(12) **EUROPEAN PATENT APPLICATION**

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(54) **Laparoscopic ultrasound robotic surgical system**

(57) A LUS robotic surgical system is trainable by a surgeon to automatically move a LUS probe in a desired fashion upon command so that the surgeon does not have to do so manually during a minimally invasive surgical procedure. A sequence of 2D ultrasound image slices captured by the LUS probe according to stored instructions are processable into a 3D ultrasound computer model of an anatomic structure, which may be displayed as a 3D or 2D overlay to a camera view or in a PIP as selected by the surgeon or programmed to assist the surgeon in inspecting an anatomic structure for abnormalities. Virtual fixtures are definable so as to assist the surgeon in accurately guiding a tool to a target on the displayed ultrasound image.
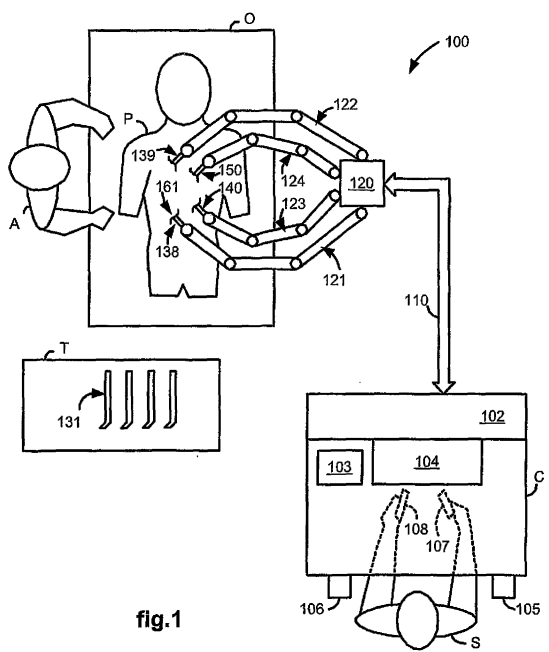
fig.1

**Description**

GOVERNMENT RIGHTS STATEMENT

**[0001]** This invention was made with Government support under Grant No. 1 R41 RR019159-01 awarded by the National Institutes of Health. The Government has certain rights to the invention.

CROSS REFERENCE TO RELATED APPLICATIONS

**[0002]** This application claims priority to U.S. provisional application S.N. 60/688,019 filed June 6, 2005, which is incorporated herein by reference.

FIELD OF THE INVENTION

**[0003]** The present invention generally relates to robotic surgical systems and in particular, to a laparoscopic ultrasound robotic surgical system useful for performing minimally invasive surgical procedures.

BACKGROUND OF THE INVENTION

**[0004]** Minimally invasive surgery offers many benefits over traditional open surgery techniques, including less pain, shorter hospital stays, quicker return to normal activities, minimal scarring, reduced recovery time, and less injury to tissue. Consequently, demand for minimally invasive surgery using robotic surgical systems is strong and growing.

**[0005]** Laparoscopy is a type of minimally invasive surgery in which a small incision is made in the abdominal wall through which an instrument called a laparoscope is inserted to permit anatomic structures within the abdomen and pelvis to be seen. The abdominal cavity is commonly distended and made visible by the instillation of absorbable gas such as carbon dioxide. Tubes may be pushed through the same or different incisions in the skin so that probes or other instruments can be introduced to a surgical site. In this way, a number of surgical procedures can be performed without the need for a large or open cavity surgical incision.

**[0006]** One disadvantage of laparoscopy, however, is the inability to manually palpate hidden or solid organs. Laparoscopic Ultrasound ("LUS") allows the surgeon to overcome this limitation by providing visualization of deeper structures. In fact, even when open cavity operations are performed, intraoperative ultrasonography may be significantly more sensitive at detecting otherwise occult lesions within anatomic structures than bimanual palpation.

**[0007]** As an example, intraoperative ultrasonography of the liver is useful in a variety of clinical settings during laparoscopic surgery. These include: staging and assessment of the liver, including ultrasound-guided needle biopsy, liver tumor ablation, and evaluation of the liver prior to laparoscopic liver resection.

**[0008]** For resection procedures, surgeons should have the ability to perform accurate staging of the liver and other sites to rule out metastatic disease prior to resection. The addition of LUS to standard laparoscopy improves the diagnosis of metastases over conventional preoperative diagnostic methods.

**[0009]** Ultrasound-directed liver biopsy is an important component of hepatic staging and assessment. When a lesion is identified by ultrasound, needle biopsy is necessary to confirm the findings histologically. Current practice requires manual free-hand LUS in conjunction with free-hand positioning of the biopsy needle under ultrasound guidance.

**[0010]** For the treatment of unresectable metastases, increasing interest has been focused on ablative approaches such as radiofrequency ("RF"), cryotherapy, microwave, or chemical ablation. While interstitial ablation can be performed percutaneously or during open surgery, laparoscopic ablation has significant advantages. First, unlike percutaneous therapy, laparoscopy can identify both hepatic and extrahepatic metastases not visualized on preoperative imaging, which misses significant tumors in about 10% to 20% of patients with colorectal liver metastases. Second, laparoscopic or operative ultrasound ("US") has been shown to be significantly more accurate than transabdominal US, CT or MR at visualizing liver lesions. Further, operative approaches, including laparoscopy, permit mobilization of structures away from a surface tumor that may be thermally injured during RF ablation. Percutaneous ablation and laparoscopic ablation both typically require general anesthesia and an overnight hospital stay. Laparoscopy, on the other hand, does not impose a significantly greater burden on the patient.

**[0011]** While ablation promises advantages compared to other approaches, the technical difficulty of manipulating the ultrasound probe, aligning the ultrasound probe with the ablation probe, and placement of the ablation probe demands considerable expertise. The surgeon must precisely place the ablation probe tip within the volumetric center of the tumor in order to achieve adequate destruction of the tumor and a 1 cm zone of surrounding normal parenchyma. Tumors are identified by preoperative imaging, primarily CT and MR, and then laparoscopically localized by LUS.

**[0012]** One major limitation of ablative approaches is the lack of accuracy in probe tip placement within the center of the tumor. This is particularly important, as histologic margins cannot be assessed after ablation as is done with hepatic

resection. In addition, manual guidance often requires multiple passes and repositioning of the probe tip, further increasing the risk of bleeding and tumor dissemination. Intraoperative ultrasound provides excellent visualization of tumors and provides guidance for RF probe placement, but its 2D-nature and dependence on the sonographer's skill limit its effectiveness.

**[0013]** Although laparoscopic instrumentation and techniques are beginning to be extended to resection of the liver, loss of the surgeon's tactile sense makes it difficult to assess the safe margins of resection necessary for safe parenchymal transection. Lack of clear visualization and mapping of intrahepatic structures with current LUS techniques could result in catastrophic injury to major adjacent structures. The surgeon must carefully examine the liver by ultrasound prior to resection in order to rule out additional tumors which may preclude curative therapy. Surgeons also require ultrasound to determine and plan safe and complete resection with sufficient surgical margin clearance.

**[0014]** Despite its theoretical advantages, intraoperative LUS is not widely practiced for such uses as laparoscopic liver cancer surgery. To expand usage in this and other applications, advances in LUS robotic surgical systems that improve surgeon efficiency in performing minimally invasive surgical procedures, as well as the ease of using those systems is desirable.

**[0015]** For example, optimization of LUS for hepatic surgery may significantly improve the clinical management of patients. In addition to minimizing morbidity and discomfort, an improved LUS robotic surgical system may significantly reduce costs. Faster, more accurate, and more complete assessment of the liver may be performed by experts, as well as potentially by surgeons who are not experts in intraoperative ultrasonography of the liver.

**[0016]** Image-guided biopsy of sometimes small and inaccessible liver lesions may be facilitated. Advanced LUS robotic tools could increase the use of resection as a definitive treatment for larger and less favorably placed tumors. Improved real-time guidance for planning, delivery and monitoring of ablative therapy may also provide the missing tool needed to allow accurate and effective application of this promising therapy.

**[0017]** <u>OBJECTS AND SUMMARY OF THE INVENTION</u>

**[0018]** Accordingly, one object of various aspects of the present invention is a laparoscopic ultrasound robotic surgical system and robotic assisted laparoscopic ultrasound methods that are easy to use and promote surgeon efficiency.

**[0019]** Another object of various aspects of the present invention is a laparoscopic ultrasound robotic surgical system and robotic assisted laparoscopic ultrasound methods that provide faster, more accurate and complete assessment of anatomic structures.

**[0020]** Another object of various aspects of the present invention is a laparoscopic ultrasound robotic surgical system and robotic assisted laparoscopic ultrasound methods that provide robotically generated intra-operative 3D ultrasound images of an anatomic structure using surgeon trained trajectories.

**[0021]** Another object of various aspects of the present invention is a laparoscopic ultrasound robotic surgical system and robotic assisted laparoscopic ultrasound methods that provide flexible display of ultrasound images on a display screen.

**[0022]** Still another object of various aspects of the present invention is a laparoscopic ultrasound robotic surgical system and robotic assisted laparoscopic ultrasound methods that provide assistance in guiding a tool to a target on an anatomic structure.

**[0023]** These and additional objects are accomplished by the various aspects of the present invention, wherein briefly stated, one aspect is laparoscopic ultrasound robotic surgical system comprising; a first robotic arm mechanically coupled to an ultrasound probe; a second robotic arm mechanically coupled to a surgery related device; a master manipulator; a control switch having user selectable first and second modes; and a processor configured to cause the second robotic arm to be locked in position and the first robotic arm to move the ultrasound probe according to user manipulation of the master manipulator when the control switch is in the first mode, and cause the second robotic arm to manipulate the tool according to manipulation of the master manipulator and the first robotic arm to move the ultrasound probe according to stored instructions upon detection of a user command associated with the stored instructions when the control switch is in the second mode.

**[0024]** Another aspect is a method for providing robotic assisted laparoscopic ultrasound, comprising: storing a current ultrasound probe position and orientation upon detection of a start of training indication; and periodically storing ultrasound probe positions and orientations to define a trajectory of positions and orientations until detection of an end of training indication.

**[0025]** Another aspect is a method for providing robotic assisted laparoscopic ultrasound, comprising: capturing an ultrasound image using an ultrasound probe disposed at a position and orientation; storing information of the position and orientation; generating a clickable thumbnail of the ultrasound image; associating the stored position and orientation with the clickable thumbnail; and displaying the clickable thumbnail on a display screen.

**[0026]** Still another aspect is a method for providing robotic assisted laparoscopic ultrasound, comprising: displaying an ultrasound view of an anatomic structure in a patient as a registered overlay to a camera view of the anatomic structure; receiving information of a target marked on the ultrasound view; determining a path for a tool to travel to the target within the patient; and generating a virtual fixture to assist in electronically constraining the tool to travel over the

determined path.

**[0027]** Additional objects, features and advantages of the various aspects of the present invention will become apparent from the following description of its preferred embodiment, which description should be taken in conjunction with the accompanying drawings.

5 **[0028]** <u>BRIEF DESCRIPTION OF THE DRAWINGS</u>

**[0029]** **FIG. 1** illustrates a top view of an operating room employing a laparoscopic ultrasound robotic surgical system utilizing aspects of the present invention.

**[0030]** **FIG. 2** illustrates a block diagram of a laparoscopic ultrasound robotic surgical system utilizing aspects of the present invention.

10 **[0031]** **FIG. 3** illustrates a laparoscopic ultrasound probe utilizing aspects of the present invention.

**[0032]** **FIG. 4** illustrates a flow diagram of a method for training a LUS robotic surgical system to robotically move a LUS probe in a trained manner upon command, utilizing aspects of the present invention.

**[0033]** **FIG. 5** illustrates a flow diagram of a method for generating a clickable thumbnail image that allows a user to command that a LUS probe be automatically moved to a position and orientation from which the image was captured, 15 utilizing aspects of the present invention.

**[0034]** **FIG. 6** illustrates a flow diagram of a method for automatically moving s LUS probe to a position and orientation associated with a clickable thumbnail image, utilizing aspects of the present invention.

**[0035]** **FIG. 7** illustrates a flow diagram of a method for robotically assisted needle guidance to a marked lesion of a cancerous structure, utilizing aspects of the present invention.

20 **[0036]** **FIG. 8** illustrates a perspective view of a 3D ultrasound image of an anatomic structure in a camera reference frame with selectable 2D image slices as used in a medical robotic system utilizing aspects of the present invention.

**[0037]** **FIG. 9** illustrates a perspective view of a 3D camera view of an anatomic structure in a camera reference as used in a medical robotic system utilizing aspects of the present invention.

**[0038]** **FIG. 10** illustrates a perspective view of a frontal 2D slice of a 3D ultrasound view of an anatomic structure 25 that overlays a 3D camera view of the anatomic structure, as displayable in a medical robotic system utilizing aspects of the present invention.

**[0039]** **FIG. 11** illustrates a perspective view of an inner 2D slice of a 3D ultrasound view of an anatomic structure that overlays a 3D camera view of the anatomic structure, as displayable in a medical robotic system utilizing aspects of the present invention.

30 **[0040]** **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT**

**[0041]** **FIG. 1** illustrates, as an example, a top view of an operating room employing a robotic surgical system. The robotic surgical system in this case is a Laparascopic Ultrasound Robotic Surgical System **100** including a Console ("C") utilized by a Surgeon ("S") while performing a minimally invasive diagnostic or surgical procedure with assistance from one or more Assistants ("A") on a Patient ("P") who is reclining on an Operating table ("O").

35 **[0042]** The Console includes a Master Display **104** (also referred to herein as a "Display Screen") for displaying one or more images of a surgical site within the Patient as well as perhaps other information to the Surgeon. Also included are Master Input Devices **107** and **108** (also referred to herein as "Master Manipulators"), one or more Foot Pedals **105** and **106**, a Microphone **103** for receiving voice commands from the Surgeon, and a Processor **102**. The Master Input Devices **107** and **108** may include any one or more of a variety of input devices such as joysticks, gloves, trigger-guns, 40 hand-operated controllers, or the like. The Processor **102** is preferably a personal computer that may be integrated into the Console or otherwise connected to it in a conventional manner.

**[0043]** The Surgeon performs a minimally invasive surgical procedure by manipulating the Master Input Devices **107** and **108** so that the Processor **102** causes their respectively associated Slave Arms **128** and **129** (also referred to herein as "Slave Manipulators") to manipulate their respective removably coupled and held Surgical Instruments **138** and **139** 45 (also referred to herein as "Tools") accordingly, while the Surgeon views three-dimensional ("3D") images of the surgical site on the Master Display **104.**

**[0044]** The Tools **138** and **139** are preferably Intuitive Surgical's proprietary EndoWrist™ articulating instruments, which are modeled after the human wrist so that when added to the motions of the robot arm holding the tool, they allow a full six degrees of freedom of motion, which is comparable to the natural motions of open surgery. Additional details 50 on such tools may be found in commonly owned U.S. Pat. No. 5,797,900 entitled "Wrist Mechanism for Surgical Instrument for Performing Minimally Invasive Surgery with Enhanced Dexterity and Sensitivity," which is incorporated herein by this reference. At the operating end of each of the Tools **138** and **139** is a manipulatable end effector such as a clamp, grasper, scissor, stapler, blade, needle, or needle holder.

**[0045]** The Master Display **104** has a high-resolution stereoscopic video display with two progressive scan cathode 55 ray tubes ("CRTs"). The system offers higher fidelity than polarization, shutter eyeglass, or other techniques. Each eye views a separate CRT presenting the left or right eye perspective, through an objective lens and a series of mirrors. The Surgeon sits comfortably and looks into this display throughout surgery, making it an ideal place for the Surgeon to display and manipulate 3-D intraoperative imagery.

**[0046]** A Stereoscopic Endoscope **140** (also referred to as a "laparoscopy") provides right and left camera views to the Processor **102** so that it may process the information according to programmed instructions and cause it to be displayed on the Master Display **104**. A Laparoscopic Ultrasound ("LUS") Probe **150** provides two-dimensional ("2D") ultrasound image slices of an anatomic structure to the Processor **102** so that the Processor **102** may generate a 3D ultrasound computer model of the anatomic structure and cause the 3D computer model (or alternatively, 2D "cuts" of it) to be displayed on the Master Display **104** as an overlay to the endoscope derived 3D images or within a Picture-in-Picture ("PIP") in either 2D or 3D and from various angles and/or perspectives according to Surgeon or stored program instructions.

**[0047]** Each of the Tools **138** and **139,** as well as the Endoscope **140** and LUS Probe **150,** is preferably inserted through a cannula or trocar (not shown) or other tool guide into the Patient so as to extend down to the surgical site through a corresponding minimally invasive incision such as Incision **166.** Each of the Slave Arms **121-124** is conventionally formed of linkages which are coupled together and manipulated through motor controlled joints (also referred to as "active joints"). Setup Arms (not shown) comprising linkages and setup joints are used to position the Slave Arms **121-124** vertically and horizontally so that their respective surgical related instruments may be coupled for insertion into the cannulae.

**[0048]** The number of surgical tools used at one time and consequently, the number of slave arms being used in the System **100** will generally depend on the diagnostic or surgical procedure and the space constraints within the operating room, among other factors. If it is necessary to change one or more of the tools being used during a procedure, the Assistant may remove the tool no longer being used from its slave arm, and replace it with another tool, such as Tool **131**, from a Tray ("T") in the Operating Room.

**[0049]** Preferably, the Master Display **104** is positioned near the Surgeon's hands so that it will display a projected image that is oriented so that the Surgeon feels that he or she is actually looking directly down onto the surgical site. To that end, an image of the Tools **138** and **139** preferably appear to be located substantially where the Surgeon's hands are located even though the observation points (i.e., that of the Endoscope **140** and LUS Probe **150**) may not be from the point of view of the image.

**[0050]** In addition, the real-time image is preferably projected into a perspective image such that the Surgeon can manipulate the end effector of a Tool, **138** or **139**, through its associated Master Input Device, **107** or **108**, as if viewing the workspace in substantially true presence. By true presence, it is meant that the presentation of an image is a true perspective image simulating the viewpoint of an operator that is physically manipulating the Tools. Thus, the Processor **102** transforms the coordinates of the Tools to a perceived position so that the perspective image is the image that one would see if the Endoscope **140** was looking directly at the Tools from a Surgeon's eye-level during an open cavity procedure.

**[0051]** The Processor **102** performs various functions in the System **100**. One important function that it performs is to translate and transfer the mechanical motion of Master Input Devices **107** and **108** to their associated Slave Arms **121** and **122** through control signals over Bus **110** so that the Surgeon can effectively manipulate their respective Tools **138** and **139**. Another important function is to implement the various methods described herein providing a robotic assisted LUS capability.

**[0052]** Although described as a processor, it is to be appreciated that the Processor **102** may be implemented in practice by any combination of hardware, software and firmware. Also, its functions as described herein may be performed by one unit, or divided up among different components, each of which may be implemented in turn by any combination of hardware, software and firmware.

**[0053]** Prior to performing a minimally invasive surgical procedure, ultrasound images captured by the LUS Probe **150,** right and left 2D camera images captured by the stereoscopic Endoscope **140,** and end effector positions and orientations as determined using kinematics of the Slave Arms **121-124** and their sensed joint positions, are calibrated and registered with each other.

**[0054]** In order to associate the ultrasound image with the rest of the surgical environment, both need to be expressed in the same coordinate frame. Typically, the LUS Probe **150** is either labeled with markers and tracked by a tracking device such as the Optotrak® position sensing system manufactured by Northern Digital Inc. of Ontario, Canada, or held by a robot with precise joint encoders. Then the rigid transformation between the ultrasound image and the frame being tracked is determined (which is typically referred to as the ultrasound calibration).

**[0055]** For example, using the Optotrak® frame for the ultrasound calibration, the ultrasound image generated by the LUS Probe **150** is calibrated to an Optotrak® rigid body using an AX=XB formulation. "AX=XB" is a rubric for a class of calibration/registration problem commonly encountered in computer vision, surgical navigation, medical imaging, and robotics. The mathematical techniques are well known. See, e.g., E. Boctor, A. Viswanathan, M. Chioti, R. Taylor, G. Fichtinger, and G. Hager, "A Novel Closed Form Solution for Ultrasound Calibration," International Symposium on Biomedical Imaging, Arlington, VA, 2004, pp. 527-530.

**[0056]** "A" and "B" in this case, are transformations between poses of the Optotrak® rigid body (A) and the ultrasound image (B). Thus, "X" is the transformation from the ultrasound image to the rigid body.

**[0057]** To perform the ultrasound calibration, the LUS Probe **150** may be placed in three known orientations defined by the AX=XB calibration phantom. The ultrasound image frame may then be defined by three fiducials which appear in each of the three poses. The three poses allow three relative transformations based on Gptotrak® readings (A) and three relative transformations based on the ultrasound images (B) for the AX=XB registration.

**[0058]** Camera calibration is a common procedure in computer vision applications. As an example, in order to determine the intrinsic and extrinsic parameters of the Endoscope **140,** a checkerboard phantom with a multi-plane formulation provided by the Caltech Camera Calibration Toolbox may be used. To construct the phantom, Optotrak® markers are added to a typical checkerboard video calibration phantom, and each corner of the checkerboard is digitized using a calibrated Optotrak® pointer. Thus, the corner positions may be reported with respect to the Optotrak®.

**[0059]** The calibration may then be performed by placing the phantom in view of the Endoscope **140** in several dozen orientations, and recording both stereo image data and Optotrak® readings of the four checkerboard corners. The images may then be fed into the calibration toolbox, which determines the intrinsic and extrinsic camera parameters, as well as the 3D coordinates of the grid corners in the camera frame. These coordinates may then be used with the Optotrak® readings to perform a point-cloud to point-cloud registration between the Endoscope **140** rigid body and camera frame.

**[0060]** The Controller **102** is configured to use the robot kinematics to report a coordinate frame for the LUS Probe 150 tip relative to the Endoscope 140. However, due to inaccuracies in the setup joint encoders, both of these coordinate frames may be offset from their correct values. Thus, it may be necessary to register the offsets between the real camera frame of the Endoscope **140** and the camera frame calculated from the kinematics as well as between the real and kinematic LUS Probe **150** frames. With this complete, the kinematics may be used in place of the Optotrak® readings to determine ultrasound image overlay placement.

**[0061]** As long as the position of the Endoscope **140** doesn't overly change, a constant transformation may be assumed between the kinematic tool tip and the laparoscopic Qptotrak® rigid body. Using an AX=XB formulation, the LUS Probe **150** may be moved, for example, to several positions, and the static offset between the tool tip and Optotrak® rigid body registered. Knowing this offset, the Endoscope 140 offset may be calculated directly:

$$C_{CD} = D_{LusD} (C_{LusUrb})^{-1} T_{OUrb} (T_{OErb})^{-1} F_{CErb} \qquad (1)$$

**[0062]** where $C_{CD}$ is the camera offset from the real Endoscope **140** (also referred to herein simply as the "camera") frame to the camera frame calculated from the kinematics, $F_{CErb}$ is the transformation from the camera to the endoscope rigid body, $T_{OUrb} \bullet (T_{OErb})^{-1}$ is the transformation from the camera rigid body to the LUS rigid body, $C_{LusUrb}$ is the transformation from the LUS rigid body to the kinematic ultrasound tool tip, and $D_{LusD}$ is the reading from the Controller **102** giving the transformation from the kinematic ultrasound tool tip to a fixed reference point associated with the Slave Arms **121-124.**

**[0063]** However, the aforedescribed registration should be redone each time the camera is moved, thus making it best suited for pre-operative calibration and registration. For intra-operative, the registration may be better performed using video tracking of a visual marker on the LUS Probe **150** instead of the Optotrak® readings. Thus, if the camera were moved while using tool tracking, the registration can be corrected on the fly as the tool is tracked. For additional details on tool tracking, see, e.g., commonly owned U.S. patent application serial no. 11/130,471 entitled "Methods and system for performing 3-D tool tracking by fusion of sensor and/or camera derived data during minimally invasive surgery," filed May 16, 2005, which is incorporated herein by reference. In addition to, or alternatively, manual registration of ultrasound and camera images may be performed using conventional grab, move and rotate actions on a 3D ultrasound computer model of an anatomic structure, so that the computer model is properly registered over a camera model of the anatomic structure in the Master Display **104.**

**[0064]** Slave Arms **123** and **124** may manipulate the Endoscope **140** and LUS Probe **150** in similar manners as Slave Arms **121** and **122** manipulate Tools **138** and **139**. When there are only two master input devices in the system, however, such as Master Input Devices **107** and **108** in the System **100,** in order for the Surgeon to manually control movement of either the Endoscope **140** or LUS Probe **150**, it may be required to temporarily associate one of the Master Input Devices **107** and **108** with the Endoscope **140** or the LUS Probe **150** that the Surgeon desires manual control over, while its previously associated Tool and Slave Manipulator are locked in position.

**[0065]** FIG. 2 illustrates, as an example, a block diagram of the LUS Robotic Surgical System **100**. In this system, there are two Master Input Devices **107** and **108**. Master Input Device **107** controls movement of either a Tool **138** or a stereoscopic Endoscope **140**, depending upon which mode its Control Switch Mechanism **211** is in, and Master Input Device **108** controls movement of either a Tool **139** or a LUS Probe **150,** depending upon which mode its Control Switch Mechanism **231** is in.

[0066]   The Control Switch Mechanisms **211** and **231** may be placed in either a first or second mode by a Surgeon using voice commands, switches physically placed on or near the Master Input Devices **107** and **108,** Foot Pedals **105** and **106** on the Console, or Surgeon selection of appropriate icons or other graphical user interface selection means displayed on the Master Display **104** or an auxiliary display (not shown).

[0067]   When Control Switch Mechanism **211** is placed in the first mode, it causes Master Controller **202** to communicate with Slave Controller **203** so that manipulation of the Master Input **107** by the Surgeon results in corresponding movement of Tool **138** by Slave Arm **121,** while the Endoscope **140** is locked in position. On the other hand, when Control Switch Mechanism **211** is placed in the second mode, it causes Master Controller **202** to communicate with Slave Controller **233** so that manipulation of the Master Input **107** by the Surgeon results in corresponding movement of Endoscope **140** by Slave Arm **123,** while the Tool **138** is locked in position.

[0068]   Similarly, when Control Switch Mechanism **231** is placed in the first mode, it causes Master Controller **222** to communicate with Slave Controller **223** so that manipulation of the Master Input **108** by the Surgeon results in corresponding movement of Tool **139** by Slave Arm **122.** In this case, however, the LUS Probe 150 is not necessarily locked in position. Its movement may be guided by an Auxiliary Controller **242** according to stored instructions in Memory **240.** The Auxiliary Controller **242** also provides haptic feedback to the Surgeon through Master Input 108 that reflects readings of a LUS Probe Force Sensor **247.** On the other hand, when Control Switch Mechanism **231** is placed in the second mode, it causes Master Controller **222** to communicate with Slave Controller **243** so that manipulation of the Master input **222** by the Surgeon results in corresponding movement of LUS Probe 150 by Slave Arm 124, while the Tool 139 is locked in position.

[0069]   Before switching back to the first or normal mode, the Master Input Device **107** or 108 is preferably repositioned to where it was before the switch to the second mode of Control Switch **211** or **231,** as the case may be, or kinematic relationships between the Master Input Device 107 or **108** and its respective Tool Slave Arm **121** or **122** is readjusted so that upon switching back to the first or normal mode, abrupt movement of the Tool **138** or **139** does not occur. For additional details on control switching, see, e.g., commonly owned U.S. Pat. No. 6,659,939 "Cooperative Minimally Invasive Telesurgical System," which is incorporated herein by this reference.

[0070]   The Auxiliary Controller **242** also performs other functions related to the LUS Probe **150** and the Endoscope **140**. It receives output from a LUS Probe Force Sensor 247, which senses forces being exerted against the LUS Probe **150,** and feeds the force information back to the Master Input Device **108** through the Master Controller **222** so that the Surgeon may feel those forces even if he or she is not directly controlling movement of the LUS Probe **150** at the time. Thus, potential injury to the Patient is minimized since the Surgeon has the capability to immediately stop any movement of the LUS Probe **150** as well as the capability to take over manual control of its movement.

[0071]   Another key function of the Auxiliary Control **242** is to cause processed information from the Endoscope **140** and the LUS Probe **150** to be displayed on the Master Display **104** according to user selected display options. As will be described in more detail below, such processing includes generating a 3D ultrasound image from 2D ultrasound image slices received from the LUS Probe **150** through an Ultrasound Processor **246,** causing either 3D or 2D ultrasound images corresponding to a selected position and orientation to be displayed in a picture-in-picture window of the Master Display **104,** and causing either 3D or 2D ultrasound images of an anatomic structure to overlay a camera captured image of the anatomic structure being displayed on the Master Display **104.**

[0072]   Although shown as separate entities, the Master Controllers **202** and **222**, Slave Controllers **203, 233, 223,** and **243,** and Auxiliary Controller **242** are preferably implemented as software modules executed by the Processor **102,** as well as certain mode switching aspects of the Control Switch Mechanisms **211** and **231.** The Ultrasound Processor **246** and Video Processor **236,** on the other hand, are separate boards or cards typically provided by the manufacturers of the LUS Probe **150** and Endoscope **140** that are inserted into appropriate slots coupled to or otherwise integrated with the Processor **102** to convert signals received from these image capturing devices into signals suitable for display on the Master Display **104** and/or for additional processing by the Auxiliary Controller **242** before being displayed on the Master Display **104**.

[0073]   **FIG. 3** illustrates a side view of one embodiment of the LUS Probe **150.** The LUS Probe **150** is a dexterous tool with preferably two distal de**grees of freedom, permitting reorientation of LUS Sensor 301** through, for example, approximately + 80⎕ in distal "pitch" and "yaw", and ± 240⎕ in "roll" about a ball joint type, pitch-yaw mechanism **311** (functioning as and also referred to herein as a "Wrist" mechanism). Opposing pairs of Drive Rods or Cables (not shown) physically connected to a proximal end of the LUS Sensor **301** and extending through an internal passage of Elongated Shaft **312** mechanically control pitch and yaw movement of the LUS Sensor **301** using conventional push-pull type action. This flexibility of the LUS Probe **150** (provided by the pitch/yaw wrist mechanism) is especially useful in optimally orienting the LUS Probe **150** for performing ultrasonography on an anatomic structure during a minimally invasive surgical procedure.

[0074]   The LUS Sensor **301** captures 2D ultrasound slices of a proximate anatomic structure, and transmits the information back to the Processor **102** through LUS Cable **304.** Although shown as running outside of the Elongated Shaft **312,** the LUS Cable **304** may also extend within it. A Clamshell Sheath **321** encloses the Elongate Shaft **312** and

LUS Cable **304** to provide a good seal passing through a Cannula **331** (or trocar). Fiducial Marks **302** and **322** are placed on the LUS Sensor 301 and the Sheath 321 for video tracking purposes.

**[0075]** A force sensing capability is provided by Strain Gauges **303** which provide direct feedback of how hard the LUS Probe **150** is pushing on a structure being sonographed, supplementing whatever limited feedback is available from joint motor torques. Potential uses of this information include: providing a redundant safety threshold check warning the Surgeon or preventing motion into the structure if forces get too great; providing the Surgeon with an approved haptic appreciation of how hard he or she is pushing on a structure; and possibly permitting some measure of compensation for unmodeled deflections of the Pitch-Yaw or "Wrist" Mechanism **311** which are not detected for some reason by joint position sensors or encoders. The Strain Gauges 303 in this case serve the function of the LUS Probe Force Sensor **247** as previously described in reference to **FIG. 2.**

**[0076]** Robotic assisted LUS has the potential to reduce variability in the ultrasound images produced, compared to freehand scanning, and can reduce operator workload and difficulty. Behaviors as simple as rocking the LUS Probe 150 back and forth can maintain an updated 3D ultrasound image without operator intervention. More complicated behaviors can include movement of the LUS Probe **150** along the surface of a target anatomical structure in a methodical pattern to generate a full image of the target, or reliably returning to a previously scanned probe location and orientation.

**[0077]** **FIG. 4** illustrates, as an example, a flow diagram of a method for training the Auxiliary Controller **242** (i.e., providing it with stored instructions) to cause the LUS Probe 150 to be robotically moved in the trained manner upon command, in order to capture a sequence of 2D ultrasound image slices of an anatomic structure, which are used by the Auxiliary Controller **242** to generate a 3D computer model of the structure. Prior to performing the training, the Control Switch Mechanism **231** is placed in its second mode so that the Surgeon may move the LUS Probe **150** for training purposes by manipulating the Master Input Device **108**. After performing training, the Control Switch Mechanism **231** is then placed back into its first or normal mode so that the Surgeon may manipulate the Tool **139** to perform a minimally invasive surgical procedure using the Master Input Device 108.

**[0078]** In **401**, the training module is initially idle (i.e., it is not being executed by the Processor **102**). In 402, the Processor **102** (or a training module agent running in the background) may periodically check whether a start of training indication is received. Alternatively, the start of training indication may act as an interrupt which initiates running of the training module. The start of training indication may be initiated by a Surgeon through a recognized voice command, selection of a training option on a graphical user interface displayed on the Master Display **104**, a switch mechanism that may physically be located on the corresponding Master Control Input **108** or other convenient location accessible to the Surgeon, or any other conventional means.

**[0079]** After the start of training indication is detected, in **403**, the training module records or stores the current LUS Probe **150** position and orientation, and periodically (or upon Surgeon command) continues to do so by looping around **403** and **404** until a stop training indication is detected or received. The stop training indication in this case may also be initiated by the Surgeon in the same manner as the start of training indication, or it may be initiated in a different, but other conventional manner. After the stop training indication is detected or received, a last position and orientation of the LUS Probe **150** is recorded or stored.

**[0080]** Between the start and stop of training, the Surgeon moves the LUS Probe **150** and the Processor 102 stores its trajectory of points and orientations so that they may be retraced later upon command. In one type of training, the Surgeon moves the LUS Probe **150** back and forth near an anatomic structure in order to capture a sequence of 2D ultrasound image slices from which a 3D version (or computer model) of the anatomic structure may be rendered by the Processor **102.** In another type of training, the Surgeon move the LUS Probe **150** once or more times along the surface of the anatomic structure in order to capture a different sequence of 2D ultrasound image slices from which a 3D version (or computer model) of the anatomic structure may be rendered by the Processor **102**.

**[0081]** Although described as recording the positions and orientations of the LUS Probe **150**, in practice, the active joint positions of its Slave Arm **124** are stored instead since their measurements are directly obtainable through encoders attached to each of the joints and their positions correspond to the LUS Probe **150** positions and orientations.

**[0082]** After storing the trajectory of positions and orientations of the LUS Probe **150** in the Memory **240**, the trajectory is then associated with a means for the Surgeon to command the Auxiliary Controller **242** to move the LUS Probe **150** in the desired fashion. For example, the trajectory may be associated with a voice command which upon its detection, the Auxiliary Controller **242** causes the Slave Arm **124** to move the LUS Probe **150** back and forth along the stored trajectory of positions and orientations. Likewise, the trajectory may also be associated with a user selectable option on a graphical user interface displayed on the Master Display **104**, or it may be associated with a switch mechanism such as a button or unused control element on the Master Input Device **108**. It may also be associated with the depression of the Foot Pedal **106**, so that the Auxiliary Controller **242** causes the Slave Arm **124** to move the LUS Probe **150** back and forth along the stored trajectory of positions and orientations as long as the Foot Pedal 106 is being depressed, and stops such motion once the Surgeon takes his or her foot off the Foot Pedal **106**.

**[0083]** FIG. 5 illustrates, as an example, a flow diagram of a method for generating clickable thumbnail images corresponding to LUS Probe 150 positions and orientations that are stored in Memory 240, so that when the Surgeon clicks

on one of the thumbnail images, the Auxiliary Controller 242 causes the Slave Arm 124 to move the LUS Probe 150 to its stored position and orientation. This allows the Surgeon to move the LUS Probe 150 to see different views of an anatomic structure while the Control Switch Mechanism 231 is in its first or normal mode. Thus, the Surgeon can continue to perform a minimally invasive surgical procedure by manipulating Tool 139 using the Master Input Device 108. The method may then be combined with that described in reference to **FIG. 4** in order to generate a sequence of 2D ultrasound image slices starting from that position and orientation, from which the Auxiliary Controller 242 may generate a 3D computer model rendition of the anatomic structure.

[0084]     Prior to performing the method, however, the Control Switch Mechanism 231 is placed in its second mode so that the Surgeon may move the LUS Probe 150 into the desired positions and orientations by manipulating the Master Input Device 108. After generating the clickable thumbnail images, the Control Switch Mechanism 231 is then placed back into its first or normal mode so that the Surgeon may manipulate the Tool 139 to perform the minimally invasive surgical procedure using the Master Input Device 108.

[0085]     In 501, the Auxiliary Controller 242 receives a snapshot command from the Surgeon. The snapshot command may be, for example, a voice command, graphical user interface selection, or switch position. In 502, the Auxiliary Controller 242 causes the LUS Probe 150 to capture a 2D ultrasound image slice, and in 503, a thumbnail of the image is generated. The thumbnail in this case may include a simple JPEG or GIF file of the captured image. In 504, the current position and orientation of the LUS Probe 150 is stored in Memory 240 along with information of its association with the thumbnail. In 505, a clickable version of the thumbnail is displayed on the Master Display 104, so that the Surgeon may command the Auxiliary Controller 242 to cause the LUS Probe to be positioned and oriented at the stored position and orientation at any time upon clicking with his or her mouse or other pointing device on the clickable thumbnail. The Surgeon may then move the LUS Probe 150 to other positions and/or orientations, and repeat 501-505 to generate additional thumbnail images.

[0086]     **FIG. 6** illustrates, as an example, a flow diagram of a method for automatically moving the LUS Probe 150 to a position and orientation associated with a clickable thumbnail upon command to do so by a Surgeon while performing a minimally invasive surgical procedure using Tool 139. In 601, the clicking of a thumbnail generated by the method described in reference to **FIG. 5** is detected by, for example, a conventional interrupt handling process. Upon such detection, in 602, the Auxiliary Controller 242 is instructed by, for example, stored instructions corresponding to the interrupt handling process, to retrieve the position and orientation stored in Memory 240 which is associated with the thumbnail. The Auxiliary Controller 242 then causes the LUS Probe 150 to move to that position and orientation by appropriately controlling Slave Arm 124. Thus, the Surgeon is able to move the LUS Probe 150 to a desired position without having to change modes of the Control Switch Mechanism 231 and halt operation of the Tool 139 until the LUS Probe 150 is moved.

[0087]     **FIG. 7** illustrates, as an example, a flow diagram of a method for robotically assisted needle guidance and penetration into a marked lesion of a cancerous structure, which allows appreciation for the aspects of robotic assisted LUS described herein. In 701, a selected 2D ultrasound image slice view of a cancerous structure such as a liver is displayed at the proper depth on the Master Display 104 as an overlay to a 3D camera view of the cancerous structure. The selected 2D ultrasound image slice view may be a frontal view or an inner slice view as taken from a previously generated 3D ultrasound computer model of the cancerous structure.

[0088]     As an example clarifying the 701 process, **FIG. 8** illustrates a simplified perspective view of a 3D ultrasound computer model 800 of the cancerous structure, which has been generated, for example, using the method described in reference to **FIG. 4**, and has been translated into the camera reference frame (EX, EY, EZ). **FIG. 9**, on the other hand, illustrates a simplified perspective view of a 3D camera view 900 of the cancerous structure as taken by the stereoscopic Endoscope 140. If the Surgeon selects a frontal slice 801 of the 3D ultrasound computer model 800 to be viewed as an overlay to the 3D camera view 900, then the overlay will appear as shown in **FIG. 10**. On the other hand, if the Surgeon selects one of the inner slices **802-804** of the 3D ultrasound computer model 800, such as inner slice **803**, to be viewed as an overlay to the 3D camera view 900, then the overlay will appear as shown in **FIG. 11** with the 2D ultrasound image slice 803 displayed at the proper depth. To avoid confusion, the portion of the 3D camera view above that depth is made transparent.

[0089]     Alternatively, in 701, the surgeon may manually control movement of the LUS Probe 150 so that 2D ultrasound image slices captured by it appear as emanating in proper perspective and direction from the 3D camera image of the LUS Probe 150 in the Master Display 104. Preferably, the emanated 2D image slices being displayed in the Master Display 104 do not occlude the anatomic structure being probed. This manual approach may be particularly useful to the Surgeon for quickly spotting lesions in the anatomic structure.

[0090]     In 702, the Surgeon marks lesions on the cancerous structure displayed as a result of 701. Each marked lesion is preferably marked using a designated color in order to clearly show that the Surgeon has already identified it, thereby avoiding double counting. The location in the camera reference frame (EX, EY, EZ) of each marked lesion is stored in Memory 240, and in 703, the Processor 102 determines an optimal needle tip path to that location.

[0091]     In 703, the Processor 102 generates a virtual fixture to help guide the needle to the marked lesion. To generate

the virtual fixture, local kinematic constraints on the Slave Arm manipulating the needle Tool may be specified by providing a table of constraints of the form:

$$\left(\vec{x}-\vec{x}_0\right)^T A_K \left(\vec{x}-\vec{x}_0\right)+\vec{b}K\left(\vec{x}-\vec{x}_0\right) \le c \qquad (2)$$

[0092]   where $\overleftarrow{x}$ represents, in simplified terms, the current 6 DOF kinematic pose of a master arm, or, in more general terms, a parameterization of a Cartesian pose F linearized about some nominal pose $F_0$ so that $(\overleftarrow{x}-\overleftarrow{x}_0) \sim F_0^{-1}$ F. The tables are to be updated periodically based on visual feedback, user interaction, etc.

[0093]   As can be appreciated, equation (2) can be easily checked and enforced.

[0094]   Similarly, a simple table-driven interface for surgeon interaction forces can be implemented approximately as follows:

$$\vec{f} \leftarrow 0; \; \vec{y} \leftarrow \vec{x} - \vec{x}_0 ; \qquad (3)$$

for k ← 1 to N do

$$\{ \varepsilon \leftarrow \vec{y}^T C_K \vec{y} + \vec{d}_K \vec{y} - e_K ;$$

$$\text{if } \varepsilon > 0 \text{ then } \left\{ \ddot{\vec{g}} \leftarrow 2 C_K \vec{y} \vec{d}_K ; \vec{f} \leftarrow \vec{f} + f\left(\varepsilon\right)\vec{g} / \left\| \vec{g} \right\| ; \right\};$$

$$\};$$

output f (after limiting & spacing)

[0095]   where ε corresponds, roughly, to a distance from a surface in state space and the function f(ε) corresponds to a (non-linear) stiffness.

[0096]   The above formulation suffices to support a variety of virtual chamfers, virtual springs, detents, etc. It is also easily extended to virtual dampers by adding velocity terms.

[0097]   Now, more particularly, in the present case where it is desired to help aim an injection needle at a target in a live ultrasound image, let:

$$\vec{P}_{\text{TROCAR}} = \text{position where needle enters patient} \qquad (4)$$

$$= \text{"RCM" point for needle insertion arm}$$

$$R_{\text{NEEDLE}} = R_0 R(\vec{\alpha}) = \text{orientation of needle arm} \qquad (5)$$

$$\vec{\alpha} = \text{vector representation for small rotation} \qquad (6)$$

$$F_{LUS} = [R_{LUS}, \vec{P}_{LUS}] = \text{pose of LUS sensor} \qquad (7)$$

$$V_{TARGET} = \text{position of target wrt LUS sensor} \qquad (8)$$

**[0098]** Then the basic constraint is that the needle axis (which is assumed for this example to be the $\overleftarrow{z}$ axis of the needle driver) should be aimed at the target lesion, which will be given by $F_{LUS} \vec{V}_{TARGET}$. One metric for the aiming direction error will be:

$$\varepsilon_{AIMING}\left(\vec{\alpha}\right) = \left\| \left(R_{NEEDLE}\ \vec{z}\right) \times \left(F_{LUS}\ \vec{V}_{TARGET} - \vec{P}_{TROCAR}\right) \right\|^2 \qquad (9)$$

$$= \left\| \left(R\left(\vec{\alpha}\right)\vec{z}\right) \times R_0^{-1} \left(F_{LUS}\ \vec{V}_{TARGET} - \vec{P}_{TROCAR}\right) \right\|^2$$

**[0099]** which can be approximated as a quadratic form in $\overleftarrow{\alpha}$ and converted to a virtual fixture using the method described above. Similarly, if the position of the needle tip is $\overleftarrow{P}_{TIP}$, the penetration depth beyond the LUS target will be given by:

$$\varepsilon_{BEYOND} = \left(R_0\ R\left(\vec{\alpha}\right)\vec{z}\right) \bullet \left(F_{LUS}\ \vec{V}_{TARGET} - \vec{P}_{TIP}\right) \qquad (10)$$

**[0100]** which can easily be transcribed into a virtual detent or barrier preventing over-penetration. Alternatively, a simple spherical attractor virtual fixture can be developed to minimize $\|F_{LUS}\ \vec{V}_{TARGET} - \overleftarrow{P}_{TIP}\|$.

**[0101]** In **705**, the Processor **102** determines the needle tip position as it moves towards the target lesion, and in **706,** the Processor **102** determines the distance between the needle tip position and the target lesion. The needle tip position may be determined from the Slave Arm kinematics and/or through visual tracking in the camera image.

**[0102]** In **707**, the color of the lesion or some other object in the display changes as the needle tip gets closer to the target. For example, the color may start off as blue when the needle tip is still far away from the target, and it may change through color spectrum so that it becomes red as it nears the target. Alternatively, a bar graph or other visual indicator may be used to give a quick sense of the distance.

**[0103]** In **708,** a determination is made whether the distance has reached a threshold distance (usually specified as some distance close to or even at the surface of the target lesion). If the threshold has not been reached, then the method loops back to **705** and continually repeats **705-708** until the threshold is reached. Once the threshold is reached, in 709, a 90 degree view of the cancerous structure and the approaching needle is shown in a picture-in-picture window of the Master Display **104**. The method may then go back to **705** and repeat **705-708** as the needle penetrates the cancerous structure or withdraws back to its start position.

**[0104]** Although the various aspects of the present invention have been described with respect to a preferred embodiment, it will be understood that the invention is entitled to full protection within the full scope of the appended claims.

**[0105]** The present application also includes the following numbered clauses:

1. A laparoscopic ultrasound robotic surgical system comprising:

   a first robotic arm mechanically coupled to an ultrasound probe;
   a second robotic arm mechanically coupled to a surgery related device;
   a master manipulator;
   a control switch having user selectable first and second modes; and
   a processor configured to cause the second robotic arm to be locked in position and the first robotic arm to

move the ultrasound probe according to user manipulation of the master manipulator when the control switch is in the first mode, and cause the second robotic arm to manipulate the tool according to manipulation of the master manipulator and the first robotic arm to move the ultrasound probe according to stored instructions upon detection of a user command associated with the stored instructions when the control switch is in the second mode.

2. The laparoscopic ultrasound robotic surgical system according to clause1, wherein the surgery related device is a surgical tool.

3. The laparoscopic ultrasound robotic surgical system according to clause 1, wherein the user command is a voice command.

4. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein, the user command derives from user selection of an option provided in a graphical user interface.

5. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the user command derives from a selection indicated by a switch position.

6. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the stored instructions instruct the processor to cause the first robotic arm to move the ultrasound probe so that 2D ultrasound image slices captured by the ultrasound probe while moving provide information for the processor to generate a 3D computer model of at least part of an anatomic structure during a minimally invasive surgical procedure.

7. The laparoscopic ultrasound robotic surgical system according to Clause 6, wherein the stored instructions instruct the processor to cause the first robotic arm to move the ultrasound probe along a trajectory of stored points.

8. The laparoscopic ultrasound robotic surgical system according to Clause 7, wherein the stored instructions instruct the processor to cause the first robotic arm to repetitively move the ultrasound probe back and forth along the trajectory of stored points.

9. The laparoscopic ultrasound robotic surgical system according to clause 7, wherein the trajectory of stored points include points on a surface of the anatomic structure.

10. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the stored instructions instruct the processor to cause the first robotic arm to move the ultrasound probe so as to be positioned and oriented at a stored position and orientation.

11. The laparoscopic ultrasound robotic surgical system according to Clause 10, wherein the stored position and orientation correspond to a clickable thumbnail of an ultrasound image generated by the ultrasound probe at the position and orientation.

12. The laparoscopic ultrasound robotic surgical system according to Clause 11, wherein the processor is configured to cause the first robotic arm to move the ultrasound probe to the stored position and orientation upon receiving an indication that a user has clicked the clickable thumbnail.

13. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the surgery related device is a surgical tool, and further comprising:

an endoscope for capturing images of a surgical site in a patient;
wherein the processor is configured to display the captured images in a picture section of a display screen and an ultrasound image captured by the ultrasound probe within a picture-in-picture section of the display screen.

14. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the surgery related device is a surgical tool, and further comprising:

an endoscope for capturing video images;
wherein the processor is configured to spatially register ultrasound images captured by the ultrasound probe with the video images captured by the endoscope.

15. The laparoscopic ultrasound robotic surgical system according to Clause 14, wherein the processor is configured to determine positions and orientations of the ultrasound images relative to a frame of reference associated with the endoscope, and display the ultrasound images so as to overlay the video images at the determined positions and orientations on a display screen.

16. The laparoscopic ultrasound robotic surgical system according to Clause 15, wherein the endoscope is a stereoscopic endoscope capturing right and left 2D camera views including captured images of the ultrasound probe, the display screen is a 3D display screen, and the processor is configured to: generate a 3D camera image from the captured right and left 2D camera views, and display the 3D camera images in the 3D display screen with 2D ultrasound image slices captured by the ultrasound probe overlayed in the 3D camera images so as to appear as emanating in proper perspective from the ultrasound probe.

17. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the control switch is placed in the first or second mode by a user voice command.

18. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the control switch is placed in the first or second mode by user selection of an option provided in a graphical user interface.

19. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the control switch is placed in the first or second mode by a user selected switch position.

20. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the ultrasound probe includes a force sensor to sense forces exerted against the ultrasound probe and provides information of the sensed forces to the processor, and the processor reflects information of the sensed forces back to the master manipulator so as to be felt by a user while manipulating the master manipulator.

21. The laparoscopic ultrasound robotic surgical system according to Clause 1, wherein the ultrasound probe comprises:

    an ultrasound sensor;
    an elongated shaft; and
    a wrist mechanism coupling the ultrasound sensor to the elongated shaft so as to allow pitch and yaw movement of the ultrasound sensor relative to an axis running along a length of the elongated shaft.

22. The laparoscopic ultrasound robotic surgical system according to Clause 21, wherein the ultrasound probe further comprises:

    a first pair of cables coupled to the ultrasound sensor such that the ultrasound sensor moves in a yaw direction by pulling on only one of the first pair of cables and moves in an opposite yaw direction when pulling on only the other of the first pair of cables.

23. The laparoscopic ultrasound robotic surgical system according to Clause 22, wherein the ultrasound probe further comprises:

    a second pair of cables coupled to the ultrasound sensor such that the ultrasound sensor moves in a pitch direction by pulling on only one of the second pair of cables and moves in an opposite pitch direction when pulling on only the other of the second pair of cables.

24. A method for providing robotic assisted laparoscopic ultrasound, comprising:

    storing a current ultrasound probe position and orientation upon detection of a start of training indication; and periodically storing ultrasound probe positions and orientations to define a trajectory of positions and orientations until detection of an end of training indication.

25. The method according to Clause 24, wherein the start and end of training indications are generated by user voice commands.

26. The method according to Clause 24, wherein the start and end of training indications are generated by user

selections using a graphical user interface.

27. The method according to Clause 24, wherein the start and end of training indications are generated by positions of one or more switch mechanisms.

28. The method according to Clause 24, further comprising: associating the trajectory of positions and orientations with a first voice command.

29. The method according to Clause 28, further comprising: causing the ultrasound probe to move along the trajectory of positions and orientations upon detection of the first voice command.

30. The method according to Clause 28, further comprising: causing the ultrasound probe to move back and forth along the trajectory of positions and orientations upon detection of the first voice command and until detection of a second voice command.

31. The method according to Clause 24, further comprising: associating the trajectory of positions and orientations with a clickable thumbnail displayed on a display screen.

32. The method according to Clause 31, further comprising: causing the ultrasound probe to move along the trajectory of positions and orientations upon detection of the clickable thumbnail having been clicked upon and until a stop indication is received.

33. The method according to Clause 24, further comprising: associating the trajectory of positions and orientations with a first switch position.

34. The method according to Clause 33, further comprising: causing the ultrasound probe to move along the trajectory of positions and orientations upon detection of a switch being in the first switch position and until detection of the switch being in a second switch position.

35. A method for providing robotic assisted laparoscopic ultrasound, comprising:

    capturing an ultrasound image using an ultrasound probe disposed at a position and orientation;
    storing information of the position and orientation;
    generating a clickable thumbnail of the ultrasound image;
    associating the stored position and orientation with the clickable thumbnail; and
    displaying the clickable thumbnail on a display screen.

36. The method according to Clause 35, further comprising:

    receiving information of a user having clicked on the clickable thumbnail; and
    causing the ultrasound probe to be disposed at the position and orientation associated with the clicked upon clickable thumbnail.

37. A method for providing robotic assisted laparoscopic ultrasound, comprising:

    displaying an ultrasound view of an anatomic structure in a patient as a registered overlay to a camera view of the anatomic structure;
    receiving information of a target marked on the ultrasound view;
    determining a path for a tool to travel to the target within the patient; and
    generating a virtual fixture to assist in electronically constraining the tool to travel over the determined path.

38. The method according to Clause 37, wherein the anatomic structure is cancerous, the target is a lesion marked by a surgeon on the displayed ultrasound view, and the tool is a needle.

39. The method according to Clause 37, further comprising:

    determining a distance of the tool from the target; and
    changing a color of the target marked on the ultrasound view so as to indicate the distance.

40. The method according to Clause 37, further comprising:

determining when a tip of the tool reaches a threshold distance from a surface of the anatomic structure; and displaying a right angle view of the ultrasound image and the tool upon determining that the tip of the tool has reached the threshold distance in a picture-in-picture window.

41. The method according to Clause 40, wherein the ultrasound image is a 3D image generated from a sequence of 2D ultrasound image slices of the anatomic structure.

**Claims**

1.  A robotic system comprising:

    a tool;
    a robotic arm coupled to the tool;
    an ultrasound probe;
    a camera;
    a display screen; and
    a processor programmed to display an ultrasound view of an anatomic structure captured by the ultrasound probe as a registered overlay to a camera view of the anatomic structure captured by the camera on the display screen, receive information of a target marked on the ultrasound view displayed on the display screen, determine a path for the tool to travel to the target, and generate a virtual fixture to assist in electronically constraining the robotic arm in moving the tool over the determined path.

2.  The robotic system according to claim 1, wherein the anatomic structure is cancerous, the target is a lesion marked by a surgeon on the displayed ultrasound view, and the tool is a needle.

3.  The robotic system according to claim 1, wherein the processor is further programmed to determine a distance of the tool from the target and change a color of the target marked on the ultrasound view on the display screen so as to indicate the distance.

4.  The robotic system according to claim 1, wherein the processor is further programmed to determine when a tip of the tool reaches a threshold distance from a surface of the anatomic structure and display a right angle view of the ultrasound image and the tool in a picture-in-picture window of the display screen upon determining that the tip of the tool has reached the threshold distance.

5.  The robotic system according to claim 4, wherein the ultrasound image is a three-dimensional image generated from a sequence of two-dimensional ultrasound image slices of the anatomic structure.
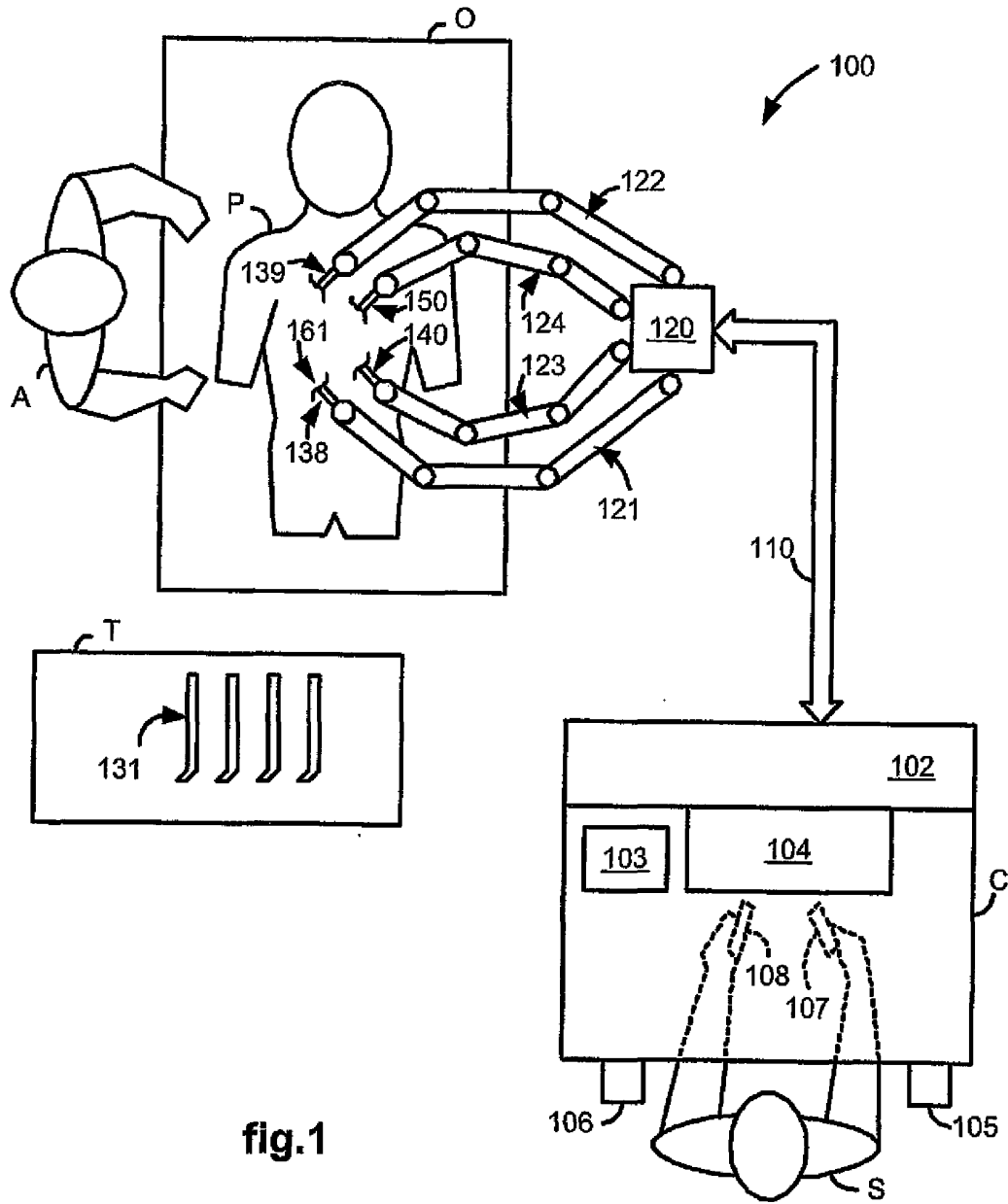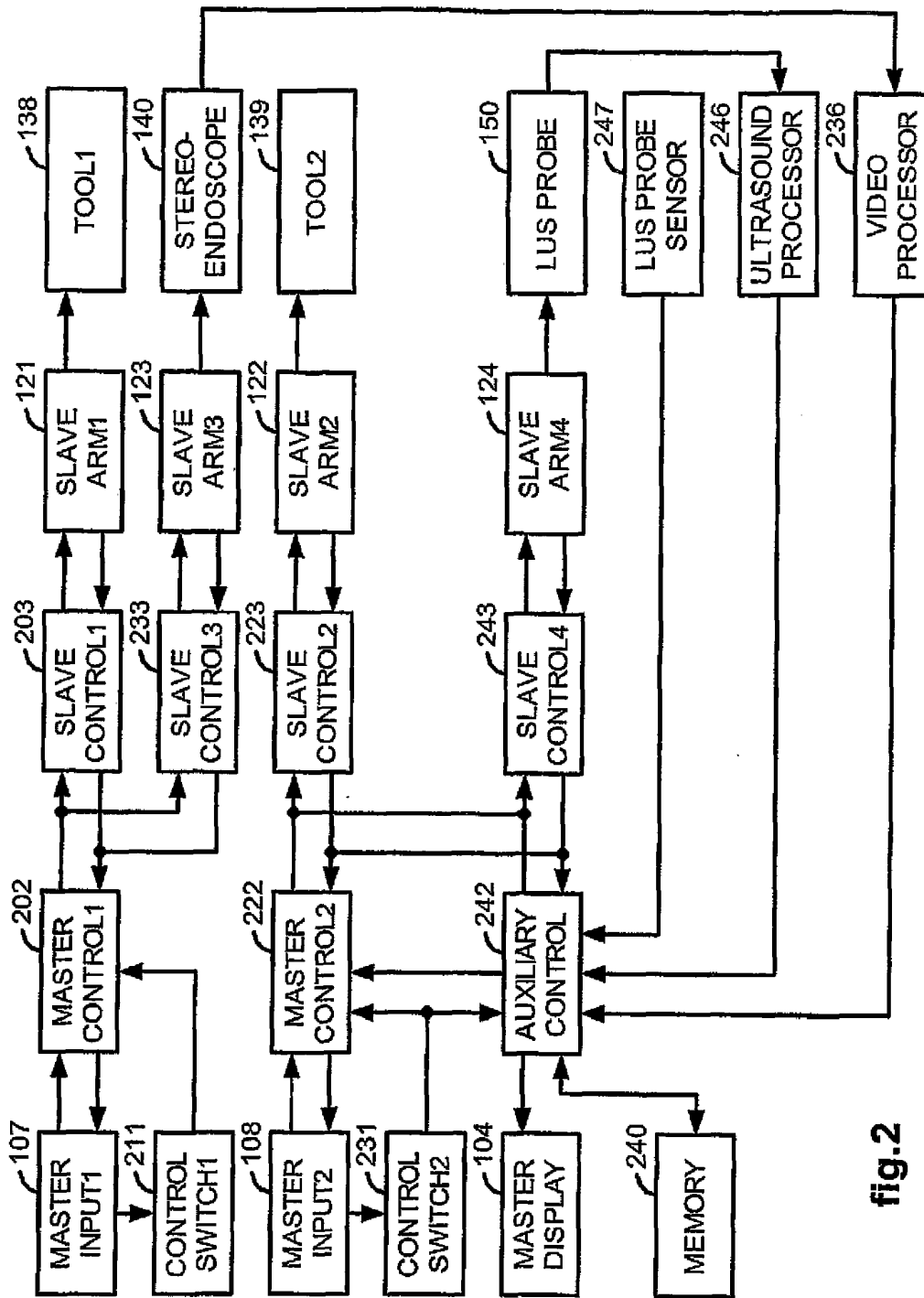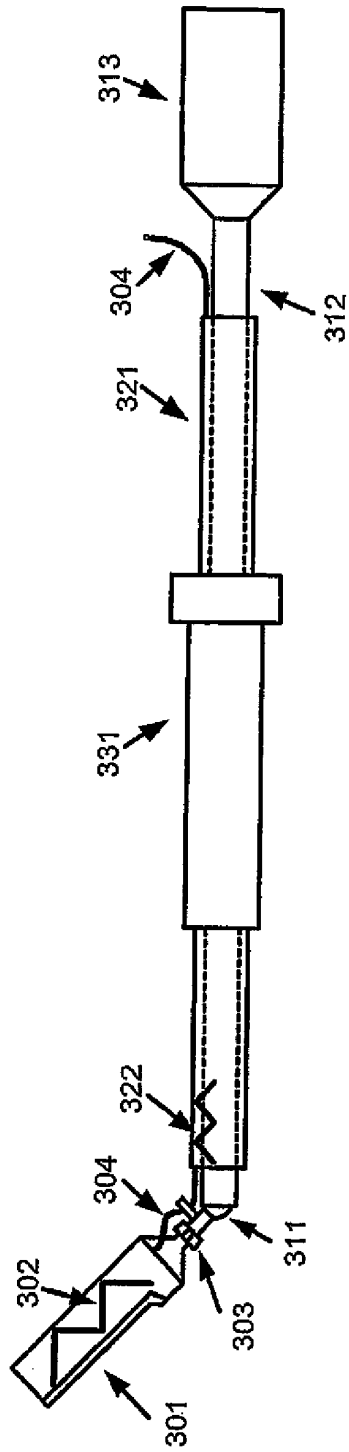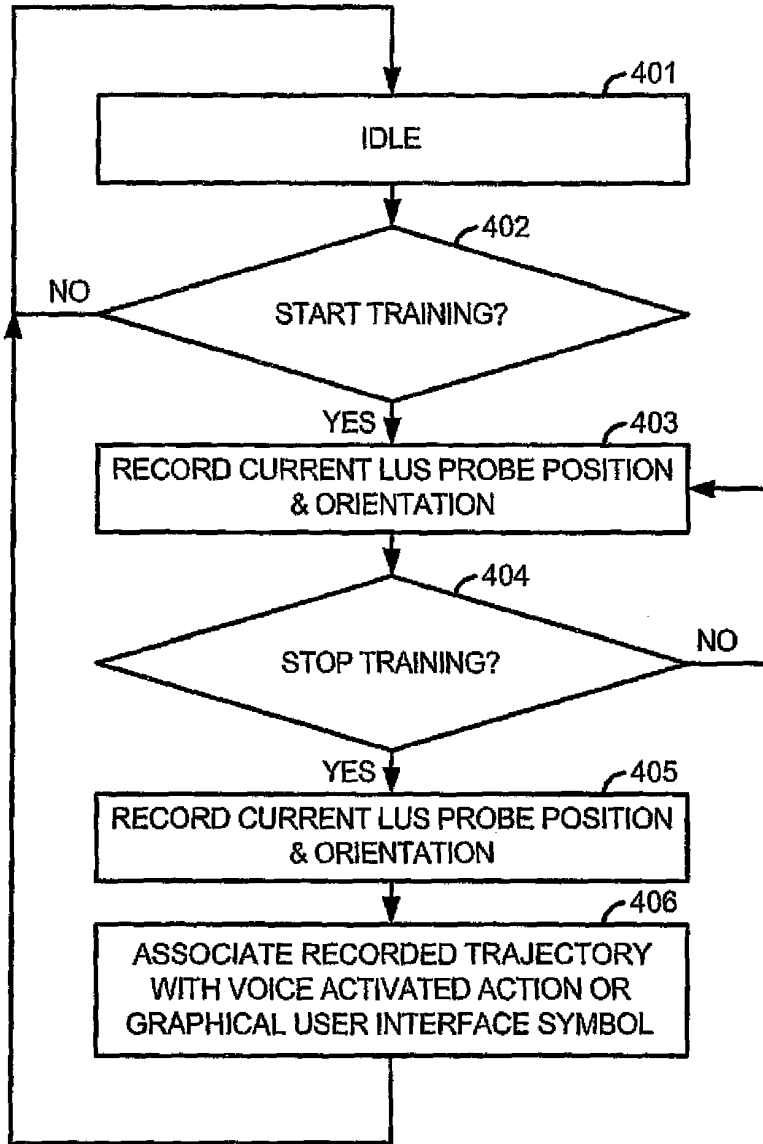
**fig.1**

**fig.2**

fig.3

fig.4

```
                                        ┌─501
┌──────────────────────────────────────────┐
│        RECEIVE SNAPSHOT COMMAND           │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─502
┌──────────────────────────────────────────┐
│      CAPTURE 2D ULTRASOUND IMAGE SLICE    │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─503
┌──────────────────────────────────────────┐
│      GENERATE THUMBNAIL OF IMAGE SLICE    │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─504
┌──────────────────────────────────────────┐
│      STORE POSITION & ORIENTATION ALONG   │
│        WITH ASSOCIATION TO THUMBNAIL      │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─505
┌──────────────────────────────────────────┐
│        DISPLAY CLICKABLE THUMBNAIL OF     │
│                   IMAGE                   │
└──────────────────────────────────────────┘
```

**fig.5**

```
                                        ┌─601
┌──────────────────────────────────────────┐
│        DETECT CLICKING OF THUMBNAIL       │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─602
┌──────────────────────────────────────────┐
│      RETRIEVE POSITION & ORIENTATION      │
│        ASSOCIATED WITH THUMBNAIL          │
└──────────────────────────────────────────┘
                     │
                     ▼              ┌─603
┌──────────────────────────────────────────┐
│      MOVE IMAGE CAPTURE DEVICE TO         │
│    RETRIEVED POSITION & ORIENTATION       │
└──────────────────────────────────────────┘
```

**fig.6**

701
DISPLAY SELECTED US VIEW OF
CANCEROUS STRUCTURE AS OVERLAY

702
RECEIVE LESION INDICATION

703
DETERMINE NEEDLE TIP PATH TO LESION

704
GENERATE VIRTUAL FIXTURE TO HELP
GUIDE NEEDLE

705
DETERMINE NEEDLE TIP POSITION

706
DETERMINE DISTANCE OF NEEDLE TIP TO
LESION SURFACE

707
DISPLAY COLOR INDICATING DISTANCE

708
THRESHOLD
DISTANCE REACHED?

NO

YES

709
DISPLAY 90 DEG VIEW OF STRUCTURE &
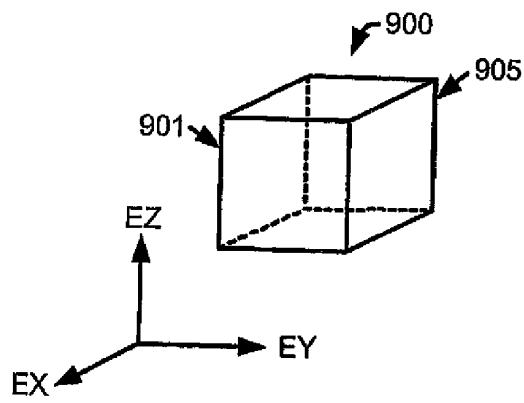NEEDLE IN PIP
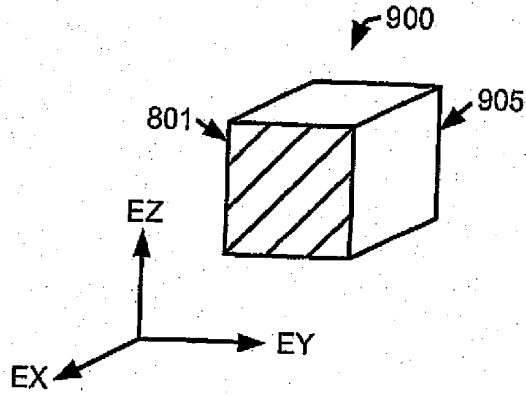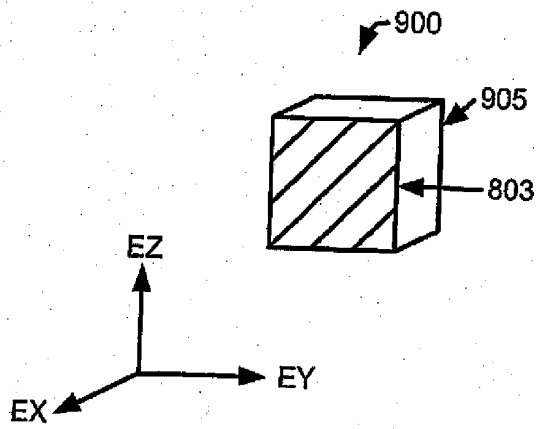
fig.7

fig.8



fig.9

fig.10



fig.11

## REFERENCES CITED IN THE DESCRIPTION

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| 优先权 | 60/688013 2005-06-06 US<br>PCT/US2006/021852 2006-06-05 WO |
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摘要(译)

LUS机器人手术系统可由外科医生训练，以在命令时以期望的方式自动移动LUS探针，使得外科医生在微创外科手术期间不必手动操作。由LUS探针根据存储的指令捕获的2D超声图像切片序列可处理成解剖结构的3D超声计算机模型，其可以显示为相机视图的3D或2D覆盖或者通过选择的PIP显示。外科医生或编程以协助外科医生检查解剖结构的异常情况。虚拟固定装置是可定义的，以便帮助外科医生将工具准确地引导到所显示的超声图像上的目标。



fig.1