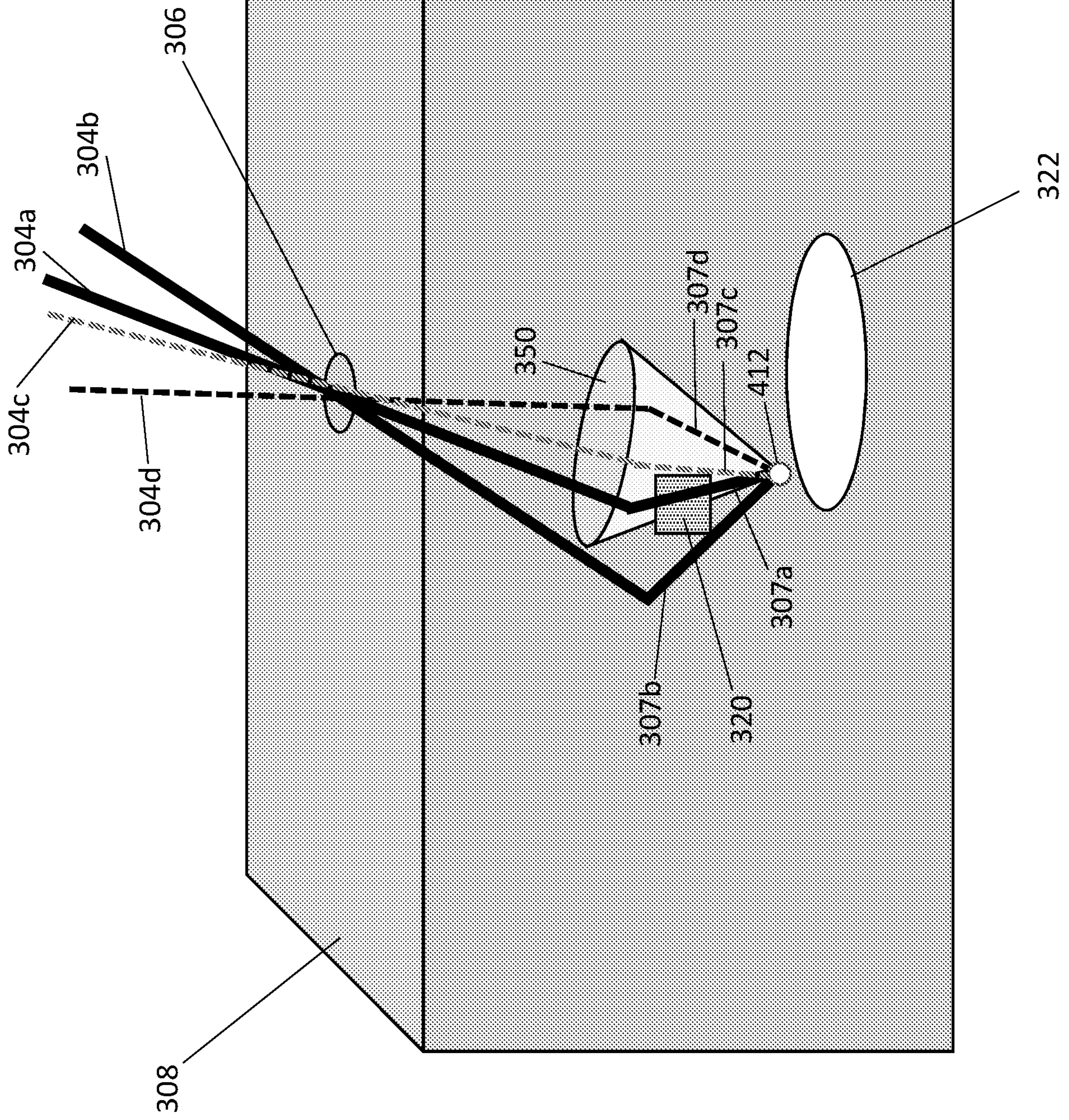
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Fig. 3B

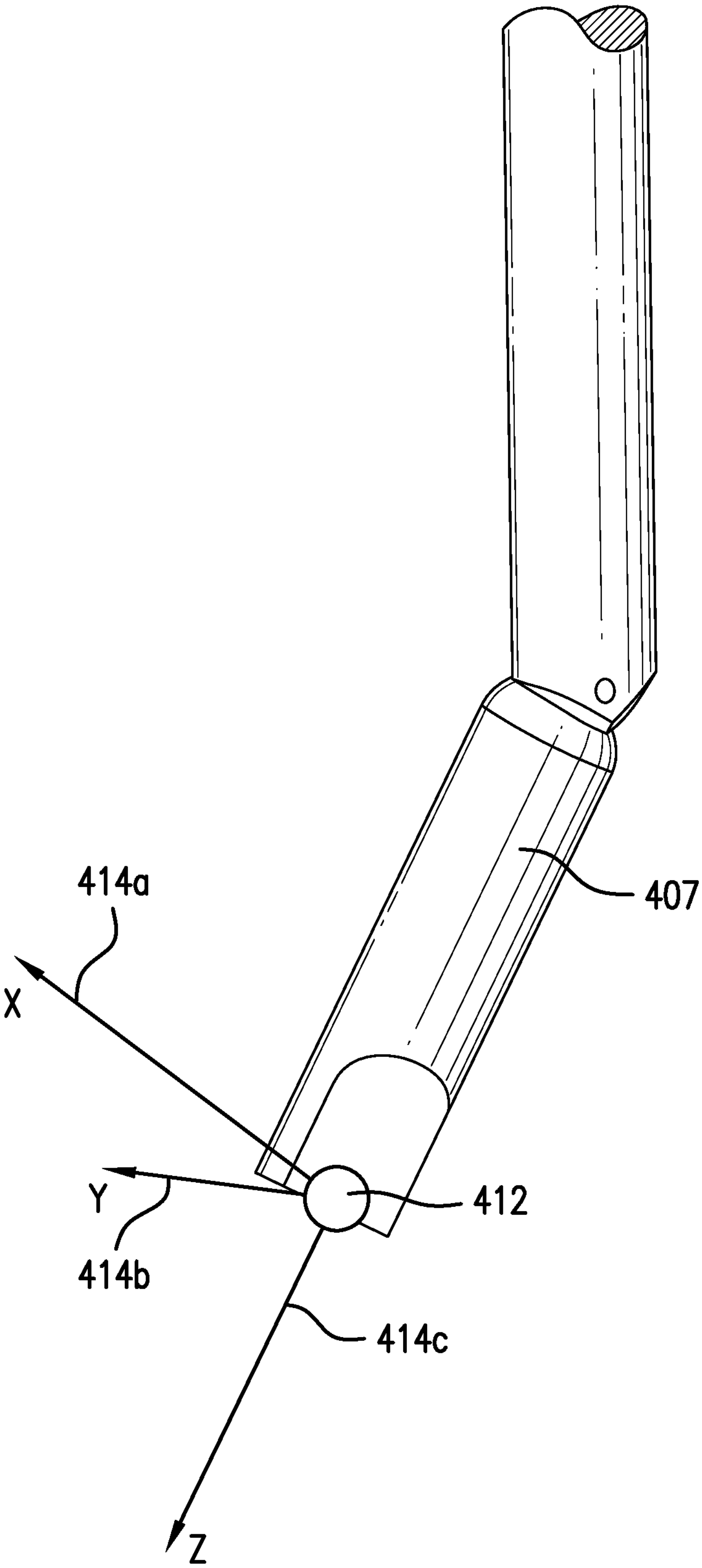

FIG.4A

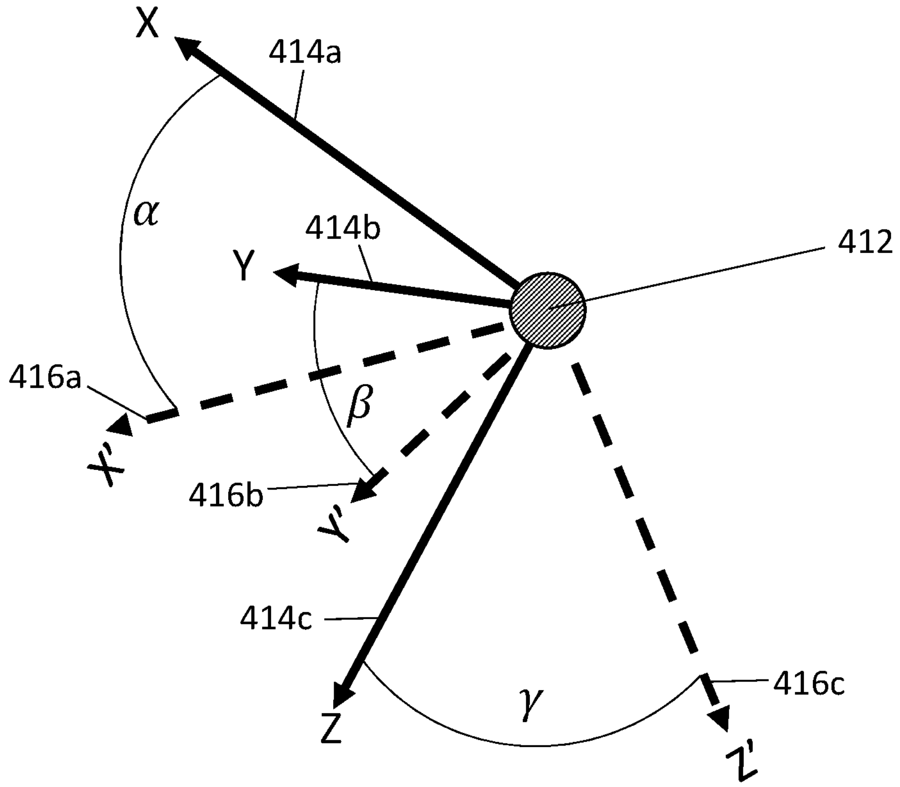

Fig. 4B

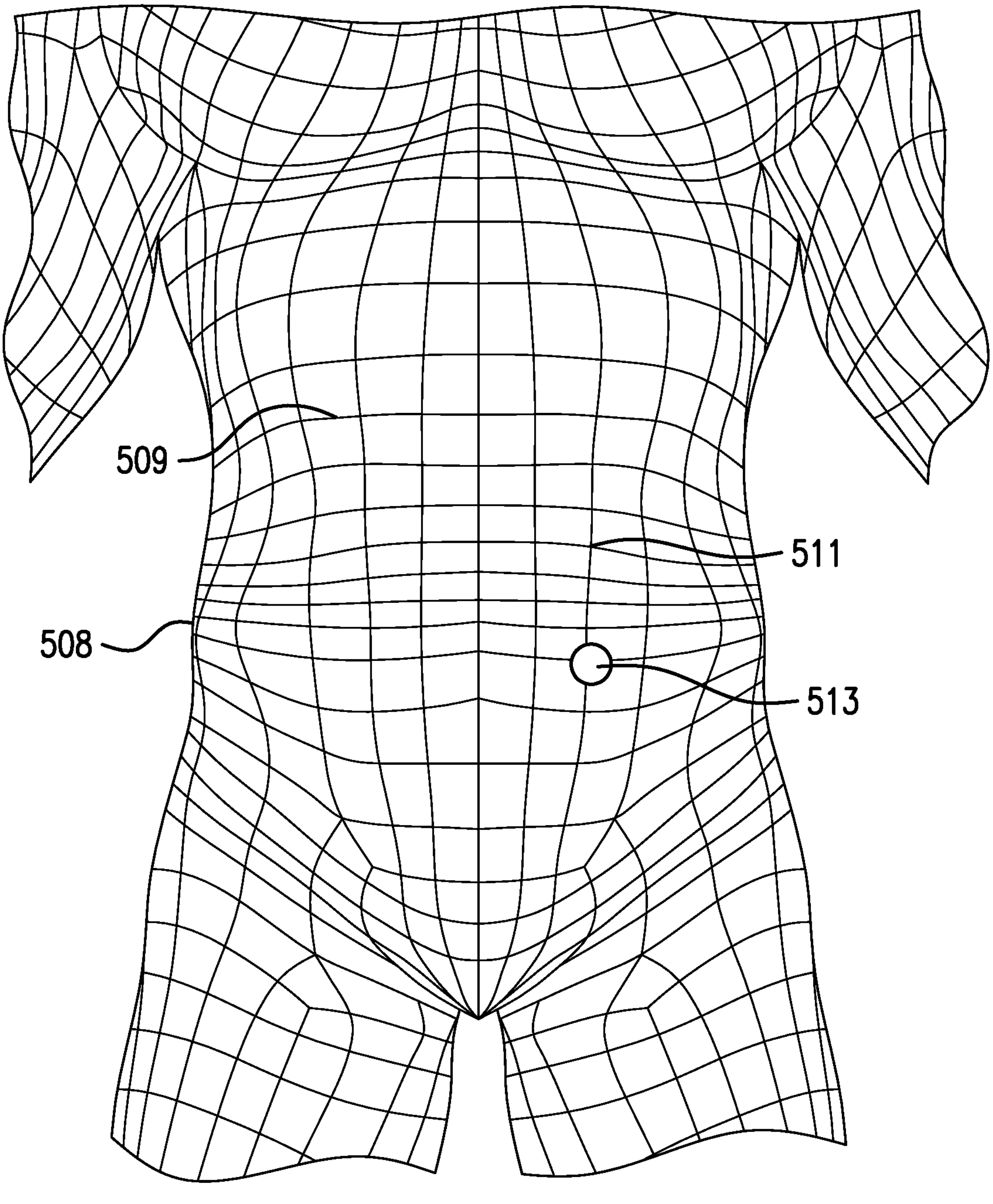

FIG.5A

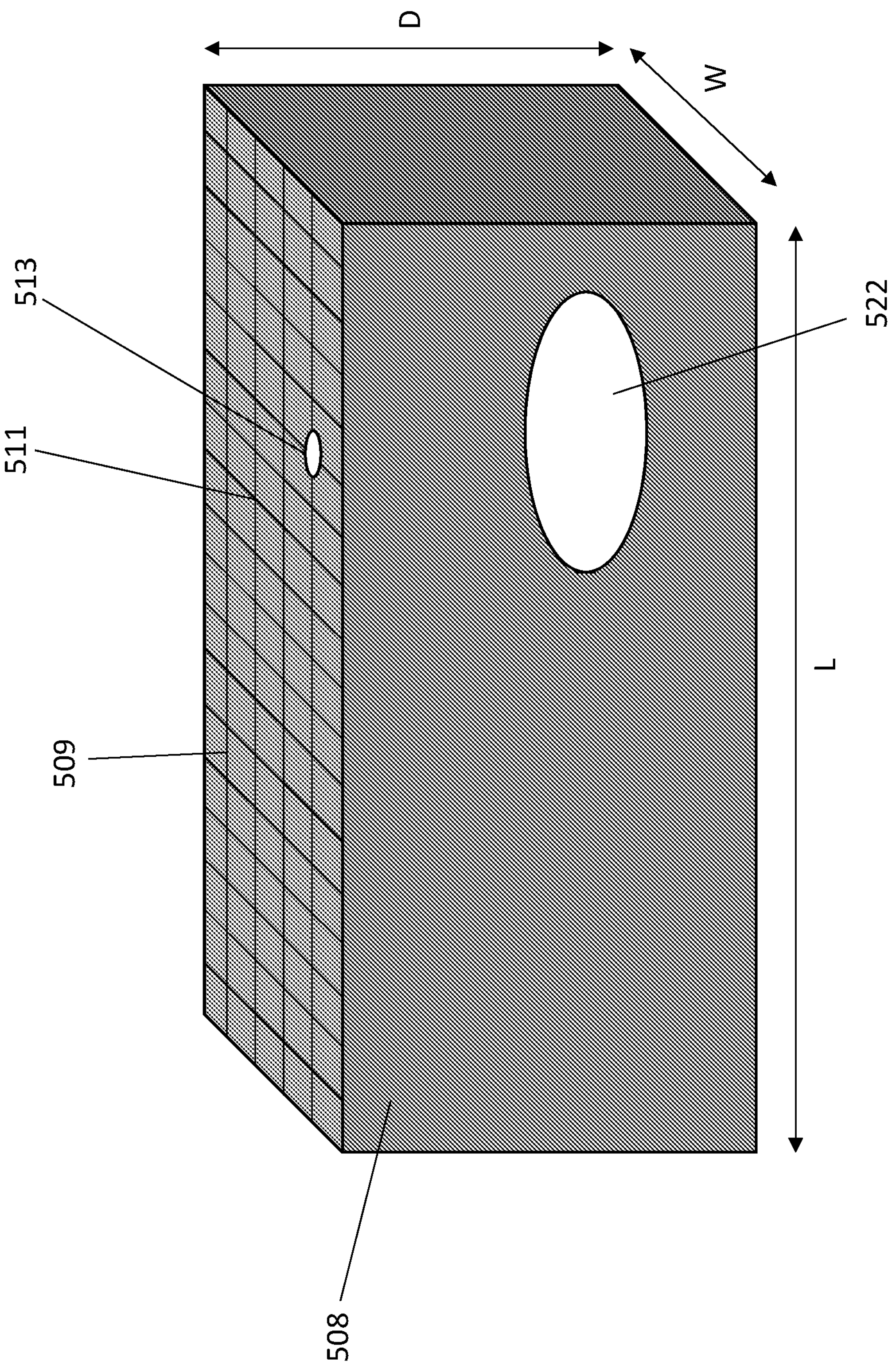

Fig. 5B

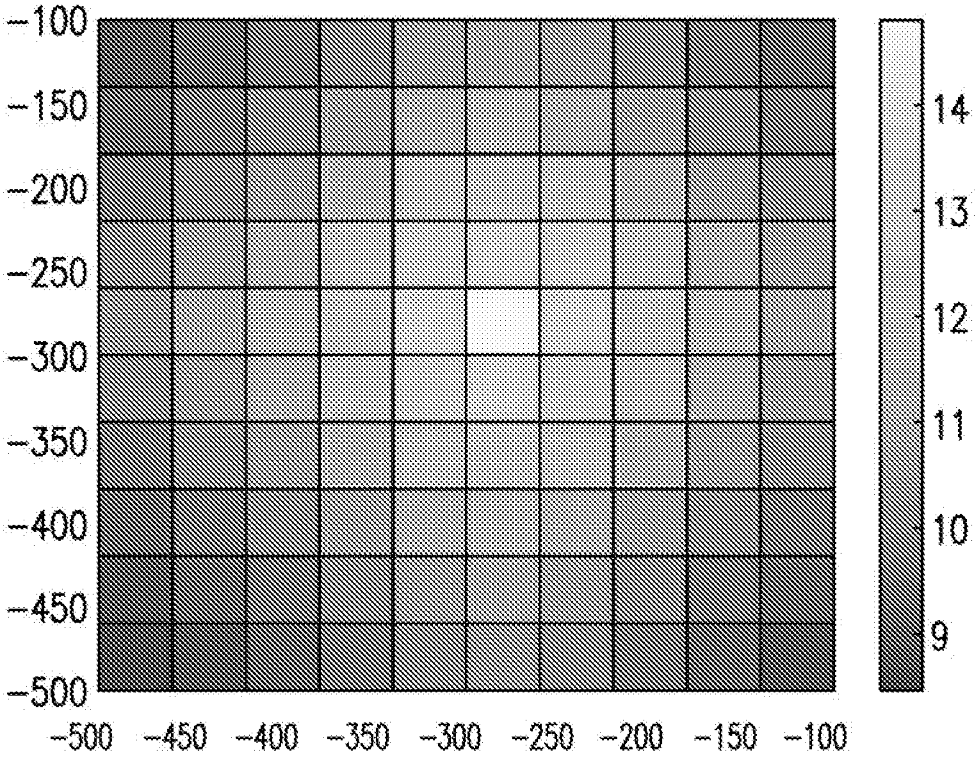

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FIG.6A

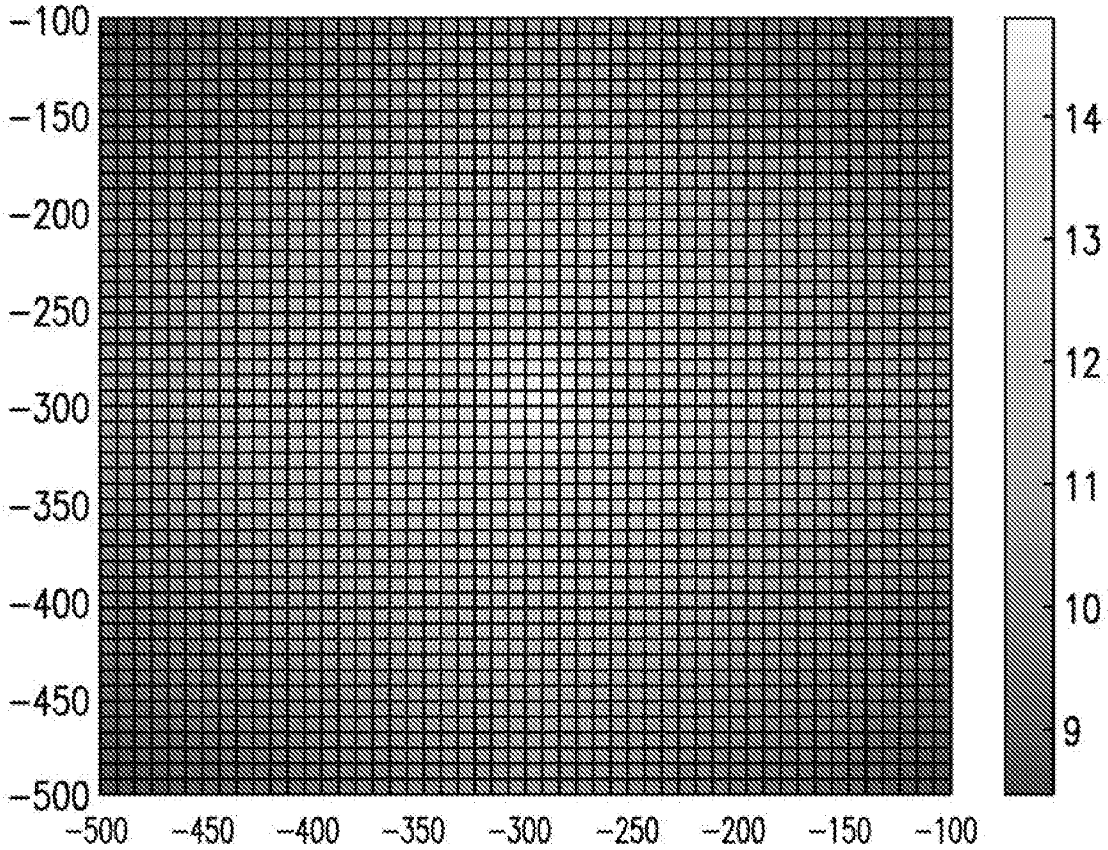
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FIG.6B

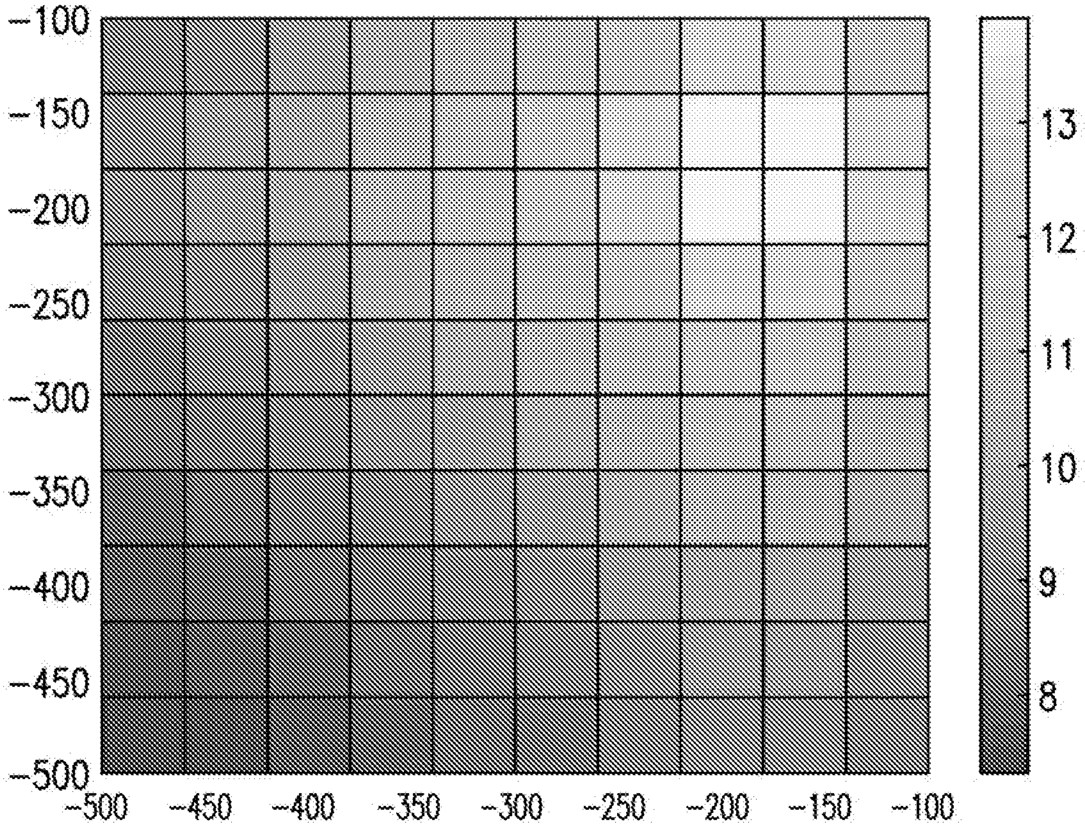
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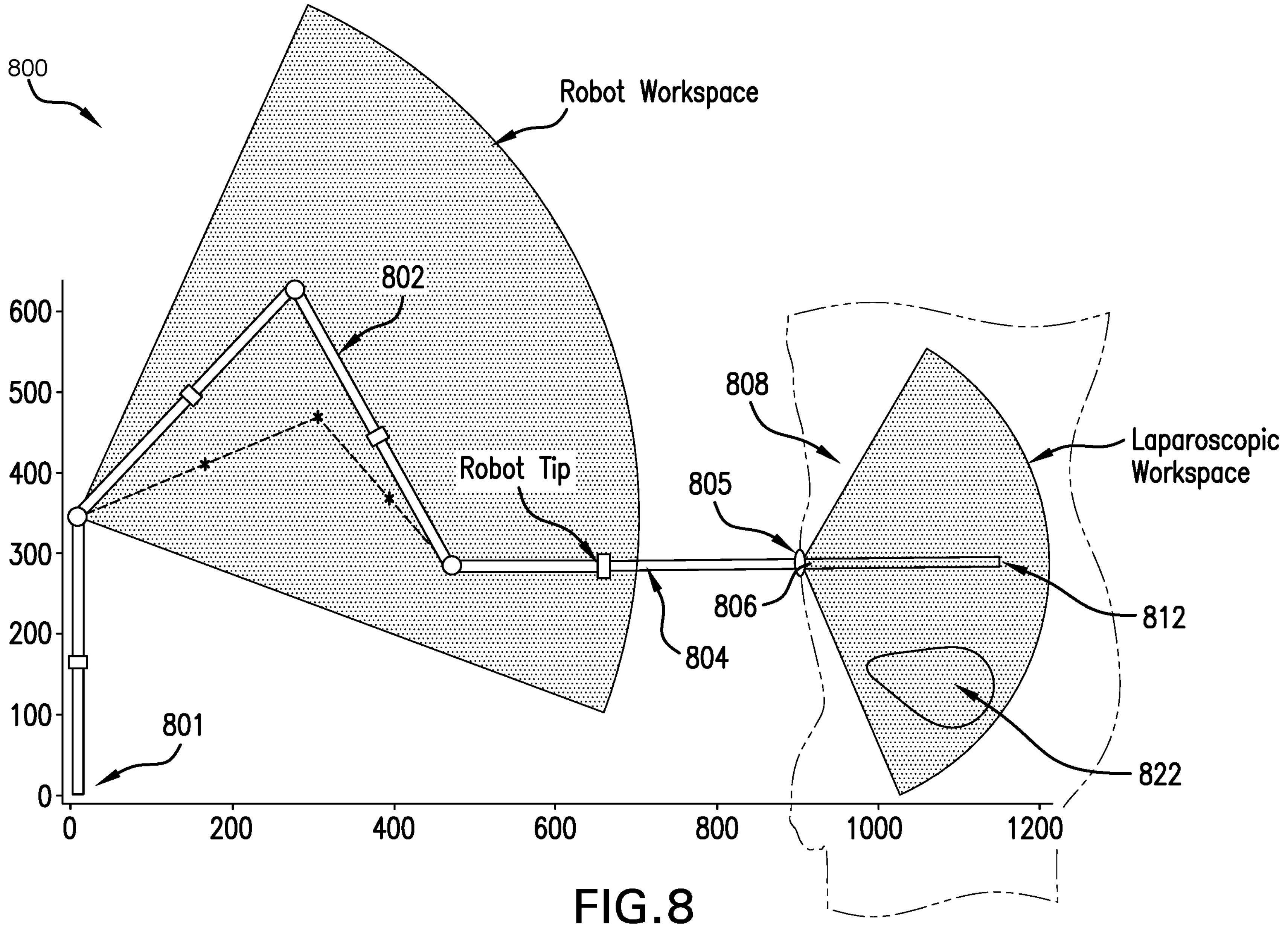
FIG.7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Robot Tip
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806
804
Laparoscopic Workspace
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FIG.8

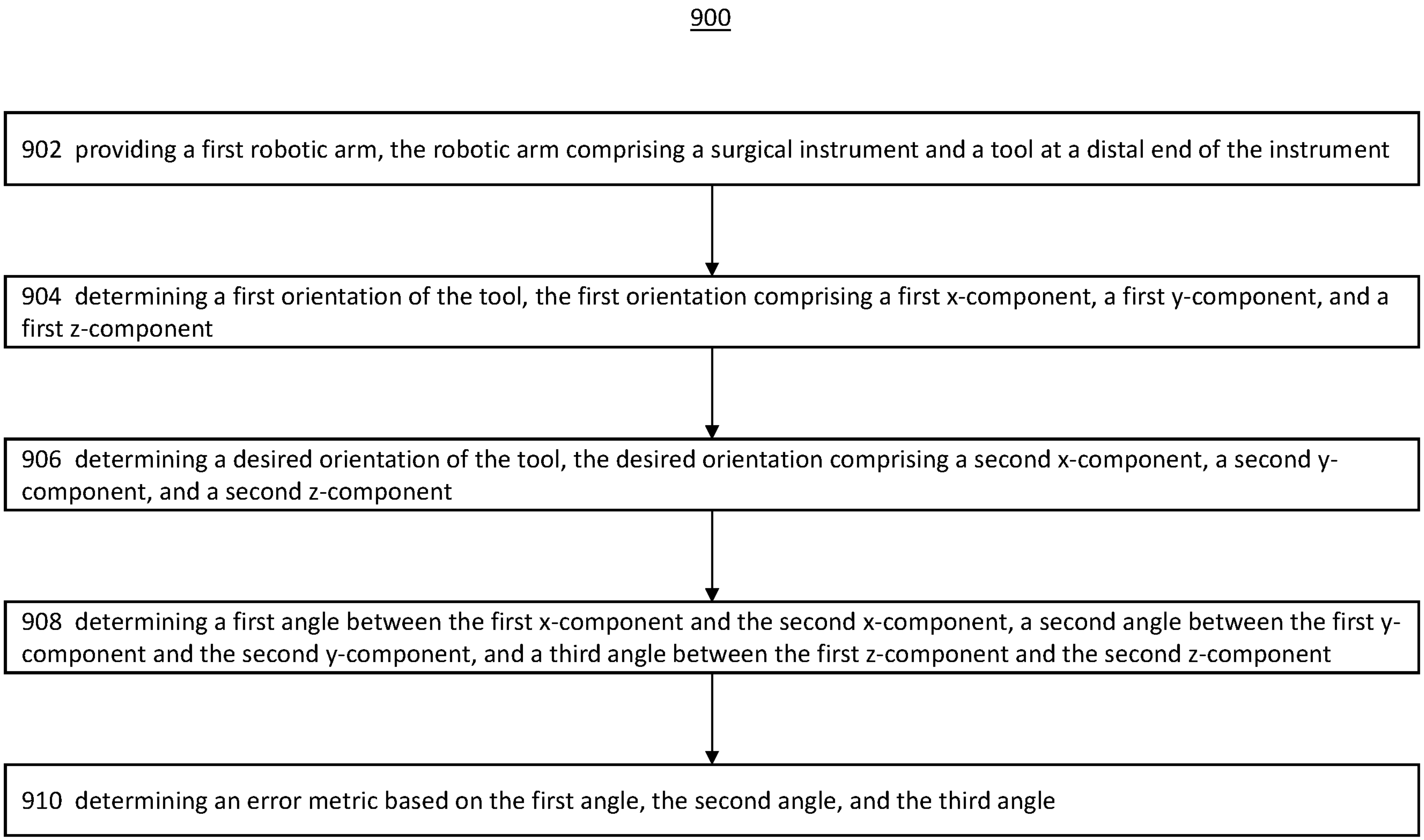
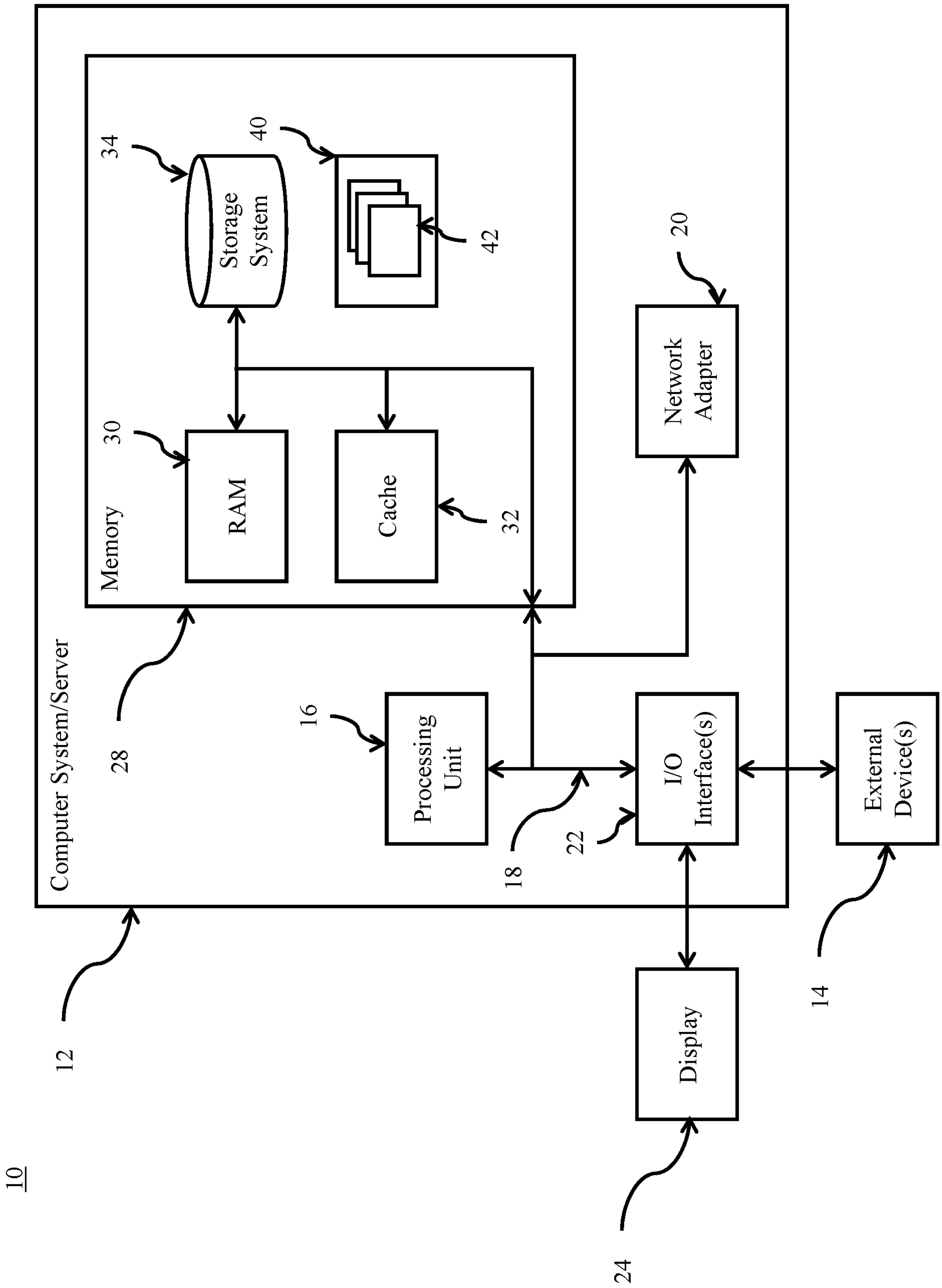

900
902 providing a first robotic arm, the robotic arm comprising a surgical instrument and a tool at a distal end of the instrument
904 determining a first orientation of the tool, the first orientation comprising a first x-component, a first y-component, and a first z-component
906 determining a desired orientation of the tool, the desired orientation comprising a second x-component, a second y-component, and a second z-component
908 determining a first angle between the first x-component and the second x-component, a second angle between the first y-component and the second y-component, and a third angle between the first z-component and the second z-component
910 determining an error metric based on the first angle, the second angle, and the third angle

Fig. 9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Memory
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RAM
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Cache
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Storage System
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42
Processing Unit
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18
I/O Interface(s)
22
Network Adapter
20
Display
24
External Device(s)
14

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 19/68778

A. CLASSIFICATION OF SUBJECT MATTER

IPC - G06F 19/00 (2020.01)

CPC - A61B 1/00193, H04N 13/398, B25J 3/04, B25J 19/023, A61B 90/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2009/0326324 A1 (MARTINEZ, ET AL.) 31 December 2009 (31.12.2009), entire document, especially para [0041]; [0043]; [0046]; [0056-0062]; [0064]; [0065]; [0068]; Fig 2; Fig 5; Fig 6; Fig 8	1-7, 13-19, 25-31, 37-38, 51-52, 65-66 -------------------------- 8-12, 20-24, 32-36, 39-50, 53-64, 67-78
Y	WO 2018/067515 A1 (WORTHEEMED, INC.) 12 April 2018 (12.04.2018), entire document, especially para [0081]; [00109]; [00110]; [00157-00159]; [00179]; [00205]	8-12, 20-24, 32-36, 39-50, 53-64, 67-78

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D"	document cited by the applicant in the international application	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E"	earlier application or patent but published on or after the international filing date	"&"	document member of the same patent family
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 04 March 2020 (04.03.2020)	Date of mailing of the international search report 01 APR 2020
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Lee Young Telephone No. PCT Helpdesk: 571-272-4300