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(54) Title: INTERACTIVE SYSTEMS AND METHODS FOR REAL-TIME LAPAROSCOPIC NAVIGATION

(57) Abstract: Systems and methods for real time laparoscopic navigation. Exemplary embodiments can comprise scanning a structure of interest internal to a patient to provide image data; generating a first three-dimensional reconstruction of the structure of interest based on the image data; annotating the first three-dimensional reconstruction of the structure of interest with a plurality of reference points; obtaining spatial coordinates of the plurality of reference points during a laparoscopic procedure; and generating a second three-dimensional reconstruction of the structure of interest based on the spatial coordinates.

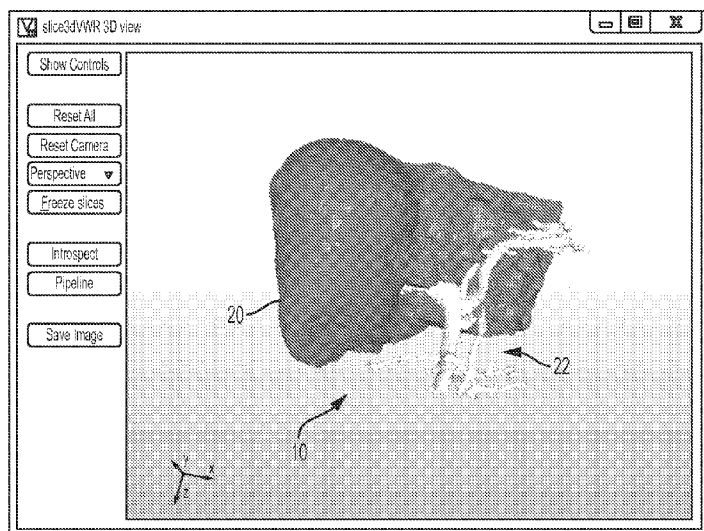


FIG. 1

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## **DESCRIPTION**

### **INTERACTIVE SYSTEMS AND METHODS FOR REAL-TIME LAPAROSCOPIC NAVIGATION**

#### **CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims priority to U.S. Provisional Patent Application Serial No. 61/969,805 filed March 24, 2014 and entitled “Interactive Systems and Methods for Real-Time Laparoscopic Navigation,” the entire contents of which are incorporated herein by  
5 reference.

#### **TECHNICAL FIELD**

Exemplary embodiments of the present disclosure relate to systems and methods for real-time laparoscopic navigation.

#### **BACKGROUND**

10 Non-invasive procedures, including laparoscopic surgery, are a common and popular alternative to open surgery due to the considerable reduction of recovery time, pain and complications. However, many obstacles make the surgeon’s work difficult and inefficient, including limited access to the operating field, indirect vision, and operating theaters originally built for open surgery. There has been an interest in the field to develop systems to  
15 aid in “operating room awareness.” Operating room awareness refers to creating an operating room that can collect data related to the operation in progress and use the data to assist the surgeon and medical staff. There is also interest using the collected data to assist in surgeon and staff training and evaluation.

One component of operating room awareness is tool identification, location and  
20 navigation. Historically, surgical tools have been identified and positioned using visual inspection by the surgeon and/or medical staff. Some automated systems exist; however, the accuracy of these systems can be compromised by the presence of metals and fluids in the operating space and the reliance on a constantly-changing point of reference for the tracking device.

25 Numerous navigation systems are based on computer tomography (CT) data acquired prior to the surgery. These systems propose an accurate three-dimensional reconstruction of the liver with its Couinau decomposition into segments, blood vessel tree and tumor location. Additionally, the biliary duct network can be provided too. IRCAD (Research Institute

against Digestive Cancer) has provided a data base of twenty patients that demonstrates a technique for this image analysis from CT.

This three-dimensional reconstruction can be displayed in the operating room: one uses various graphic tools to represent the structure of interest by combining rotation in the  
5 three dimensional space and transparency. As the procedure progresses, the surgeon can use a mouse or similar control device to remove virtually on that representation the tissue that has been taken away. This manually driven correction through the Graphic User Interface (GUI) may help the surgeon to visualize the next structure of interest to be reached or preserved.

This approach is quite pragmatic but loses its accuracy and relevance as soft tissue  
10 gets greatly shifted and deformed during the procedure. The surgeon has to keep connecting mentally his observation during the procedure through the endoscope camera display, to the display of the subset of preoperative data.

A technique that has potential in laparoscopy is “virtual endoscopy” or image-enhanced endoscopy. This approach uses computer graphics to render the view seen by a  
15 navigated video laparoscope inside the abdomen, based on a representation of the cavity calculated from preoperative MRI or CT images. Using segmented structures (e.g. tumor and vessels) overlaying the real laparoscopic video, is often termed augmented reality or multimodal image fusion visualization. Such a view may help the surgeons to quickly interpret important information beyond the surface of the organs as seen by the conventional  
20 video camera. More research into segmentation of anatomic and pathologic structures may improve the usefulness of e.g. overlay or side-by-side view of virtual endoscopy and tracked laparoscopic images. But the fundamental problem of shifted positions due to tissue deformation and resection remains.

Ultrasound can be used intra-operatively to follow up this displacement and replace in  
25 context the tumor location for example. In 1991, Jakimowicz and Reuers introduced Laparoscopy Ultrasound (LUS) scanning for examination of the biliary tree during laparoscopic cholecystectomy. Intraoperative ultrasound is becoming routine in some surgical disciplines, e.g. neurosurgery. LUS is today applied in laparoscopy in numerous ways for screening, diagnostics and therapeutic purposes.

Combining imaging, virtual reality and LUS could help detect organ shifts and also  
30 augment the scene view further for the surgeon, providing more details in depth and in real time.

However, manipulating the LUS probe requires additional work and may go into the way of the laparoscopic instruments. For example, the LUS probe is inserted through a trocar,

which limits the ability of the probe to acquire the right view and may cause disorientation. In addition, LUS has also a lower signal to noise ratio than CT.

LUS may be useful to guide a biopsy or stage a tumor, but it is not however designed to follow continuously a surgical procedure. Finally, LUS provides a fairly limited field of view and does not help laparoscopy in that respect.

Therefore, a need in the art exists for a minimally intrusive, yet robust, system to analyze data generated during a medical procedure and provide real-time context awareness to the surgery team as well as post-procedure evaluation tools.

### **SUMMARY OF THE INVENTION**

Presented are systems and methods directed to real-time navigation for minimally invasive procedures, including for example, laparoscopic procedures. Exemplary embodiments of the present disclosure are able to combine tissue deformation with preoperative data to produce accurately intraoperative map of a structure of interest (*e.g.*, a liver) anatomy adapted to the real surgical procedure itself as the procedure progresses.

Exemplary embodiments of the invention may comprise: (a) a “smart” trocar and an endoscope camera, going through that smart trocar, equipped with a system that gives the distance from the lens of the endoscope camera to the tissue location centered in the endoscope camera view; and (b) a simulator of tissue deformation that starts from preoperative imaging data.

Exemplary embodiments may use the elements described in (a) and (b) above to compute at any time of the surgery, and on-demand, the three-dimensional map of the tissue in the region of interest. In exemplary embodiments, this map can to help the surgeon to navigate through this anatomy and achieve exact resection as planned. Embodiments of the system are designed to make surgery safer, *e.g.* by avoiding damage to tissue that should not be cut during the surgery.

Certain embodiments include a method of scanning a structure of interest internal to a patient to provide image data, and generating a first three-dimensional reconstruction of the structure of interest based on the image data. Exemplary methods can also include annotating the first three-dimensional reconstruction of the structure of interest with a plurality of reference points, and obtaining spatial coordinates of the plurality of reference points during a laparoscopic procedure. Exemplary methods may further comprise generating a second three-dimensional reconstruction of the structure of interest based on the spatial coordinates.

In particular embodiments, obtaining the spatial coordinates of the plurality of reference points comprises obtaining a distance from each of the plurality of reference points to a camera on a surgical port used during the laparoscopic procedure. In some embodiments, the distance is obtained via a laser. In specific embodiments, the distance is obtained via acoustic waves. In certain embodiments, the distance is obtained via an autofocus feature of the camera. In particular embodiments, the autofocus feature incorporates an algorithm to increase local pixel contrast. In specific embodiments, the structure of interest is a liver. In some embodiments, the plurality of reference points comprise locations where hepatic arteries enter the liver and where a portal vein exits the liver. In particular embodiments, the plurality of reference points comprise locations including a transverse fissure of the liver that divides a left portion of the liver into four segments. In certain embodiments, the plurality of reference points comprises a coupling point between the liver and a gall bladder. In particular embodiments, the plurality of reference points comprises a location of the hepatic lymph node. In some embodiments, the plurality of reference points comprise the ligamentum venosum and the ligament teres.

Certain embodiments include a real time laparoscopic navigation system comprising a scanner configured to provide image data of a structure of interest internal to a patient, and a processor. In particular embodiments, the processor is configured to: generate a first three-dimensional reconstruction of the structure of interest based on the image data; annotate the first three-dimensional reconstruction of the structure of interest with a plurality of reference points; obtain spatial coordinates of the plurality of reference points during a laparoscopic procedure; and generate a second three-dimensional reconstruction of the structure of interest based on the spatial coordinates. In certain embodiments, the scanner is a magnetic resonance imaging (MRI) scanner. In some embodiments, the scanner is a computed tomography (CT) scanner.

Specific embodiments further comprise a camera coupled to a surgical port, and wherein the processor is configured to obtain the spatial coordinates of the plurality of reference points by obtaining a distance from each of the plurality of reference points to the camera. In particular embodiments, the processor is configured to obtain the distance via a laser. In some embodiments, the processor is configured to obtain the distance via acoustic waves. In specific embodiments, the processor is configured to obtain the distance via an autofocus feature of the camera. In particular embodiments, the autofocus feature incorporates an algorithm to increase local pixel contrast.

Certain embodiments can comprise a scanner (*e.g.* a magnetic resonance imaging [MRI] scanner or a computer tomography [CT] scanner) to scan the structure of interest. Exemplary embodiments may also comprise one or more processors and graphic displays to  
5 analyze the image data and generate reconstructions of the structure of interest.

Exemplary embodiments of the present disclosure extract spatially and timely accurate data from the minimally invasive procedures. In certain embodiments, the system can be passive in the sense that it can provide feedback, but the surgical team has still the ability to ignore or override the outcome. In certain embodiments, it may be desirable to  
10 implement the system in a passive manner to allow the surgical team to become familiar and comfortable using the system.

In other embodiments, the system may be operated in an active manner (*e.g.* after the surgeon team has become familiar the operation of the system in a passive aspect). In such embodiments, the system can be configured to restrict or stop the procedure when it  
15 determines the surgical instrument has entered a restricted area (*e.g.* a “no-fly zone”) that could place critical structures in danger.

Challenges faced in such systems and methods include the difficulty in tracking landmarks that can be acquired in a non invasive way. Exemplary embodiments of the present disclosure utilize a global positioning system to provide the location of the surgical  
20 port used during the laparoscopic procedure, as well as image data from the structure of interest to address such challenges.

Exemplary embodiments of the system can also include a surgical port, and one or more reference markers and tracking elements associated with a surgical tool and a camera. The surgical port may have a proximal end configured to be located outside the body of a  
25 patient and a distal end configured to be located within an internal portion of the body of the patient. The surgical port may also have a channel extending between the proximal end and the distal end. The surgical tool may be sized and configured to access the internal portion of the body of the patient through the channel of the surgical port. The reference markers may be located distal to the camera, and the tracking elements may be removably coupled to the  
30 surgical tool and a camera mounted to the proximal end of the surgical port may be configured to capture image data associated with the tracking element.

Another aspect of the present disclosure is directed to a method of tracking a surgical tool. The method may include providing a surgical tool to a surgical port where the surgical tool may include a tracking element and the surgical port may include a camera mounted

thereto. The method may further include capturing image data at the camera. The method may further include providing the image data to a processor and determining, at the processor, tracking information associated with the surgical tool.

5 A further aspect of the present disclosure is directed to an information management system for managing medical procedure information. The system may receive image data from a camera associated with a surgical port, the image data representative of a reference marker and/or a tracking element associated with a surgical tool. The image data is not associated with a particular finite set of known tools. The system may further determine an identity and a location of the surgical tool based on the image data. The system may also  
10 determine a surgical step of a medical procedure using the image data and determine procedure management information by comparing the image data associated with the surgical step with the medical procedure.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below.

15 Certain terminology is used in the following description are for convenience only and is not limiting. The words “right”, “left”, “lower”, and “upper” designate direction in the drawings to which reference is made. The words “inner”, “outer” refer to directions toward and away from, respectively, the geometric center of the described feature or device. The words “distal” and “proximal” refer to directions taken in context of the item described and,  
20 with regard to the instruments herein described, are typically based on the perspective of the surgeon using such instruments. The words “anterior”, “posterior”, “superior”, “inferior”, “medial”, “lateral”, and related words and/or phrases designate preferred positions and orientation in the human body to which reference is made. The terminology includes the above-listed words, derivatives thereof, and words of similar import.

25 In the following, the term “coupled” is defined as connected, although not necessarily directly, and not necessarily mechanically.

The use of the word “a” or “an” when used in conjunction with the term “comprising” in the claims and/or the specification may mean “one,” but it is also consistent with the meaning of “one or more” or “at least one.” The terms “about”, “approximately” or  
30 “substantially” means, in general, the stated value plus or minus 5%. The use of the term “or” in the claims is used to mean “and/or” unless explicitly indicated to refer to alternatives only or the alternative are mutually exclusive, although the disclosure supports a definition that refers to only alternatives and “and/or.”

The terms “comprise” (and any form of comprise, such as “comprises” and “comprising”), “have” (and any form of have, such as “has” and “having”), “include” (and any form of include, such as “includes” and “including”) and “contain” (and any form of contain, such as “contains” and “containing”) are open-ended linking verbs. As a result, a method or device that “comprises,” “has,” “includes” or “contains” one or more steps or elements, possesses those one or more steps or elements, but is not limited to possessing only those one or more elements. Likewise, a step of a method or an element of a device that “comprises,” “has,” “includes” or “contains” one or more features, possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

Other objects, features and advantages of the present invention will become apparent from the following detailed description. It should be understood, however, that the detailed description and the specific examples, while indicating specific embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will be apparent to those skilled in the art from this detailed description.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

Exemplary embodiments of the present disclosure are provided in the following drawings. The drawings are merely examples to illustrate the structure of exemplary devices and certain features that may be used singularly or in combination with other features. The invention should not be limited to the examples shown.

FIGS. 1-2 illustrate an initial three-dimensional image reconstruction of a structure of interest.

FIGS. 3-4 illustrate an image reconstruction annotated with landmarks or reference points.

FIGS. 5-6 a tissue deformation simulation is illustrated for a structure of interest.

FIG. 7 is a validation of a tissue deformation model for a structure of interest.

FIG. 8 is a schematic view of an example system configured for surgical tool global positioning;

FIG. 9 is view of example reference markers of the system of FIG. 8;

FIG. 10 is a schematic diagram of an example tool configured for use with the system of FIG. 8;

FIG. 11 is a schematic view of a tracking element configured for use with the tool of FIG. 10;

5 FIG. 12 is a schematic diagram of a surgical port of the system of FIG. 8;

FIG. 13 is a schematic of the surgical port of the system of FIG. 8 in a coordinate system;

FIG. 14 is a graph of the trajectory of a reference marker of the system of FIG. 8;

FIG. 15 is a schematic of the rotation of the surgical port of the system of FIG. 8;

10 FIG. 16 is a schematic of the relationship of the surgical port of the system of FIG. 8 to new image coordinates;

FIG. 17 is a schematic of the initial reconstruction of the coordinates of the surgical port of FIG. 8;

15 FIG. 18 is a photograph of the camera used to validate data acquired by the system of FIG. 8;

FIG. 19 is a schematic of the camera of FIG. 18.

FIG. 20 is a photograph of reference marks.

FIG. 21 is a photograph of reference marks before and after rotation.

FIG. 22 is a graph of a computational result with different angles.

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### **DETAILED DESCRIPTION**

Referring now to FIGS. 1-2, an initial three-dimensional image reconstruction 10 of a structure of interest 20 (e.g. a liver in this embodiment) is generated from image data obtained from a preoperative scan. In certain embodiments, the image data may be obtained via a computed tomography (CT) scanner, while in other embodiments the image data may be obtained from a magnetic resonance imaging (MRI) scanner. While a liver is shown as structure of interest 20 in this embodiment, it is understood that other embodiments may be directed to other anatomical structures.

As shown in the figures, initial three-dimensional image reconstruction 10 includes representations 22 of the Couinaud system, arteries, venous and hepatic ductal structures of structure of interest 20. As shown in FIGS. 3 and 4, image reconstruction 10 can be annotated with landmarks or reference points 25 that will be encountered during the planned laparoscopic procedure. In certain embodiments, reference points 25 can include the locations where hepatic arteries enter the liver and portal vein exit the liver, as well as the

transverse fissure of the liver which divides the left portion of the liver into four segments. Other exemplary embodiments may include reference points 25 such as gall bladder attachment location and the location of the hepatic lymph node. As shown in FIG. 4, still other reference points 25 may include, for example, the location where the falciform ligament  
5 which attaches the liver to the posterior portion of the anterior body wall, as well as the locations of the ligamentum venosum (ligamentum of Arancio) and the round ligament (ligamentum Teres). The foregoing list of reference points is merely exemplary, and other embodiments may comprise different reference points than those listed here.

Referring now to FIG. 5-6, a tissue deformation simulation is illustrated for a  
10 structure of interest 40 (e.g. a liver) from zero gravity to standard gravity with a support surface 30 comprising two articulated plates. The figures illustrate a simulation set up of the tissue mechanical deformation module, with an initial shape for structure of interest 40 shown in FIG. 5. The tissue deformation simulation for structure of interest 40 is shown in FIG. 6. Such a deformation can be used to simulate the changes in the shape of the structure of  
15 interest that may be encountered during a non-invasive procedure such as a laparoscopic surgery. Such procedures can make it difficult for the surgeon to visualize the shape of the structure of interest due to limited visual access. In exemplary embodiments, the simulation of the structure deformation can be established with boundary conditions that match the three-dimensional reconstruction from preoperative computer tomography data.

Referring now to FIG. 7, a validation of a tissue deformation model is illustrated  
20 utilizing a pig liver as structure of interest 40. The upper right portion of the figure shows structure of interest 40 on support surface 30 with two articulated plates. The solid line in FIG. 7 illustrates the tissue surface of structure of interest 40 before articulation of support surface 30, and tissue surface deformation as recorded in a magnetic resonance imaging  
25 (MRI). The dashed line in FIG. 7 illustrates the tissue deformation of structure of interest 40 after articulation of support surface 30 as modeled with a linear elastic model (LEM). Although the LEM utilized to generate the data shown in FIG. 7 can be computed in real-time, exemplary embodiments can utilize a hyper elastic model along with a reduction method. Such features can be implemented to combine accuracy and computational speed  
30 improvements in real-time accuracy.

Exemplary embodiments of the present disclosure can rely on a real-time navigation system that utilizes the image base simulation of the structure of interest deformation. Exemplary methods may comprise scanning a structure of interest to provide image data and generating a first three-dimensional reconstruction of the structure of interest based on the

image data. Exemplary methods can also comprise annotating the first three-dimensional reconstruction of the structure of interest with a plurality of reference points, and obtaining spatial coordinates of the plurality of reference points during a laparoscopic procedure. Furthermore, methods may comprise generating a second three-dimensional reconstruction of the structure of interest based on the spatial coordinates.

Referring now to FIGS. 8 - 9, a system 100 configured for surgical tool global positioning is displayed. As explained in further detail below, system 100 can be used to obtain position data for system components (e.g. a surgical tool or a camera coupled to a surgical port). The position data of the system components can be used to assist in obtaining spatial coordinates for reference points of the structure of interest.

In the embodiment shown, system 100 comprises a surgical port 110 comprising a proximal end 125 configured to be located outside a body of a patient 119 and a distal end 115 configured to be located within an internal portion of the body of patient 119. In the illustrated embodiment, surgical port 110 comprises a channel 117 extending between proximal end 125 and distal end 115.

In the embodiment of FIGS. 8-9, system 100 further comprises a plurality of reference markers 130 positioned at a first fixed location 140 distal to surgical port 110. In the embodiment shown, the plurality of reference markers 130 comprises individual reference markers 131-138. In particular embodiments, fixed location 140 may be positioned on the ceiling of a room in which surgical port 110 is located, including for example, a ceiling of an operating room.

In addition, the embodiment of system 100 shown comprises a camera 120 coupled to proximal end 125 of surgical port 110. In this embodiment, camera 120 comprises a field of view 122 configured to capture image data associated with one or more reference markers 131-138. As shown in FIG. 9, reference marker 131 may comprise a first segment 141 intersecting with a second segment 151 to form a cross shape. Similarly, reference marker 132 comprises intersecting segments 142 and 152, while reference marker 133 comprises intersecting segments 143 and 153. The remaining reference markers 134-138 can be similarly constructed. It is understood that the geometry, arrangement and number of reference markers shown is merely one example of several different configurations possible in embodiments of the present disclosure.

As explained in more detail below, image data associated with one or more reference markers 131-138 may be used to determine a global position of surgical port 110, as well as a tool inserted into surgical port 110. Certain embodiments can utilize camera 120 in a manner

similar to a “virtual optical pointer” to get accurate spatial coordinate of landmarks as they appear in the procedure. For each new set of landmarks that has been selected, system 100 can compute on demand (*e.g.* via a processor) the new three-dimensional map of the structure of interest that matches the landmark and visualizes the internal structure of interest.

5           With a new coordinate system, camera 120 can be used as a pointer to let system 100 register where the cut or resection should occur for the structure of interest. In exemplary embodiments, camera 120 can be directed toward a landmark, similar to how one would use a laser pointer in a presentation. Camera 120 may not include the capability of providing accurate three-dimensional spatial coordinates. However, surgical port 110 can provide the  
10           three-dimensional spatial coordinates of the camera 120 and its orthogonal optical axis (as explained in the discussion of FIGS. 8-9).

          The distance from the camera 120 to the point of interest along that axis on the surface of a structure of interest needs to be computed in order to complete the registration. There are multiple ways of providing such information. For example, a hardware solution  
15           may comprise laser measurement or acoustic wave measurement. Furthermore, a software solution may be implemented using a passive autofocus technique that for example increases the local pixel contrast, or any similar algorithmic technique to get the depth map. Still other embodiments may utilize a hybrid solution by projecting two light spots from some fixed optical fibers coupled to the surgical port 110, and using the known view angle of the  
20           endoscope camera to give this distance accurately.

          In certain exemplary embodiments, the number of constraints in the tissue mechanical problem set up from landmark identifications should be larger than needed to provide redundancy. If matching the structure of interest position to the landmark generates too much local mechanical stress in the simulation, the system can interpret that result as a fault, and  
25           may require new recalibration of the landmark to the operator.

          Once the structure of interest position has been recalculated, one can use the surgical port 110 to tentatively show the location of a planned resection: the system may then compute estimates of the margin to structure such as vessel that should be preserved, or volume of the tissue that will be removed or even negative margin for tumor removal. In  
30           exemplary embodiments, the plan for cut can be set in the new coordinate system at that step of the intervention with the updated position of the structure of interest.

          It is anticipated that exemplary embodiments can be even more powerful if used with existing methods that are not fully satisfactory as standalone solution. For example, pattern recognition on the structure of interest surface image of the endoscope is not a robust method

by itself. However, the same method combined with landmark annotation according to exemplary embodiments would perform better since it becomes a local optimization mathematical problem as opposed to a global mathematical one that has to deal with many local optimums. Laparoscopic ultrasound (LUS) also provides local information on  
5 localization that complements registration techniques based on spatially distributed landmarks according to exemplary embodiments. LUS that comes with elastography measurements can also improve image base tissue deformation models by providing more accurate tissue properties to feed the mechanical model.

Systems and methods to provide global position and orientation coordinates will be  
10 described in the discussion of FIGS. 8-22. As previously mentioned, image data associated with one or more reference markers 131-138 may be used to determine a global position of surgical port 110, as well as a tool inserted into surgical port 110.

Referring now to FIG. 10, a tool 200 is configured for insertion into surgical port 110 (shown in FIG. 8). In this embodiment, a tracking element 210 is coupled to surgical tool  
15 200. As shown in FIG. 10, tracking element 210 is circular in shape and includes a pattern of geometric shapes on one side (*e.g.* segments of a circle in this embodiment). During use, tool 200 may be inserted into surgical port 110 such that the circular shape and pattern of tracking element 210 can be detected by camera 120. In certain embodiments, tracking element 210 may be configured similar or equivalent to the tool identification marker as disclosed in U.S.  
20 Patent Serial No. 14/099,430, incorporated by reference herein. Particular embodiments may also comprise separate cameras for detecting image data associated with tracking element 210 and reference markers 131-138.

In exemplary embodiments, surgical port 110 can be placed into an incision in the body of patient 119 and provide an access point through which surgical instruments may be  
25 introduced into an internal surgical site. In certain embodiments, surgical port 110 can include a needle, a cannula, a trocar, or any other style of surgical port known in the art. Surgical port 110 can be composed of a biocompatible material. It is contemplated that the surgical port 110 can be constructed from a disposable material thereby reducing cost and avoiding problems of sterilization and battery change. Surgical port 110 can have a proximal  
30 end 125 configured for location on the outside of the patient's body and a distal end 115 sized and configured to extend into the internal portion of the patient's body. Channel 117 can extend through surgical port 110 to provide access to an internal portion of the patient's body such that a surgical tool 200 (*e.g.* a laparoscope, endoscope or other tool as shown in FIG. 10), can be inserted into the patient's body via channel 117.

Exemplary embodiments of surgical tool tracking system 100 can include a camera 120 mounted to proximal end 125 of surgical port 110. Camera 120 can capture visible spectrum and/or infra-red light or include any other imaging modality suitable for use with surgical procedures. Camera 120 can be configured to capture and store video and/or still  
5 images. Camera 120 may also be configured to capture and store audio data. Camera 120 can be configured to capture image data associated with reference markers 130 and tracking element 210 including still and/or video images. Camera 120 may be further configured to capture image data associated with a surgeon performing the medical procedure. For example, camera 120 can capture image data providing surgeon-identifying information such  
10 as a surgeon-specific tracking element or marker. An example surgeon-specific marker can include a particular colored glove worn during the medical procedure. The image data associated with the surgeon can also include motion information with respect to surgical tool 106 and/or the surgeon's hand. The motion information can be used to track the motion/path of the surgeon's hands and/or surgical tool 106 during the medical procedure.

15 In certain exemplary embodiments, camera 120 can be coupled to surgical port 110 via mounting to base 114 of proximal end 125. In other exemplary embodiments, camera 120 can be incorporated with or otherwise integral to base 114. The location of camera 120 with respect to the surgical port 110 can be fixed such that camera 120 can be mounted to or otherwise incorporated into the base 114 at a fixed and set position. In other embodiments,  
20 the location of camera 120 can be changed or adjusted with respect to surgical port 110. For example, camera 120 can be mounted to base 114 using an adaptor that controls the position and orientation of camera 120.

In certain embodiments, camera 120 can be mounted to the base 114 such that the optical lens/field of view of camera 120 is directed away from the body of the patient. For  
25 example, camera 120 can be mounted to the base 114 such that the optical lens/field of view of camera 120 is provided in a direction of reference markers 131-138, tracking element 210 and/or the surgeon's hand as surgical tool 200 approaches and/or is inserted into surgical port 110. In a further example, camera 120 can be mounted to base 114 such that the optical lens/field of view of camera 120 is both directed away from the body of the patient and in a  
30 direction of reference markers 131-138, tracking element 210 and/or the surgeon's hand as surgical tool 200 approaches and/or is inserted into surgical port 110. For example, it is contemplated that the optical lens/field of view of camera 120 can be configured to capture image data of reference markers 131-138, tracking element 210 and/or surgeon's hand as surgical tool 106 approaches and is located within surgical port 110.

In particular embodiments, camera 120 can include a light element for illuminating reference markers 131-138, tracking element 210 and/or the surgeon. For example, light element can include an ultraviolet LED that illuminates a UV sensitive feature on reference markers 131-138 and/or tracking element 210. The use of a non-visible light range should not disturb a surgeon preferring to operate in low light conditions. Use of the a UV sensitive feature on reference markers 131-138 and/or tracking element 210 can also have positive effects on the recognition process because reference markers 131-138 and tracking element 210 will appear to the system a bright and colorful item in the image, thus making it more distinguishable from the background and/or image noise.

In certain embodiments, camera 120 may be capable of operating on a wired or wireless communication network. Camera 120 may be configured to communicate with other devices using the communication network, the other devices including computers, personal data assistants (PDAs), mobile telephones, and mobile computers. For example, tracking system 100 can include a computer system (not shown). Camera 120 can be in communication with the computer system to transmit image data to the computer system for analysis and/or storage. Tracking system 100 may include other components capable of acquiring, storing, and/or processing any form or type of data. Any such component may be coupled to or integrated into base 114 or may be communicatively coupled to tracking system 100 and/or the computer system.

As explained in further detail below, image data obtained by camera 120 and associated with reference markers 131-138 can be used to calculate a global position of laparoscopic tool 200. In the mathematical equations presented herein, it is assumed that the geometry and shape of laparoscopic tool 200 with precise measurement is known. In principle, this information can be provided by the vendor for tool 200. It is also assumed tracking element 210 has a rigid attachment to the tool and is perpendicular to the axis of the tool. The location of the tracking element 210 on the axis is known as shown in FIG. 10.

The motion of laparoscopic tool 200 is channeled by surgical port 110. The motion can be decomposed into: (a) a translation along the main axis of surgical port 110; and (b) a small deviation from the port axis allowed by the difference in diameters between surgical port 110 and tool 200.

The position of the tool 200 in a coordinate system coupled to surgical port 110 can then be determined. If the axis of tool 200 is perfectly aligned to the axis of surgical port 110, the distance from tracking element 210 to surgical port 110 can be computed from the apparent diameter of tracking element 210 in the image data (*e.g.* video stream). If the port

and tool axes are not aligned, tracking element 210 will appear as an ellipse, instead of a circle, in the image data. The axis of the ellipse small diameter and the axis of laparoscopic tool 210 can provide the plan of the rotation.

The ratio of the largest diameter of the ellipse to the smallest diameter of the ellipse can provide the angle  $\alpha$  via a basic trigonometric formula (see FIG. 11). In practice,  $\alpha$  will be small because the diameter of tool 200 is close to that of surgical port 110. For example, a port that is 5 inches in length with a diameter 2 mm larger than the inserted tool will result in a maximum angle  $\alpha$  of approximately 1 degree. Based on the geometric constraints and formulas described above, it is possible to localize an end of tool 200 in a coordinate system coupled to surgical port 110.

Surgical port 110 can have complex motion in three dimensions. Referring now to FIG. 12, the body of a patient 119 has elasticity, and port 110 can change angle in two independent spatial directions. The motility of patient 119 (*e.g.* an abdominal wall) can be used by the surgeon to direct the end of tool 200 in the region of interest (ROI). The orientation of the axis of port 110 in the (x, y, z) coordinate system of the operating room corresponds to two unknown angles denoted  $\Theta$  and  $\Phi$  in FIG. 13. In addition, patient 119 or the support surface (*e.g.* operating room table) can move during the procedure due to breathing or other movements. Larger movements may correspond to the fact that the surgeon modified the angle of inclination of the support surface to facilitate access to the region of interest. The displacement of location at which port 110 enters patient 119 in three spatial directions is denoted by  $dx$ ,  $dy$ , and  $dz$ .

Referring now to FIG. 14, image data (*e.g.* captured by camera 120) associated with a cross-shaped reference marker (*e.g.* one of reference markers 131-138) is displayed. From this image data, one can extract the trajectory of five points corresponding to the end points of the intersecting segments and the center of the reference marker. This trajectory corresponds to the motion of surgical port 110. As shown in the sections below entitled “A1 Method” and “A2 Experiment”, mathematical calculations can be performed to determine  $\Theta$ ,  $\Phi$ ,  $dx$ ,  $dy$ , and  $dz$ . With these values known, one can then reconstruct the spatial trajectory of surgical port 110 in a coordinate system established, for example, in an operating room.

Combining the above parameters and calculations can provide a complete three-dimensional, real-time positioning system for a rigid laparoscopic tool and the tip or end of the tool.

In general, if the tool has mobile parts such as a scissor insert as shown in FIG. 10, one will need to identify the motion of the mobile parts versus the main body of the tool. In

many cases, this can be done with a single degree of freedom. One can reconstruct the angle of the opening of the scissor from the image data (*e.g.* video streaming from an endoscope) to fully reconstruct the position of the tool. Simulated results indicate that accuracy can be obtained on the order of one millimeter for the position of a tool inside an abdominal cavity, and preliminary experimental results confirm the theoretical result.

In certain embodiments, the view angle of camera 120 may be limited and/or obstructed. It may therefore be desirable to include a plurality of reference markers on the ceiling of the operating room. Such a configuration can help to ensure that the system has sufficient input data and can ensure accuracy since the system can use redundant computation. In certain embodiments, the least square fitting method can be used to limit the impact of errors in the pattern recognition of the reference markers. This redundancy may also be used to correct optical distortion when the reference markers are far from the optical axis of the camera. Similarly, in the unlikely event that the surgical port rotates in the plan perpendicular to its axis, one can retrieve the angle of rotation ( $\psi$ ) as shown in FIG. 12, since there will be multiple reference marker shapes (*e.g.* crosses of intersecting segments) to reconstruct the additional unknown.

It has been observed that an approximation of the position of a patient abdominal wall can be obtained by virtue of the smart trocars attached to the wall. Provided that one has a three-dimensional reconstruction of the anatomy of the patient in the operating room, one can position the tip of the laparoscopic tool with respect to anatomical structures. The operating room system should then be able to provide information to the surgeon on locations that should not be crossed by the crossed by the laparoscopic tool (*e.g.* a “secure no fly zone” used in training, but not currently in actual clinical conditions). Similarly, if an optimum access position has been decided during preparation of the operation, the system can guide the surgeon to that optimum maneuver.

Embodiments disclosed herein provide a low cost system that does not require new techniques from the surgeon. In addition, the system is robust and accurate, can be installed in a standard operating environment. The system also does not present additional risks to patients.

It is understood that the methods and mathematical models described in the sections below are exemplary of one embodiment, and that other embodiments are contemplated in this disclosure. For example, while a trocar is referenced in the discussion below, other types of surgical ports may be used in other embodiments.

## A1 Method

For clarity, most of the mathematical presentation below is restricted first to motion in the vertical plan (x,z) that contain trocar. We will discuss briefly second the generalization to three spacial dimension in the (x,y,z) coordinate system of the OR.

### Rotation:

Let us consider a rotation of the trocar clockwise in the (x,z) plan. We note this rotation  $\mathcal{T}_\theta$ . The trocar has a fixed point that is the center of the rotation. Let us assume that the trocar and the marker denoted by the triplet  $(x_{-1}, x_0, x_1)$  are in the same vertical plan.

We consider first the direct problem: given  $\theta$ , what would be the position of the marker in the new image?

In the new coordinate system  $(\tilde{x}, \tilde{y})$  - see Figure 15 - the coordinate of the marker  $(\tilde{x}_{-1}, \tilde{x}_0, \tilde{x}_1)$ , is, for  $j = -1, 0, 1$  :

$$\tilde{x}_j = \cos(\theta) (-H \tan(\theta) + x_j), \quad (1)$$

$$\tilde{y}_j = \sin(\theta) (-H \tan(\theta) + x_j), \quad (2)$$

Let us denote  $\Theta_c$  the view angle of the camera - see Figure 16 - The physical dimension of the new image frame is  $(-\tilde{L}, \tilde{L})$ , on the line  $\tilde{y} = \tilde{y}_j$ , is:

$$\tilde{L} = \tan\left(\frac{\Theta_c}{2}\right) \left( \frac{H}{\cos(\theta)} + \tilde{y}_j \right). \quad (3)$$

The position of the marker  $x_j$  in the image  $(-1, 1)$  will be

$$\tilde{I}_j = \frac{\tilde{x}_j}{\tilde{L}}. \quad (4)$$

For any landmark of coordinate  $x_j$  in the initial image, the map

$$\theta \longrightarrow \tilde{I}(x_j)$$

for the range of rotation we do consider is bijective. As a matter of fact this map is a strictly decreasing function of  $\theta$ . The inverse problem consist to solve the non linear set of equation (1) to (4) with for example a Newton scheme.

However we have assumed that the initial position of the trocar in the OR was given. Let us show that this problem can be solved with two landmarks - See Figure 17. The two unknown are the physical location of point  $O$  at the vertical of the trocar and the distance between the trocar and the ceiling denoted  $H$ . For simplicity we will still restrict ourselves to the (x,z) plan. The generalization to 3d is straightforward.

To start we get the coordinate  $I_0$  and  $I_1$  of the landmark  $x_0$  and  $x_1$  in the image. We know also a priori the physical dimension  $d = x_1 - x_0$ , of our marker.

We have:

$$\tan(\theta_0) = \frac{x_0}{H}, \tan(\theta_1) = \frac{x_1}{H}, \tan\left(\frac{\theta_c}{2}\right) = \frac{L}{H}. \quad (5)$$

and

$$x_0 = I_0 L, \quad x_1 = I_1 L. \quad (6)$$

We obtain:

$$H = d \left( (I_1 - I_0) \tan\left(\frac{\theta_c}{2}\right) \right)^{-1}.$$

and

$$x_0 = I_0 H \tan\left(\frac{\theta_c}{2}\right), \quad x_1 = I_1 H \tan\left(\frac{\theta_c}{2}\right).$$

This conclude the reconstruction of the rotation of the trocar by tracking the landmarks on the ceiling.

However the motion of the trocar can be more complex and involve two translations in respectively  $x$  and  $z$  direction. We will denote  $dx$  and  $dz$  this displacement and as before  $\theta$  the rotation.

#### Translation:

To take into account these two translations, denoted  $\mathcal{T}_{dx}$  and  $\mathcal{T}_{dz}$ , the landmark of initial coordinate  $x_j$  has for new coordinates

$$\tilde{x}_j = \cos(\theta) (-H - dz \tan(\theta) + x_0 - dx), \quad (7)$$

$$\tilde{y}_j = \sin(\theta) (-H - dz \tan(\theta) + x_0 - dx), \quad (8)$$

We have now three unknowns that are  $dx$  and  $dy$  and  $\theta$ . We need then three landmarks. We needs to solve the nonlinear set of equations with the image coordinate  $I_{-1}, I_0, I_1$  from three landmarks. We can use a Newton scheme to solve numerically that non linear problem, since we can explicitly compute the Jacobian of the system. So far we have restricted ourselves to two space dimension and we worked with a combination of three geometric transform:

$$\mathcal{T}_\theta \circ \mathcal{T}_{dx} \circ \mathcal{T}_{dz}.$$

A similar reasoning can be applied in three space dimensions. We consider the three d coordinate system  $(x, y, z)$  of the OR. We work with the transformation:

$$\mathcal{T}_\theta \circ \mathcal{T}_\phi \circ \mathcal{T}_{dx} \circ \mathcal{T}_{dy} \circ \mathcal{T}_{dz}.$$

We need then to identify 5 unknowns  $\theta, \phi, dx, dy, dz$  and will need 5 landmarks. We wrote with a matlab code a small simulator based on a cross motif - see Figure 15. This code applies successively each transformation to the image viewed from the trocar. This simulator help us to compute the sensitivity of the system. Let us assume that the image comes with a resolution of 500 pixels in each dimension. One can show from simulation that an accumulated error of 4 pixel in each spatial direction will result in an error of about 1 mm at the end of the laparoscopic tool. This error is very small indeed because the relative distance from the trocar to the ceiling is much larger than from the trocar to the ROI inside the abdomina cavity.

The exact accuracy of the system needs to be checked with an experiment that will carry various type of uncertainties, from optical defect of the camera, imperfection in focussing, and noise in the image segmentation of the landmark. We expect

however to have a fairly robust and accurate result from our design. Next we will present some preliminary experimental results that validate our approach.

## A2 Experiment

Our goal here is to validate the quality of the method to reconstruct *separately* each component of the motion of the trocar, from tracking the landmark on the ceiling.

### Rotation:

Let's start with the rotation component in one space direction. Figures 18 and 19 show a rapid prototyping to check that result.

We have set on the ceiling two black crosses that are visible from the digital camera - see Figure 20. We set first the camera in the flat position, and measure on the wall the height of the laser beam projection. We shoot in that position an image of the ceiling - see Figure 21 on left. The auto focuss option of the camera was turned off. The image of the ceiling is somehow out of focuss. We made this image noisy on purpose to get more realistic conditions.

We set second the camera in a position that forms a small angle with the desk as in Figure 18. We measure on the wall the new position of the laser beam projection. From these two measures on the wall, we get the angle  $\alpha$  with an accuracy of about  $0.5^\circ$ . We shoot in that new position an image of the ceiling - see Figure 21 on right.

We observe indeed the displacement of the markers due to the change of orientation of the camera.

We apply then our algorithm to reconstruct the angle  $\alpha$  from these two images: first we compute the coordinate of the three points A, B and C using the graphic interface of the GIMP2 software. An automatic image segmentation will be actually more accurate.

Second we map the transform we defined earlier

$$\theta \longrightarrow \tilde{I}(x_j)$$

and look for the angle that minimize the matching between the computed coordinate of the point A, B and C after rotation, in the L2 norm - Figure 22. Our result are for  $\alpha = 5.3^\circ$  and  $\alpha = 9.6^\circ$ . Our algorithm based on computer vision gives:  $\alpha = 4.4^\circ$  and  $\alpha = 9.2^\circ$ . We did this experiment several time, and observe a good reliability of the method

In other words we get an error of less than a degree on the trocar position. This may represent an error on the lateral position of the tip of a laparoscopic tool of the order of 3 mm for a ROI with a 20cm depth from the abdominal wall.

### Translation:

Next let us consider a different displacement of the trocar that can be for example resulting from the patient breathing.

We have run a similar experiment to check the accuracy of a displacement of the "trocar" in the vertical direction  $z$  toward the ceiling. Here the camera stays flat, and we change the thickness of the support, to increase the height of few centimeters. Lets denote  $\delta z$  the increase in thickness of the support. For  $\delta z = 2 \text{ cm}$  we get from our computer vision algorithm a computed value of  $\delta z = 1.62 \text{ cm}$ . Similarly for  $\delta z = 3 \text{ cm}$  we get from our computer vision algorithm a computed value of  $\delta z = 3.23 \text{ cm}$ . Overall the error on the vertical displacement is less than

4 mm. We suspect that we can improve much that result by using landmarks separated by larger distances.

\*\*\*

While the foregoing description and drawings represent examples of the present invention, it will be understood that various additions, modifications, combinations and/or  
5 substitutions may be made therein without departing from the spirit and scope of the present invention as defined in the accompanying claims. In particular, it will be clear to those skilled in the art that the present invention may be embodied in other specific forms, structures, arrangements, proportions, and with other elements, materials, and components, without departing from the spirit or essential characteristics thereof. One skilled in the art  
10 will appreciate that the invention may be used with many modifications of structure, arrangement, proportions, materials, and components and otherwise, used in the practice of the invention, which are particularly adapted to specific environments and operative requirements without departing from the principles of the present invention. In addition, features described herein may be used singularly or in combination with other features. The  
15 presently disclosed examples are, therefore, to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims and not limited to the foregoing description.

It will be appreciated by those skilled in the art that changes could be made to the examples described above without departing from the broad inventive concept thereof. It is  
20 understood, therefore, that this invention is not limited to the particular examples disclosed, but it is intended to cover modifications within the spirit and scope of the present invention, as defined by the following claims.

## REFERENCES

The contents of the following references are incorporated by reference herein:

- 5 U.S. Provisional Patent Application 61/734,506.  
WO 2014/089439.

3D IRCAD Liver Data Base <http://www.ircad.fr/software/3Dircadb/3Dircadb1/?lng=en>

- 10 Agarwal S, Joshi A, Finin T, Yesha Y (2007). A Pervasive Computing System for the Operating Room of the Future. *Mobile Networks and Applications*; 12:215-28.
- Aggarwal R, Moorthy K, and Darzi A (2004). Laparoscopic skills training and assessment. *Br J Surg*; Vol. 91, No. 12, pp. 1549-58.
- Allan M, Ourselin S, Thompson S, Hawkes DJ, Kelly J and Stoyanov D (2013).
- 15 Toward detection and localization of instruments in minimally invasive surgery. *Biomedical Engineering. IEEE Transactions*; Vol. 60, No. 4, pp. 1050-1058.
- Asano, TK, Soto, C, Poulin EC, Mamazza J, and Boushey RP (2011). Assessing the impact of a 2-day laparoscopic intestinal workshop. *Can J Surg*, 4, pp. 223-6.
- Bano J, Hostettler A, Nicolau S, Cotin S, Doignon C, Wu HS, Huang MH, Soler L,
- 20 Marescaux J (2012). Simulation of Pneumoperitoneum for Laparoscopic Surgery Planning. *MICCAI*; Vol. 7510, pp. 91-98.
- Bardram JE, Doryab A, Jensen RM, Lange PM, Nielsen KLG, and Petersen ST (2011). Phase recognition during surgical procedures using embedded and body-worn sensors. *PerCom*; pp. 45-53.
- 25 Blasinski H, Nishikawa A, and Miyazaki F (2007). The application of adaptive filters for motion prediction in visually tracked laparoscopic surgery. *Robotics and Biomimetics, ROBOT 2007; IEEE International Conference*; pp.360-365.
- Blum T, Padoy N, Feussner H, and Navab N (2008). Modeling and online recognition of surgical phases using Hidden Markov Models. *Med Image Comput Comput Assist Interv*;
- 30 11:627-35.
- Blum T, Padoy N, Feussner H, Navab N. (2008). Modeling and online recognition of surgical phases using Hidden Markov Models. *Med Image Comput Comput Assist Interv*; 11:627-35.

Breedveld P, Stassen H, Meijer DW, and Jakimowicz JJ (2000). Observation in laparoscopic surgery: overview of impeding effects and supporting aids. *J Laparoendosc Adv Surg Tech*; Vol. 10, No. 5, pp. 231-41.

Bucholz RD, Yeh DD, Trobaugh J, McDurmott LL, Sturm CD, Baumann C,  
5 Henderson JM, Levy A, and Kessman P. (1997). The correction of stereotactic inaccuracy caused by brain shift using an intraoperative ultrasound device. *Lecture Notes in Computer Science (MICCAI)*; Vol. 1205, No. 1997, pp. 459–66.

Carter TJ, Sermesant M, Cash DM, Barratt DC, Tanner C, and Hawkes DJ (2005). Application of soft tissue modelling to image-guided surgery. *Med Eng Phys*; Vol. 27, No.  
10 10, pp. 893-909.

Climent J and Mares P. (2003). Real-time tracking system for assisted surgical operations. *Latin America Transactions, IEEE (Revista IEEE America Latina)*; 1(1):8-14.

Colombo, JR, Haber, GP Jr, Rubinstein M, and Gill IS (2006). Laparoscopic surgery in urological oncology: brief overview. *Int Braz J Urol*; 32(5):504-12.

15 Doryab A, and Bardram JE (2011). Designing activity-aware recommender systems for operating rooms. *Proceedings of the Workshop on Context-awareness in Retrieval and Recommendation*, pp; 43-6.

Doryab A, Togelius J, and Bardram J (2012). Activity-aware recommendation for collaborative work in operating rooms. *Proceedings of the ACM international conference on*  
20 *Intelligent User Interfaces*; pp. 301-4.

Dutkiewicz P, Kielczewski M, and Kowalski M. (2004). Visual tracking of surgical tools for laparoscopic surgery. *Robot Motion and Control, 2004. RoMoCo'04. Proceedings of the Fourth International Workshop*; pp. 23-28.

Dutkiewicz P, Kietczewski M, Kowalski M, and Wroblewski W (2005).  
25 Experimental verification of visual tracking of surgical tools. *Robot Motion and Control, RoMoCo '05. Proceedings of the Fifth International Workshop*; pp. 237-242.

Estebanez B, del Saz-Orozco Rivas PI, Bauzano E, Muoz VF and Garcia-Morales I, (2012). Maneuvers recognition in laparoscopic surgery: Artificial Neural Network and hidden Markov model approaches. *4th IEEE RAS & EMBS International Conference on Biomedical*  
30 *Robotics and Biomechatronics*; pp. 1164-1169.

Fasquel J, Brocker G, Moreau J, Agnus V, Papier N, Koehl C, Soler L, and Marescaux J (2006). A Modular and Evolutive Software for Patient Modeling Using Components, Design Patterns and a Formal XML-Based Component Management System. *CBMSm 19<sup>th</sup> IEEE International Symposium*; pp. 43-50.

Franco D, (2001), Right hepatectomy, *WeBSurg.com*; 1(12).

Garbey, M, Salmon R, Thanoon D, Bass B (2013). Multiscale Modeling and Distributed Computing to Predict Cosmesis Outcome After a Lumpectomy. *J. Comput. Physics*; 244: 321-335.

5 Gould J, and Frydman J (2007). Reverse-alignment surgical skills assessment. *Surgical Endoscopy*; Vol. 21, No. 4, pp. 669-671.

Hawkes DJ, Barratt D, Blackall JM, Chan C, Edwards PJ, Rhode K, Penney GP, McClelland J and Hill DLG. (2005). Tissue deformation and shape models in image-guided interventions: a discussion paper. *Medical Image Analysis*; Vol. 9, No. 2, pp. 163-75.

10 Herron D, Gagner M, Kenyon T, and Swanström, L (2001). The minimally invasive surgical suite enters the 21st century. *Surgical Endoscopy*; Vol. 15, No. 4, pp. 415-422.

Hodgson AJ, Pantazopol, RA, Visser, MD, Salcudean, SE, and Nagy, AG, (1997). "Assessing potential benefits of enhanced dexterity in laparoscopic surgery." *Engineering in Medicine and Biology Society. Proceedings of the 19<sup>th</sup> Annual International Conference of the IEEE*; Vol. 5, pp. 1966-1969.

Ikuta K, Kato T, Ooe H, and Ando S. (2007). Surgery recorder system for recording position and force of forceps during laparoscopic surgery. *Advanced intelligent mechatronics, 2007 IEEE/ASME international conference*; pp. 1-6.

Jakimowicz JJ, and Ruers TJM (1991). Ultrasound-Assisted Laparoscopic Cholecystectomy: Preliminary Experience. *Dig Surg*; Vol. 8(2), pp. 114-17.

Jakimowicz JJ. (2006). Intraoperative ultrasonography in open and laparoscopic abdominal surgery: an overview. *Surg Endosc*, Vol. 20 Suppl 2, pp. S425-35.

Konishi K, Nakamoto M, Kakeji Y, Tanoue K, Kawanaka H, Yamaguchi S, Ieiri S, Sato Y, Maehara Y, Tamura S, and Hashizume M. (2007). A real-time navigation system for laparoscopic surgery based on three-dimensional ultrasound using magneto-optic hybrid tracking configuration. *IJCARS*; Vol. 2, No. 1, pp. 1-10.

Kranzfelder M, Schneider A, Blahusch G, Schaaf H, and Feussner H (2009). Feasibility of opto-electronic surgical instrument identification. *Minim Invasive Ther Allied Technol*; 18(5):253-8.

30 Kranzfelder M, Schneider A, Gillen S, and Feussner H (2011). New technologies for information retrieval to achieve situational awareness and higher patient safety in the surgical operating room: the MRI institutional approach and review of the literature. *Surg Endosc*; Vol. 25, No. 3, pp. 696-705

Kühnapfel U, Çakmak HK, and Maass H. (2000). Endoscopic surgery training using virtual reality and deformable tissue simulation. *Computer & Graphics*, Vol. 24, No., pp. 671-82.

Langø T, Tangen GA, Mårvik R (2012). Navigated ultrasound in laparoscopic surgery. *Advances in Laparoscopic Surgery*; pp.77-98.

Liu CC, Chang CH, Su MC, Chu HT, Hung SH, JWong JM, and Wang PC (2010). RFID-initiated workflow control to facilitate patient safety and utilization efficiency in operation theater. *Comput Methods Programs Biomed*; 3, pp. 435-42.

Liu CC, Chang CH, Su, MC, Chu HT, Hung SH, Wong JM and Wang P-C (2011). RFID-initiated workflow control to facilitate patient safety and utilization efficiency in operation theater. *Comput Methods Programs Biomed*; 104(3):435-42.

Mackay S, Datta V, Chang A, Shah J, Kneebone R, and Darzi A (2003). Multiple Objective Measures of Skill (MOMS): a new approach to the assessment of technical ability in surgical trainees. *Ann Surg*; 2, pp. 291-300.

Mahmoud N, Nicolau S, Keshk A, Ahmad MA, Soler L, Marescaux J (2012). Fast 3D Structure From Motion with Missing Points from Registration of Partial Reconstructions. *AMDO*; pp. 73-183.

Marjamaa R, Vakkuri A, and Kirvelä O (2008). Operating room management: why, how and by whom? *Acta Anaesthesiologica Scandinavica*; 52:596-600.

Mårvik R, Langø T, Tangen GA, Andersen JO, Kaspersen JH, Ystgaard B, Sjølie E, Fougner R, Fjøsne HE, and Hernes TA. (2004). Laparoscopic navigation pointer for 3-D image guided surgery. *Surg Endosc*; Vol. 18, No. 8, pp. 1242-8.

Nakamoto M, Hirayama H, Sato Y, Konishi K, Kakeji Y, Hashizume M, and Tamura S. (2007). Recovery of respiratory motion and deformation of the liver using laparoscopic freehand 3D ultrasound system. *Medical Image Analysis*; Vol. 11, No. 5, pp. 429-42.

Nakamoto M, Nakada K, Sato Y, Konishi K, Hashizume M, and Tamura S (2008). Intraoperative Magnetic Tracker Calibration Using a Magneto-Optic Hybrid Tracker for 3-D Ultrasound-Based Navigation in Laparoscopic Surgery. *Medical Imaging, IEEE Transactions*; 27(2):255-270.

Navarro AA, Hernansanz A, Villarraga EA, Giralt X, and Aranda J (2007). Enhancing Perception in Minimally Invasive Robotic Surgery through Self-Calibration of Surgical Instruments. *Engineering in Medicine and Biology Society, EMBS 2007, 29th Annual International Conference of the IEEE*; pp. 457-460.

Neumuth D, Loebe F, Herre H, and Neumuth T (2011). Modeling surgical processes: a four-level translational approach. *Artif Intell Med. Netherlands*; 51(3):147-61.

Neumuth T, Jannin P, Schlomberg J, Meixensberger J, Wiedemann P, and Burgert O (2011). Analysis of surgical intervention populations using generic surgical process models.  
5 *Int J Comput Assist Radiol Surg*; 6:59-71.

Neumuth T, Jannin P, Strauss G, Meixensberger J, and Burgert O (2009). Validation of knowledge acquisition for surgical process models. *J Am Med Inform Assoc*; 16(1):72-80.

Neumuth T, Strauss G, Meixensberger J, Lemke H, and Burgert O (2006). Acquisition of Process Descriptions from Surgical Interventions. *Database and Expert*  
10 *Systems Applications*; pp. 602-11.

Nicolau S, Mendoza-Burgos L, Soler L, Mutter D, Marescaux J (2008). In Vivo Evaluation of a Guidance System for Computer Assisted Robotized Needle Insertion Devoted to Small Animals. *MIAR*; pp 241-250.

Padoy N, Blum T, Ahmadi S-A, Feussner H, Berger M-O, and Navab N (2012).  
15 Statistical modeling and recognition of surgical workflow. *Medical Image Analysis*; 16:632-41.

Payandeh S, Xiaoli Z, and Li A. (2001). Application of imaging to the laproscopic surgery. *Computational Intelligence in Robotics and Automation, Proceedings 2001, IEEE International Symposium*; pp. 432-437.

Reddy SK, Tsung A, Geller DA. (2010) Laparoscopic Liver Resection. *World Journal of Surgery*; 35:1478-1486.  
20

Reinertsen I, Lindseth F, Unsgaard G, and Collins DL (2007). Clinical validation of vessel based registration for correction of brain-shift. *Medical Image Analysis*; 11(6):673-84.

Richardson W, Stefanidis D, Mittal S, and Fanelli RD (2010). SAGES guidelines for  
25 the use of laparoscopic ultrasound. *Surg Endosc*; 24:745-56.

Sarker SK, Chang A., and Vincent C (2006). Technical and technological skills assessment in laparoscopic surgery. *JSLs*; Vol. 10, No. 3, pp 284-92.

Scheuring M, Schenk A, Schneider A, Preim B, and Greiner G. (2003). Intraoperative Augmented Reality for Minimally Invasive Liver Interventions. *Proc SPIE*;  
30 Vol. 5029, pp. 407-17.

*Schoepp H. Surgical Navigation System* (2012).

Shahidi R, Bax MR, Maurer CR, Johnson JA, Wilkinson EP, Wang B, West, JB, Citardi MJ, Manwaring KH and Khadem R (2002). Implementation, Calibration and

Accuracy Testing of an Image Enhanced Endoscopy System. *IEEE Trans Med Imaging*; Vol. 21, No. 12, pp. 1524-35.

*Society of American Gastrointestinal and Endoscopic Surgeons*,  
<http://www.sages.org/>

5 Soler L, Nicolau S, Fasquel J, Agnu V, d Charnoz A, Hostettler A, Moreau J, Forest C, Mutter D, and Marescaux J (2008). Virtual reality and augmented reality applied to laparoscopic and notes procedures. *ISBI*; pp. 1399-1402.

10 Staub C, Lenz C, Panin G, Knoll A, and Bauernschmitt R (2010). Contour-based surgical instrument tracking supported by kinematic prediction. *Biomedical Robotics and Biomechatronics (BioRob), 2010 3rd IEEE RAS and EMBS International Conference*; pp. 746-752.

Stoll J, Ren H and Dupont PE (2012). Passive Markers for Tracking Surgical Instruments in Real-Time 3-D Ultrasound Imaging. *IEEE Transactions on Medical Imaging*; Vol. 31, No. 3, pp. 563-575.

15 Tatar F, Mollinger J, Bossche A (2003). Ultrasound system for measuring position and orientation of laparoscopic surgery tools. *Sensors, Proceedings of IEEE*; Vol. 2, pp. 987-990.

20 Tatar F, Mollinger JR, Bastemeijer J, and Bossche A (2004). Time of flight technique used for measuring position and orientation of laparoscopic surgery tools. *Sensors, 2004. Proceedings of IEEE*, p. 1596.

Thanoon D, Garbey M. and Bass BL (2013). Deriving Indicators for Breast Conserving (BCS) using Finite Element Analysis (FEM). *Computer Methods in Biomechanics and Biomedical Engineering*; pp. 1-12.

25 Tsai C-C and Wang T-Y (2008). Small humanoid robot localization by landmarks. *7th World Congress on Intelligent Control and Automation*; pp. 6584-6589.

Uchida T, Koyama H, Komeda T, Miyagi M and Funakubo H (1996). Measuring method of three dimensional position and orientation of a moving object for medical robots, *IEEE International Conference on Systems, Man, and Cybernetics*; Vol. 2, pp. 887-892.

30 Unsgaard G, Rygh OM, Selbekk T, Müller TB, Kolstad F, Lindseth F, and Hernes TA. (2006). *Intra-operative 3D ultrasound in neurosurgery. Acta Neurochirurgica*; Vol. 148, No. 3, pp. 235-53.

Voros S, Orvain E, Cinquin P, and Long JA (2006). Automatic detection of instruments in laparoscopic images: a first step towards high level command of robotized

endoscopic holders. *Biomedical Robotics and Biomechatronics, BioRob 2006. The First IEEE/RAS-EMBS International Conference*; pp. 1107-12.

Wein W, Khamene A, Clevert D-A, Kutter O, Navab N (2007). Simulation and Fully Automatic Multimodal Registration of Medical Ultrasound. *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2007, Lecture Notes in Computer Science*; Vol. 4791, pp. 136-14.

Wolpert S, Bosseau Murray W, Gorman PJ, and Bholat OS (1999). Movement trajectories in laparoscopic tools. *Engineering in Medicine and Biology. 21st Annual Conf. and the Annual Fall Meeting of the Biomedical Engineering Soc. BMES/EMBS Conference. Proceedings of the First Joint*; Vol. 2.

Wytyczak-Partyka A, Nikodem J, Klempous R, Rozenblit J, Radoslaw Klempous, and Rudas I (2009). Safety Oriented Laparoscopic Surgery Training System. *Computer Aided Systems Theory – EUROCAST*; Vol. 5717, pp. 889-896.

Yuan JS-C (1989). A general photogrammetric method for determining object position and orientation. *IEEE Transactions on Robotics and Automation*; Vol. 5, Issue 2, pp. 129-142.

Zhu W, Nicolau S, Soler L, Hostettler A, Marescaux J, and Rémond Y (2012). Fast Segmentation of Abdominal Wall: Application to Sliding Effect Removal for Non-rigid Registration. *Abdominal Imaging*; pp. 198-207.

**CLAIMS****WHAT IS CLAIMED IS:**

1. A method for real time laparoscopic navigation, the method comprising:
  - 5 scanning a structure of interest internal to a patient to provide image data;  
generating a first three-dimensional reconstruction of the structure of interest based on the  
image data;  
annotating the first three-dimensional reconstruction of the structure of interest with a  
plurality of reference points;
  - 10 obtaining spatial coordinates of the plurality of reference points during a laparoscopic  
procedure; and  
generating a second three-dimensional reconstruction of the structure of interest based on  
the spatial coordinates.
- 15 2. The method of claim 1 wherein obtaining the spatial coordinates of the plurality of  
reference points comprises obtaining a distance from each of the plurality of reference  
points to a camera on a surgical port used during the laparoscopic procedure.
3. The method of claim 2 wherein the distance is obtained via a laser.
- 20 4. The method of claim 2 wherein the distance is obtained via acoustic waves.
5. The method of claim 2 wherein the distance is obtained via an autofocus feature of the  
camera.
- 25 6. The method of claim 5 wherein the autofocus feature incorporates an algorithm to increase  
local pixel contrast.
7. The method of claim 1 wherein the structure of interest is a liver.
- 30 8. The method of claim 7 wherein the plurality of reference points comprise locations where  
hepatic arteries enter the liver and where a portal vein exits the liver.

9. The method of claim 7 wherein the plurality of reference points comprise locations including a transverse fissure of the liver that divides a left portion of the liver into four segments.
- 5 10. The method of claim 7 wherein the plurality of reference points comprises a coupling point between the liver and a gall bladder.
11. The method of claim 7 wherein the plurality of reference points comprises a location of the hepatic lymph node.
- 10 12. The method of claim 7 wherein the plurality of reference points comprise the ligamentum venosum and the ligament teres.
13. A real time laparoscopic navigation system comprising:
- 15 a scanner configured to provide image data of a structure of interest internal to a patient; and
- a processor configured to:
- generate a first three-dimensional reconstruction of the structure of interest based on the image data;
- 20 annotate the first three-dimensional reconstruction of the structure of interest with a plurality of reference points;
- obtain spatial coordinates of the plurality of reference points during a laparoscopic procedure; and
- generate a second three-dimensional reconstruction of the structure of interest
- 25 based on the spatial coordinates.
14. The system of claim 13 wherein the scanner is a magnetic resonance imaging (MRI) scanner.
- 30 15. The system of claim 13 wherein the scanner is a computed tomography (CT) scanner.
16. The system of claim 13 further comprising a camera coupled to a surgical port, and wherein the processor is configured to obtain the spatial coordinates of the plurality of

reference points by obtaining a distance from each of the plurality of reference points to the camera.

17. The system of claim 16 wherein the processor is configured to obtain the distance via a  
5 laser.

18. The system of claim 16 wherein the processor is configured to obtain the distance via acoustic waves.

10 19. The system of claim 16 wherein the processor is configured to obtain the distance via an autofocus feature of the camera.

20. The system of claim 19 wherein the autofocus feature incorporates an algorithm to increase local pixel contrast.

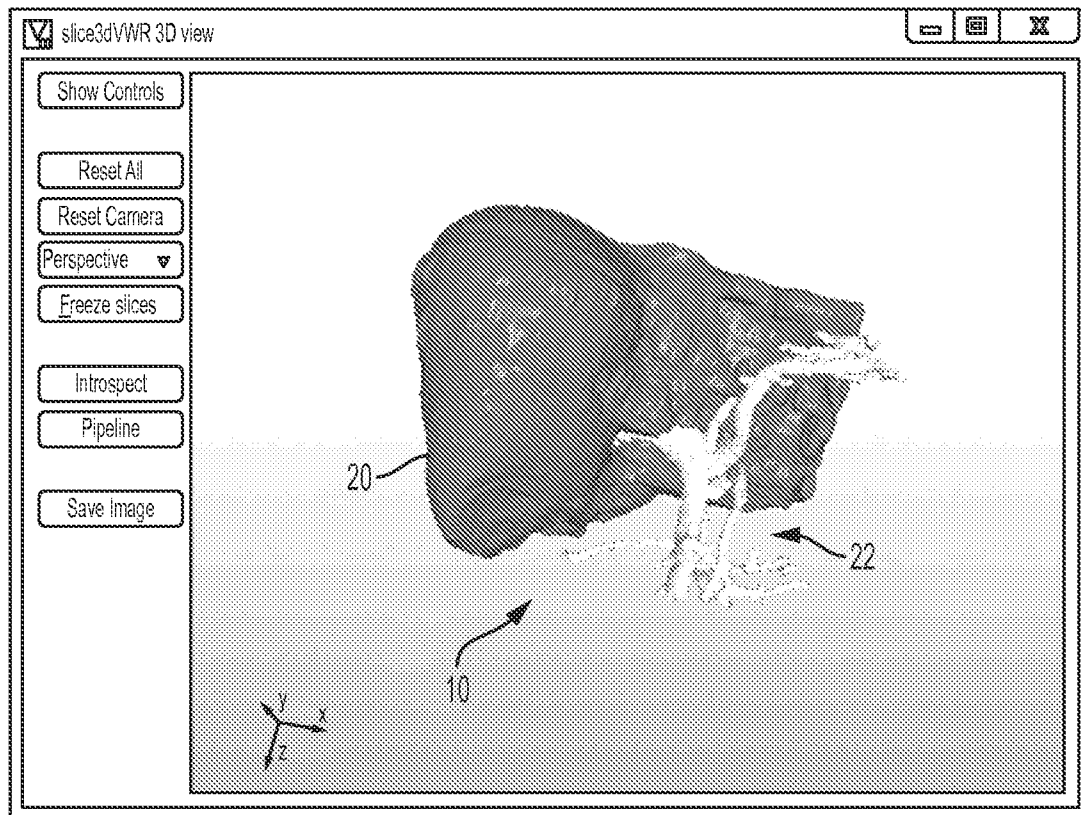


FIG. 1

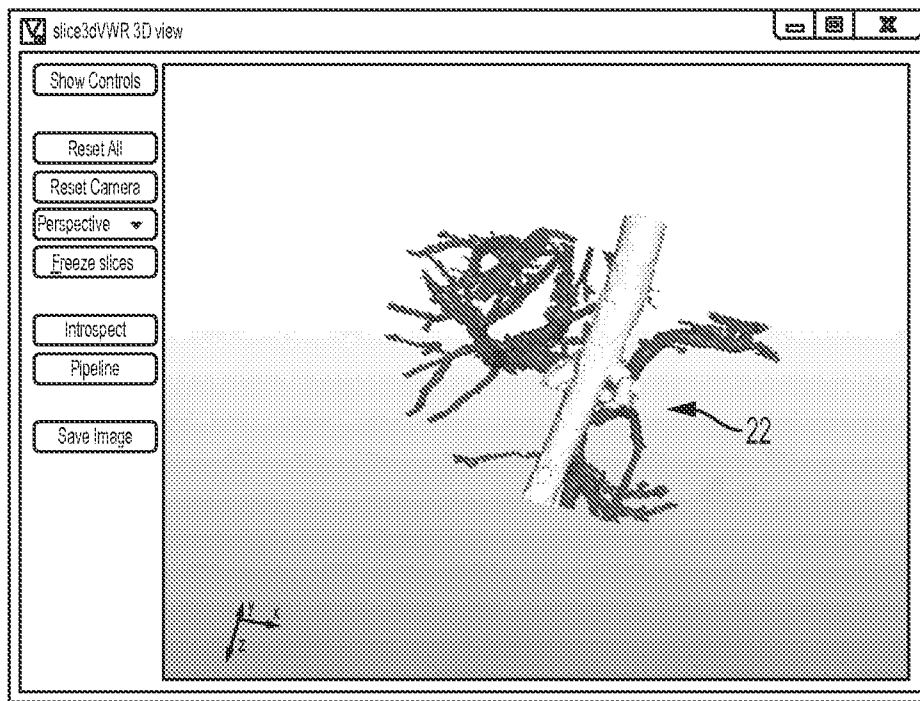


FIG. 2

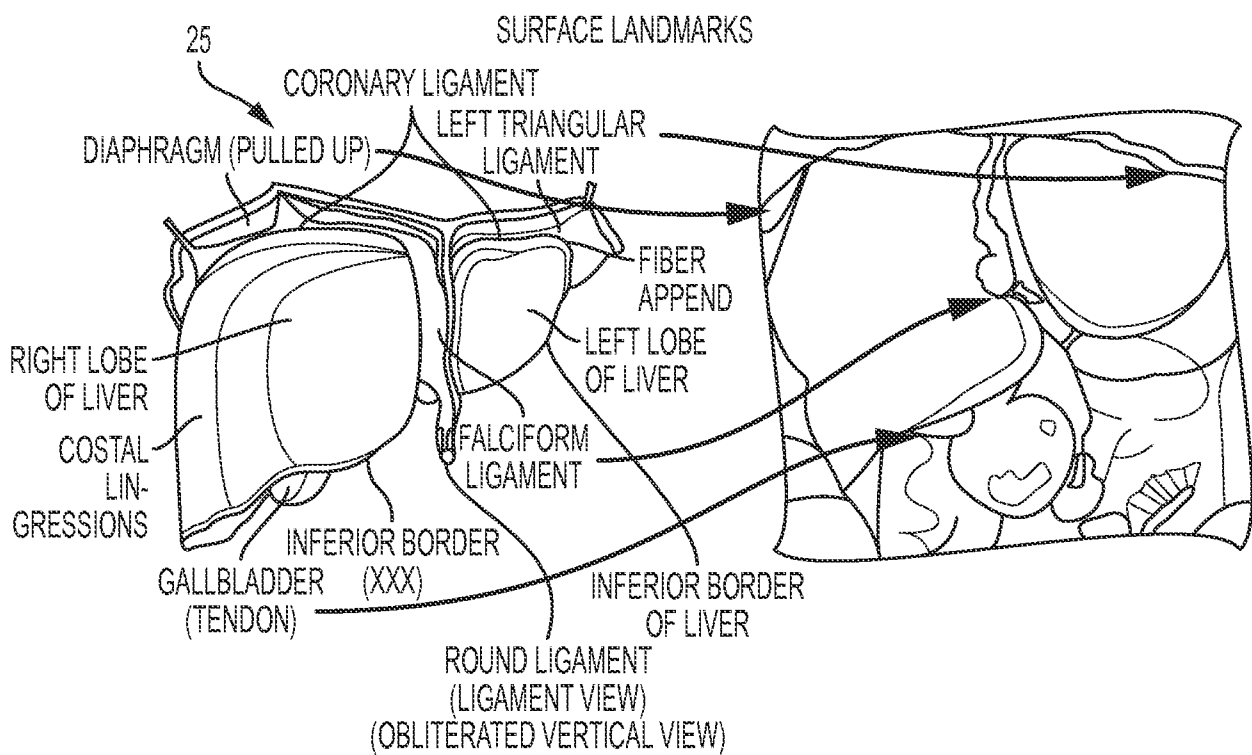


FIG. 3

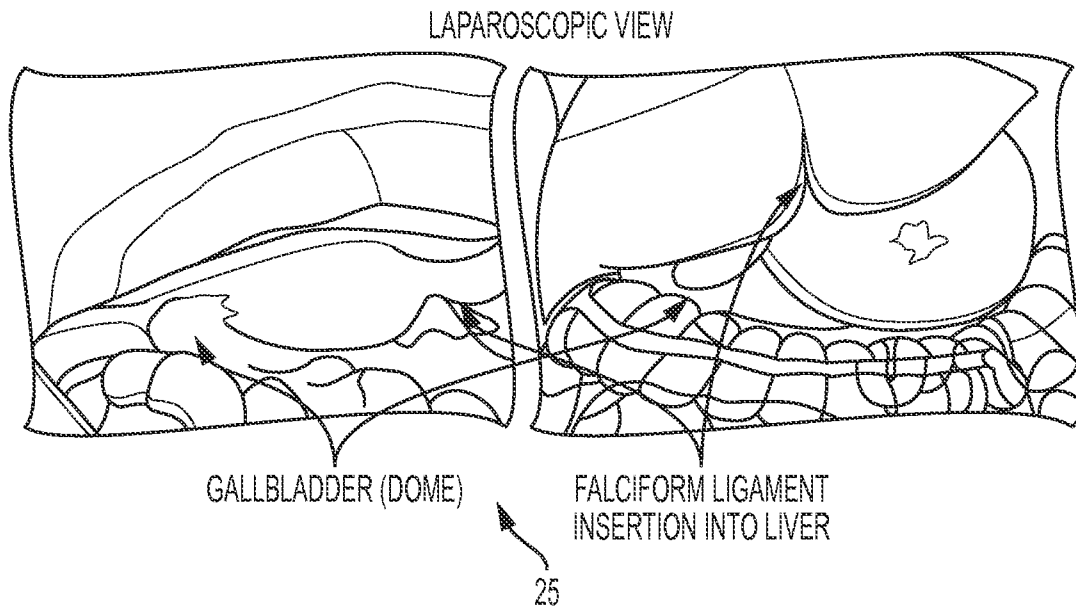


FIG. 4

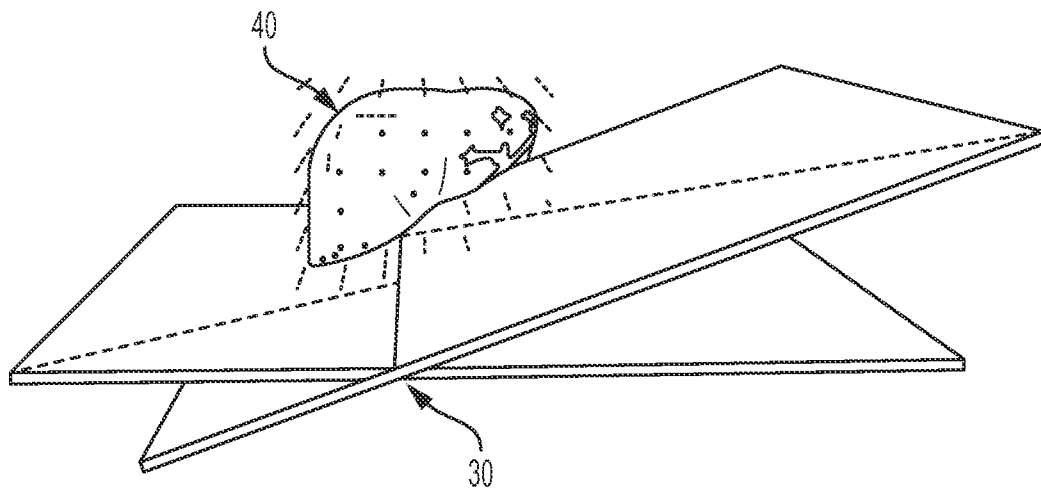


FIG. 5

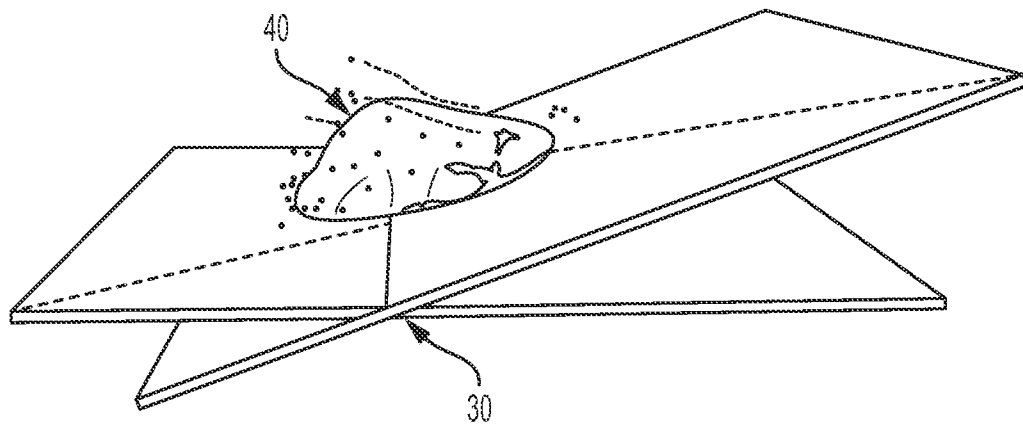


FIG. 6

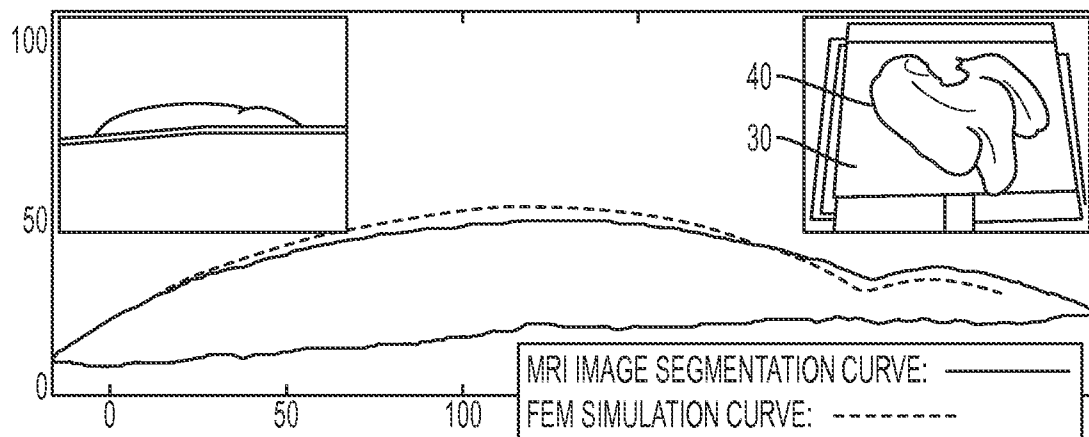


FIG. 7

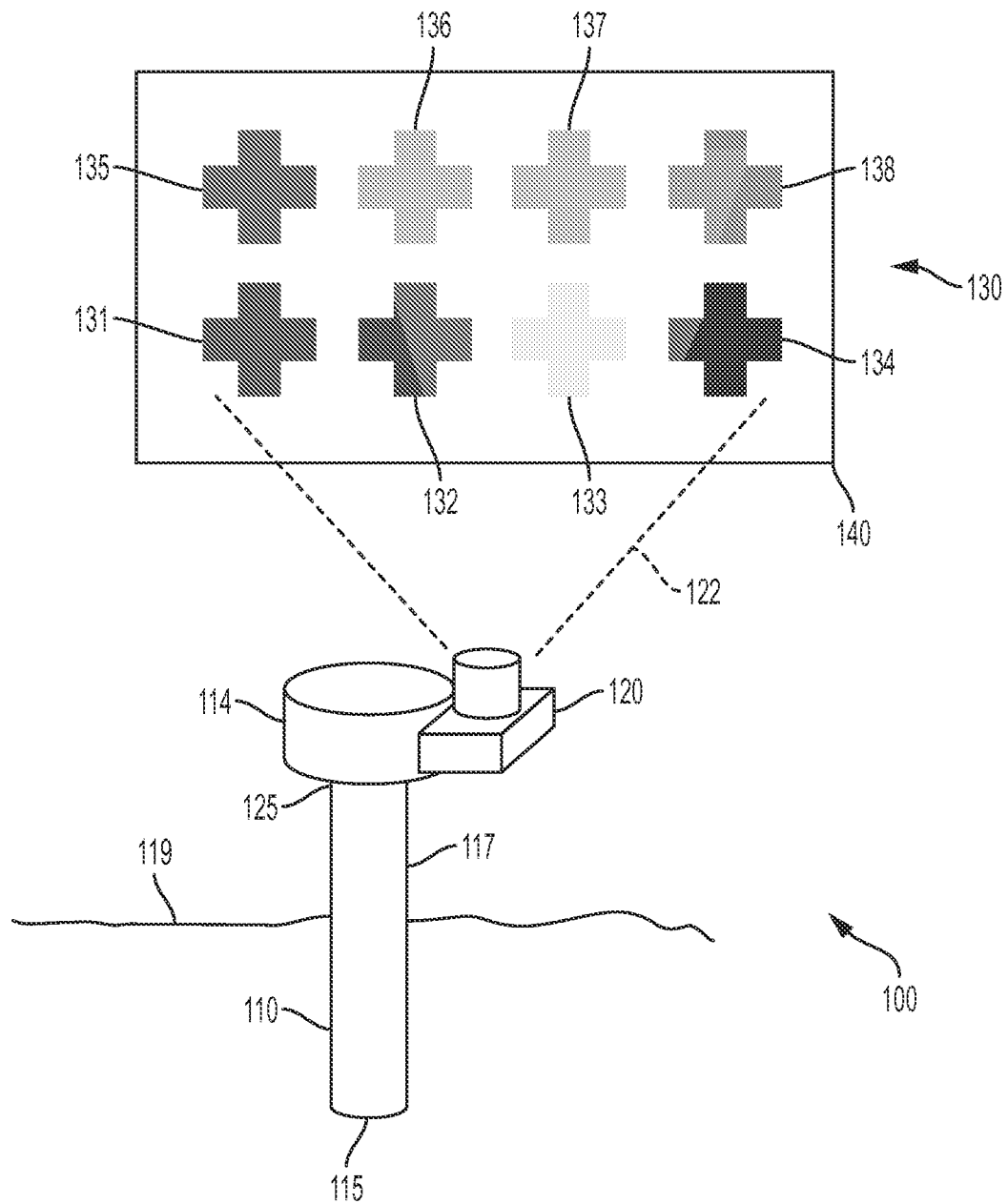


FIG. 8

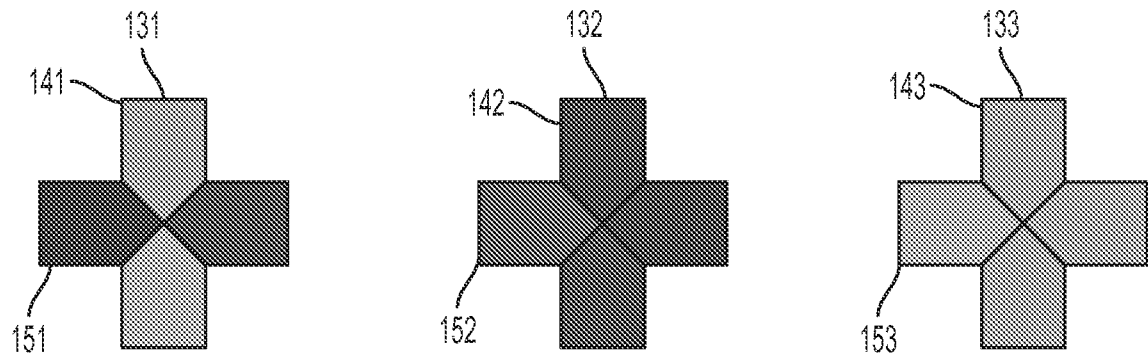


FIG. 9

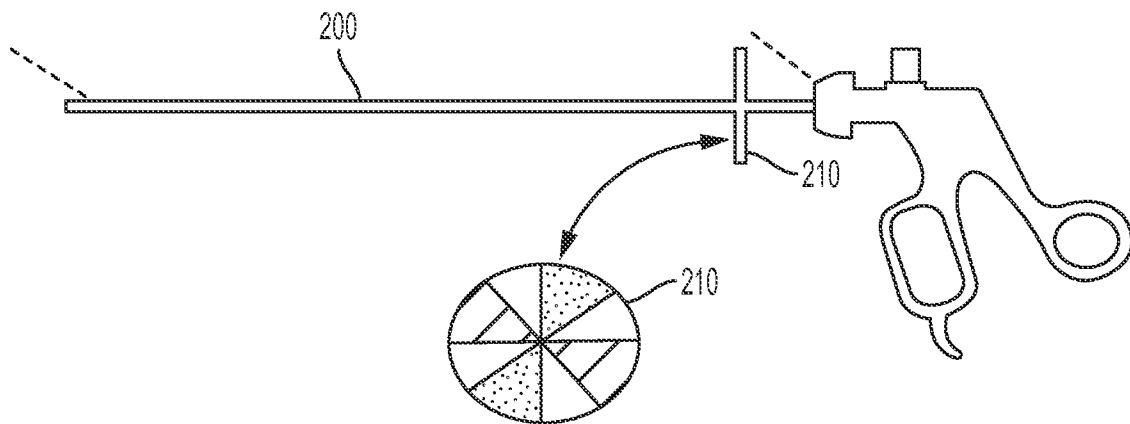


FIG. 10

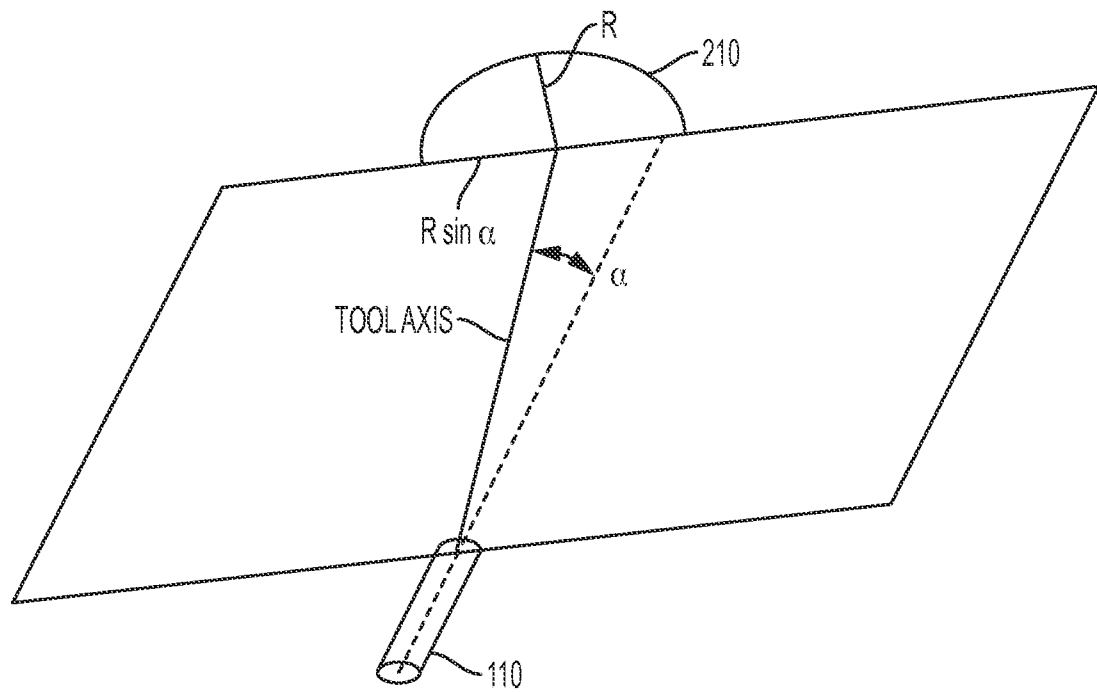


FIG. 11

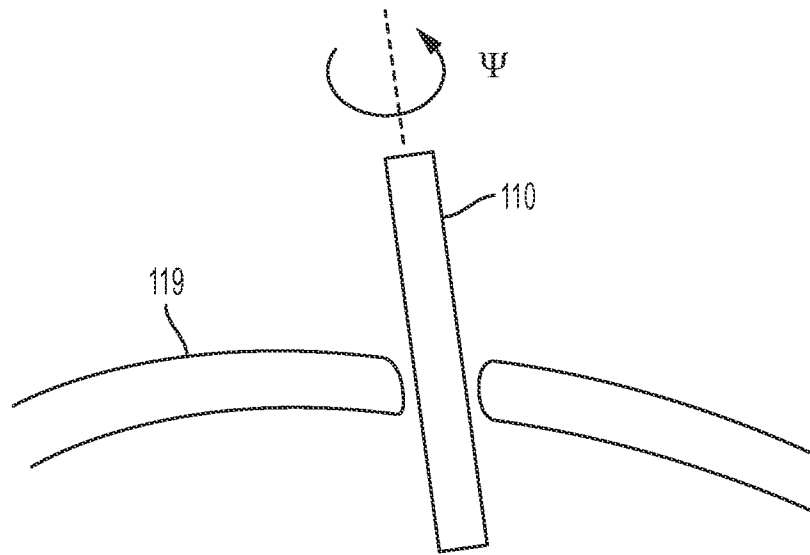


FIG. 12

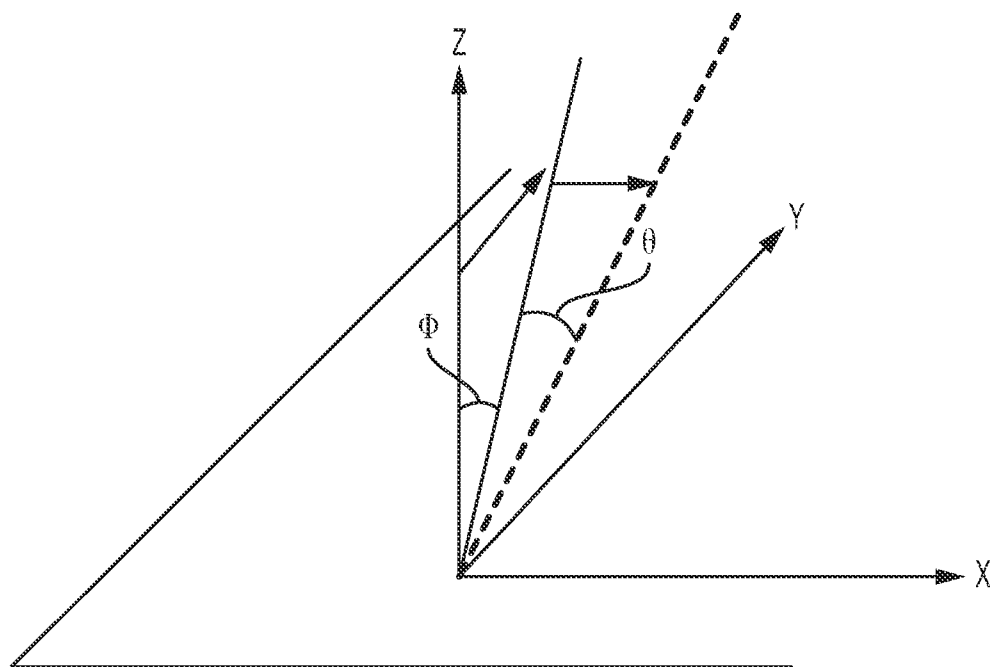


FIG. 13

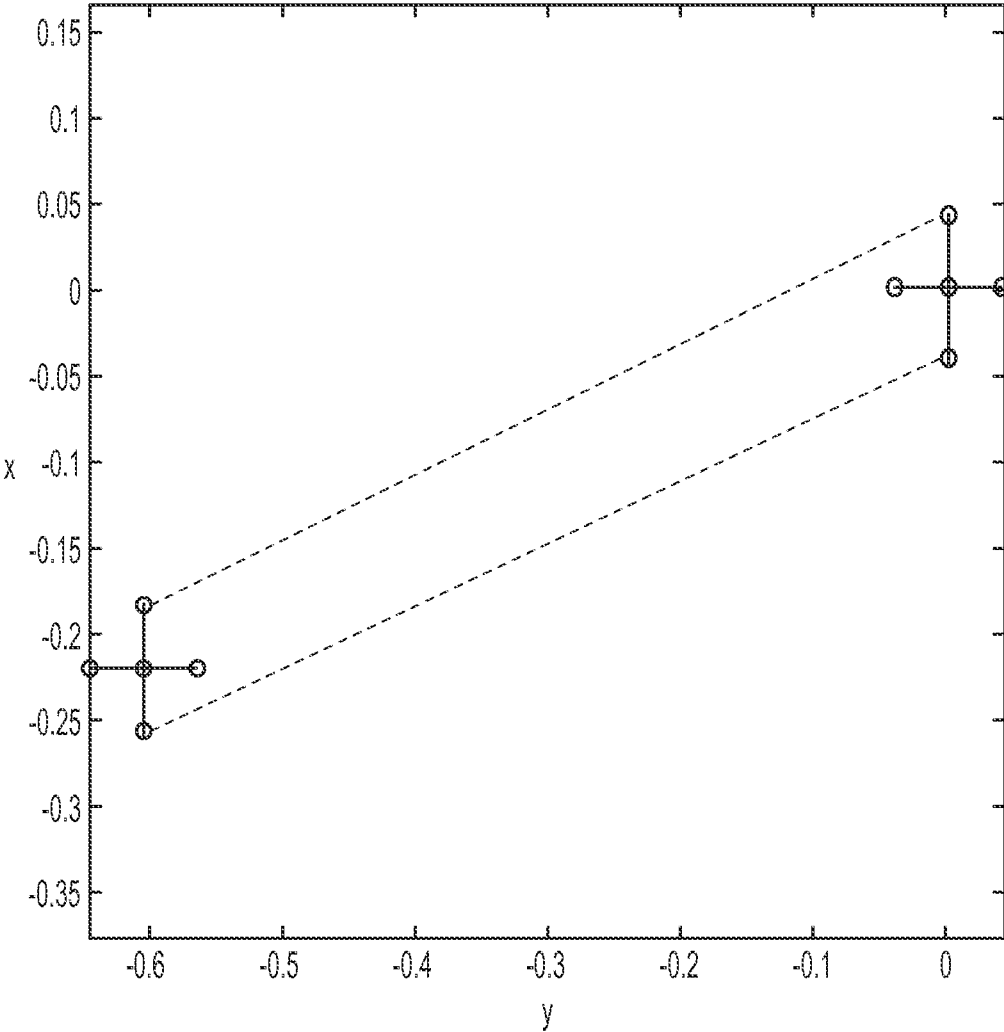


FIG. 14

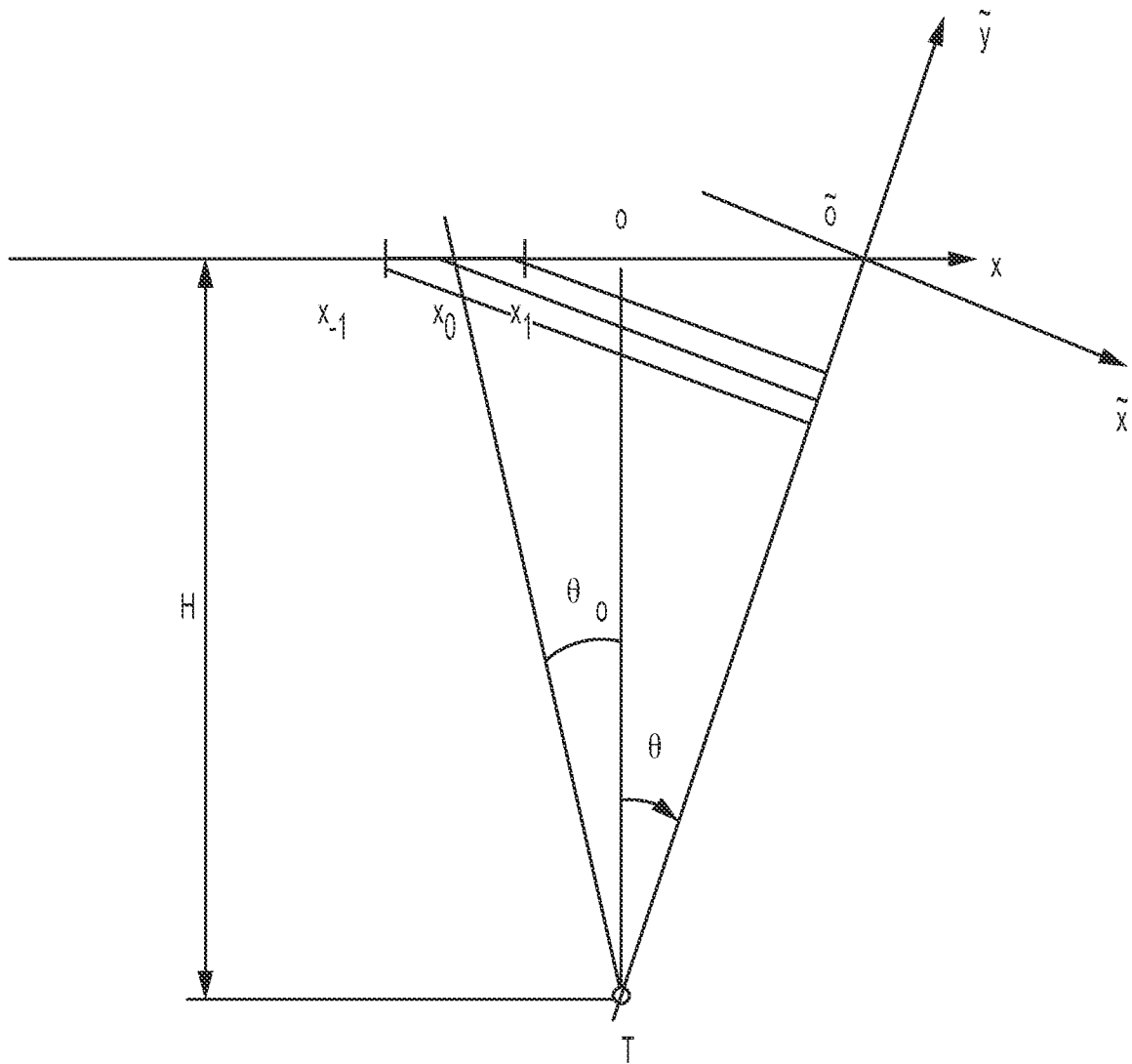


FIG. 15

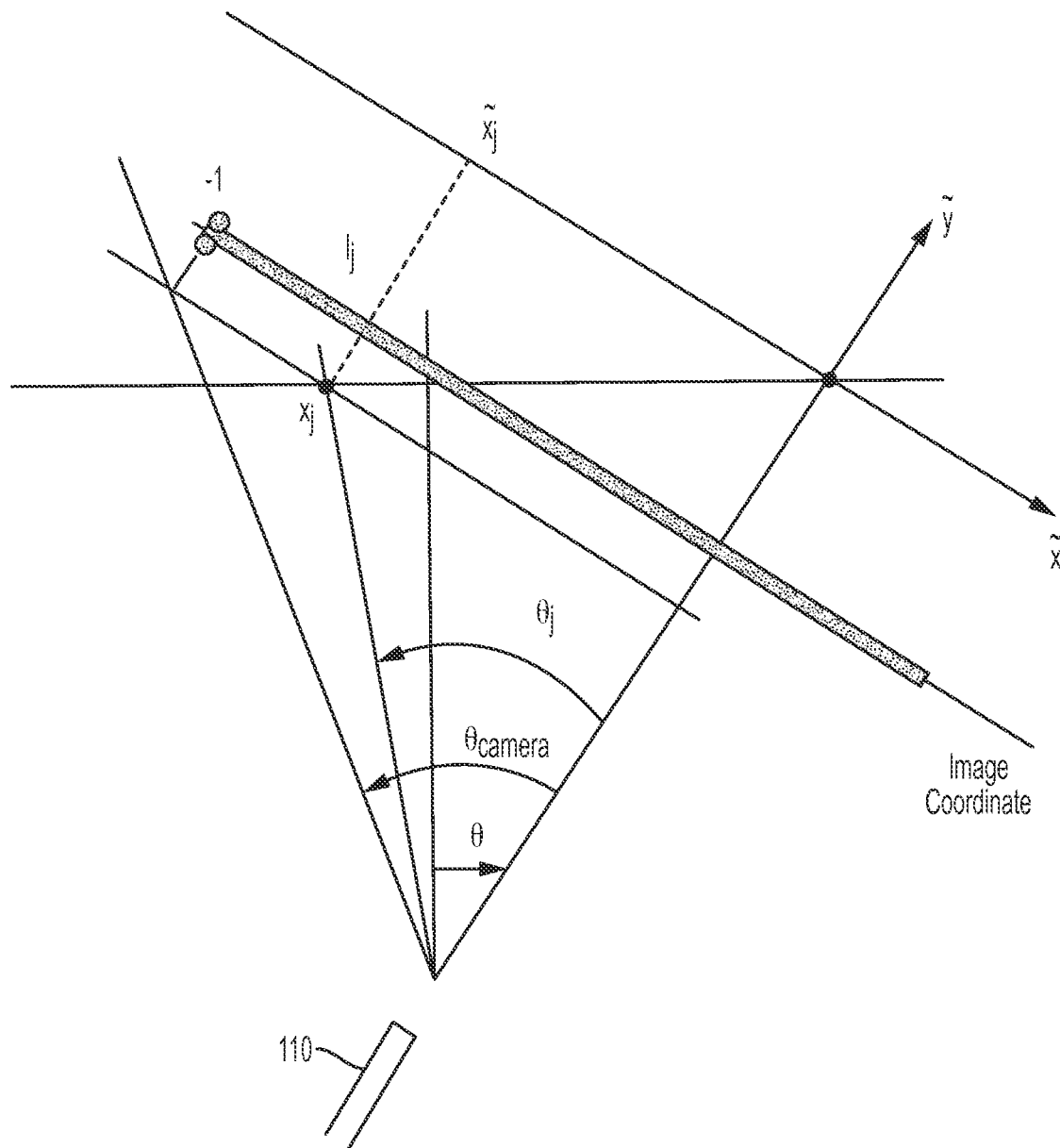


FIG. 16

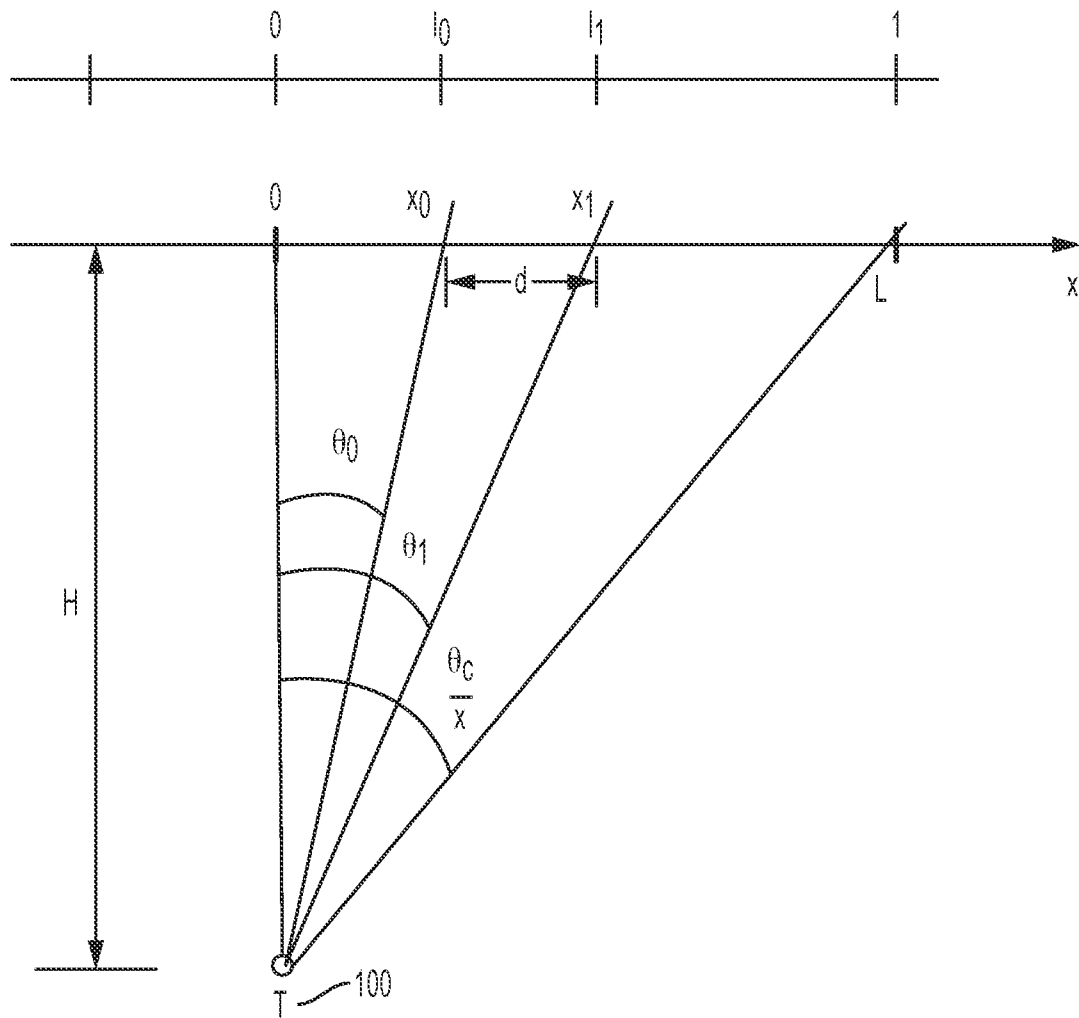


FIG. 17

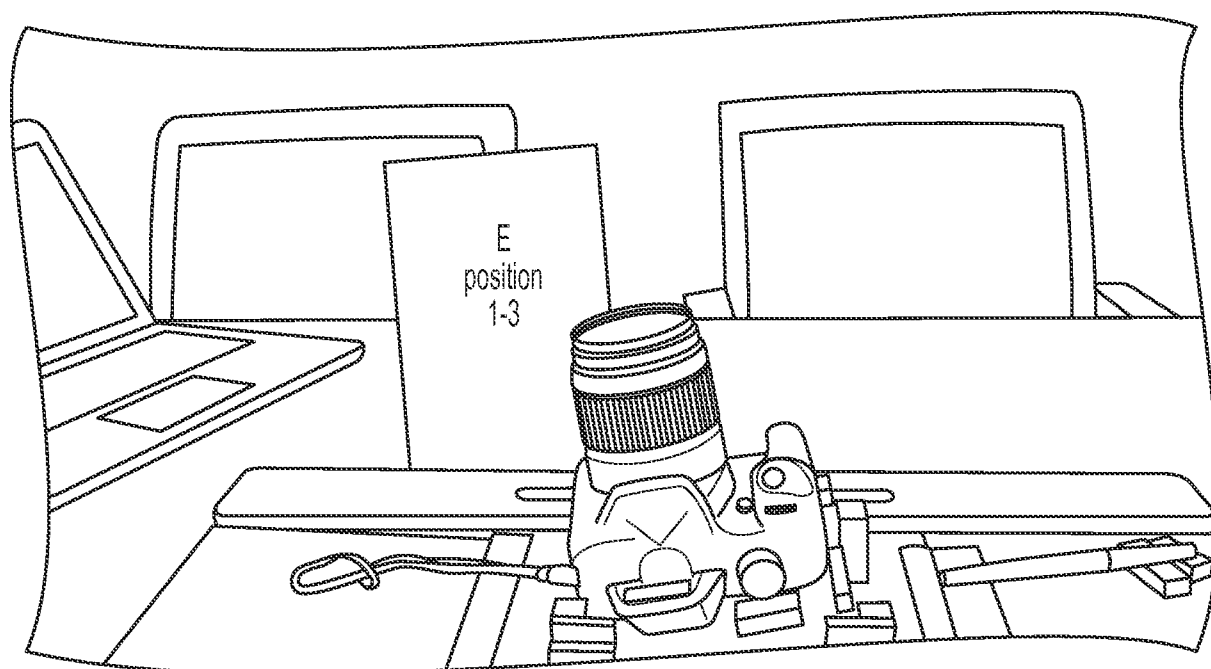


FIG. 18

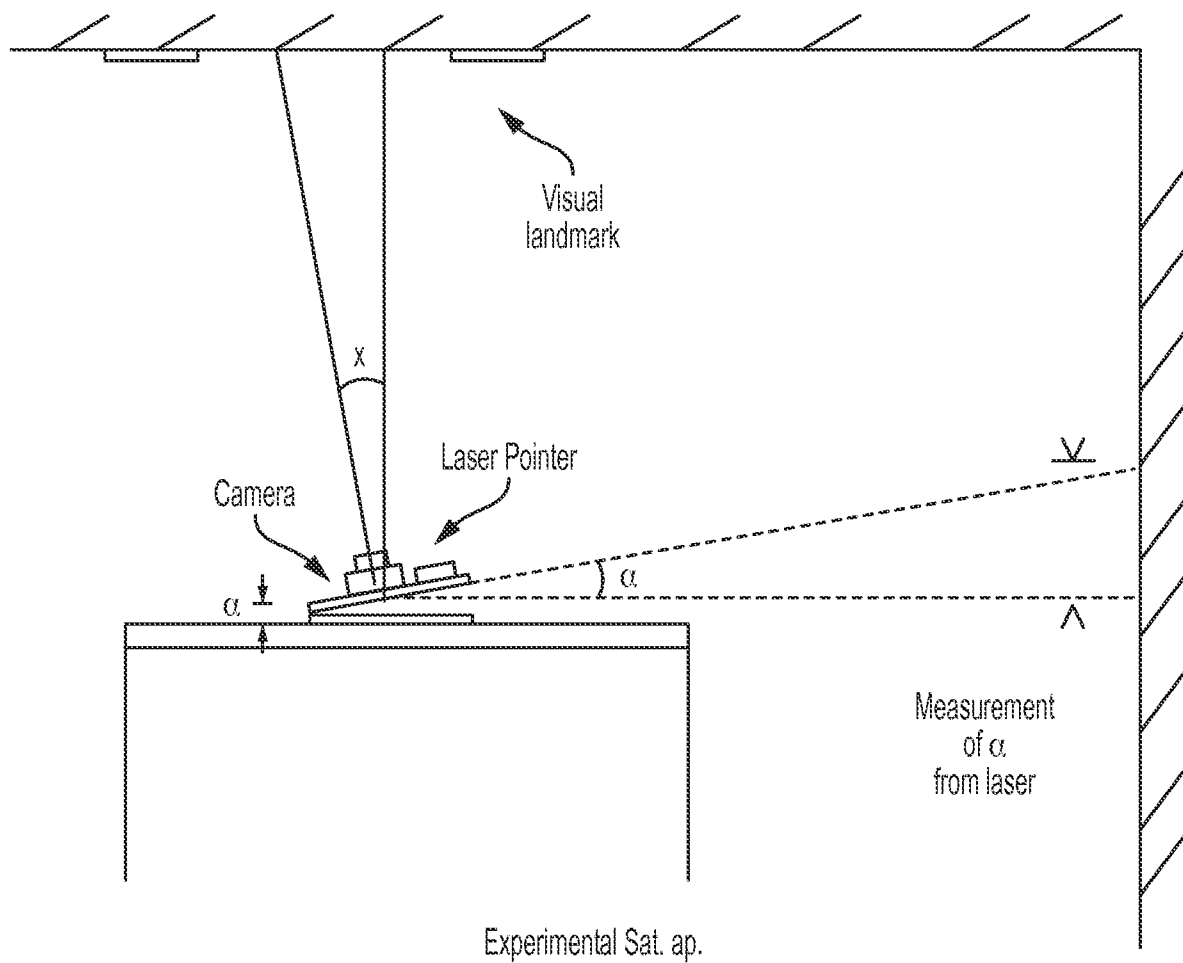


FIG. 19

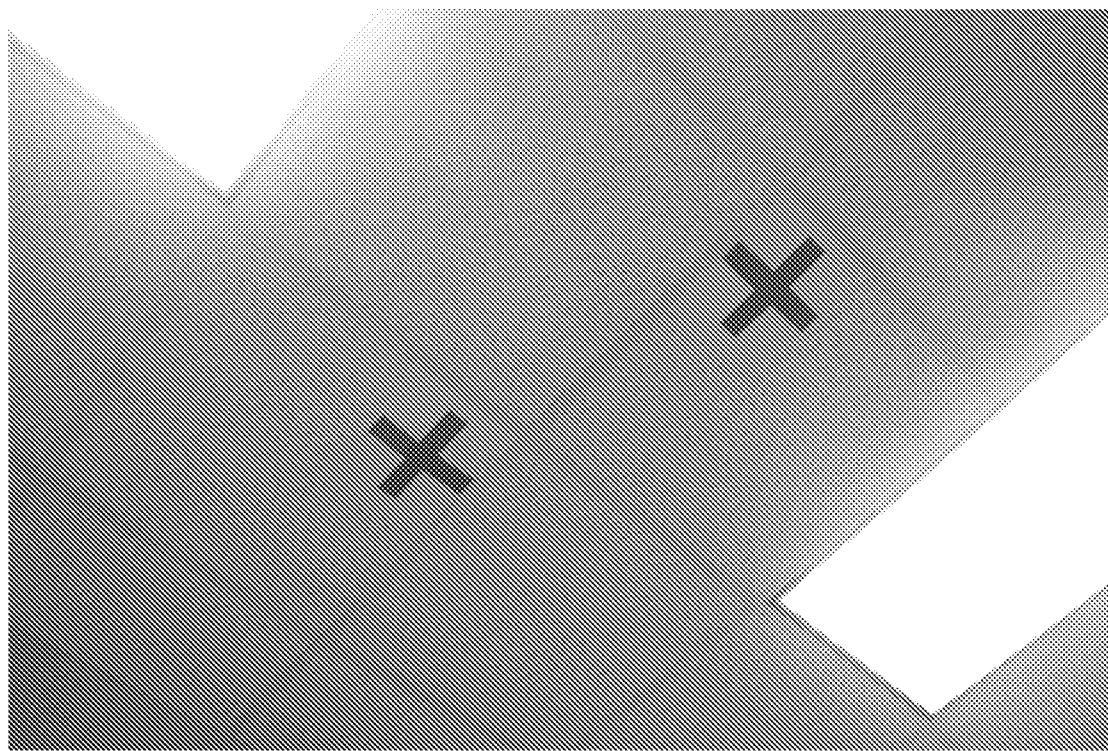


FIG. 20

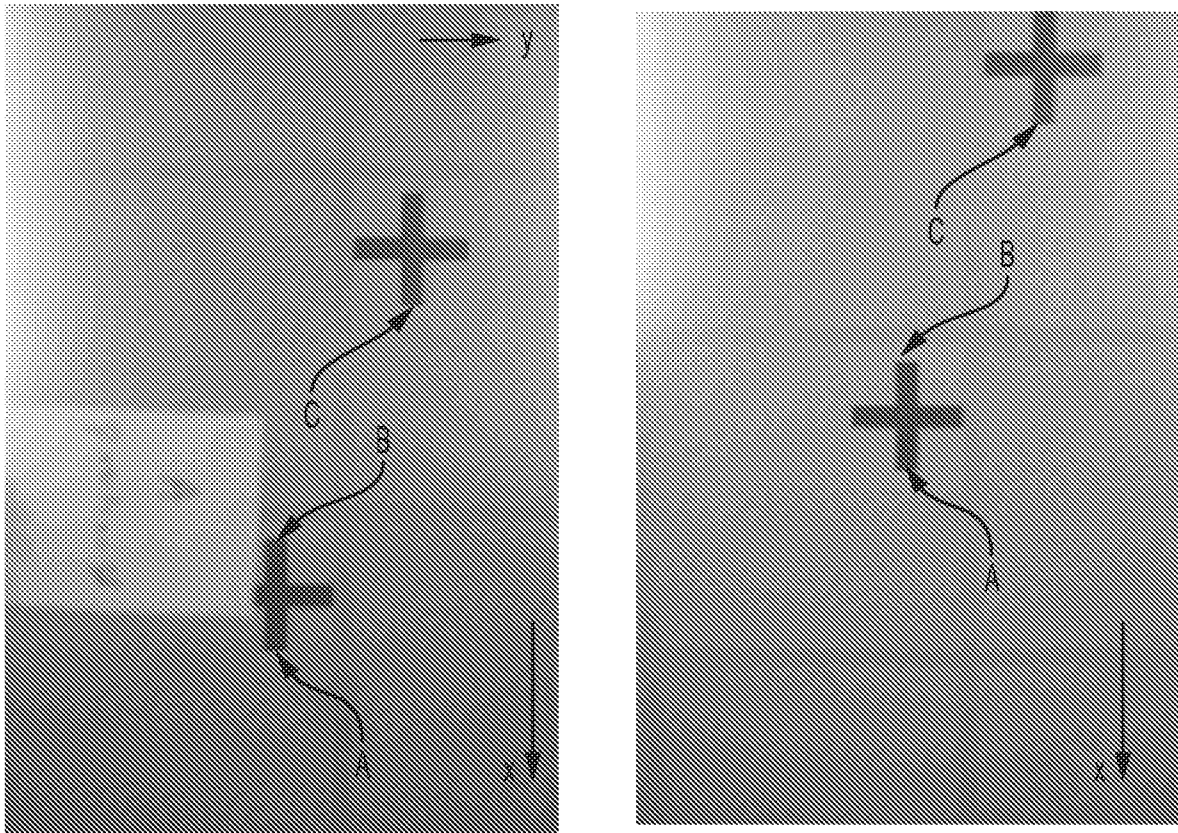


FIG. 21

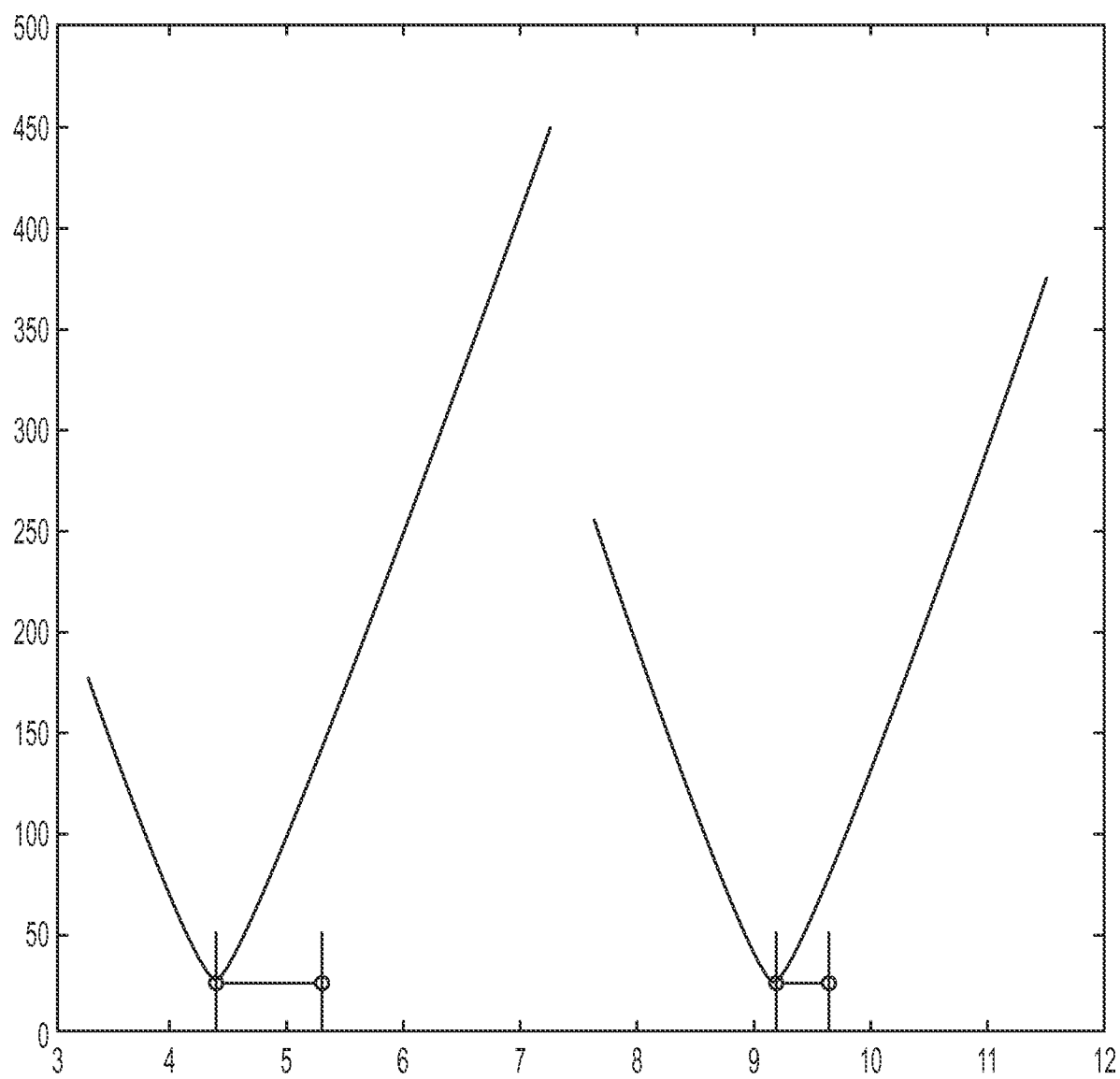


FIG. 22

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2015/022279

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 8/00 (2015.01)

CPC - A61B 8/00 (2015.04)

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)

IPC(8) - A61B 1/00, 1/045, 5/05, 5/06, 6/00, 8/00, 17/00, 19/00; G06K 9/00 (2015.01)

CPC - A61B 1/00, 5/00, 6/12, 8/00, 17/00, 19/00, 19/2203, 19/5212, 19/5244 (2015.04) (keyword delimited)

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

USPC - 382/128, 154; 600/103, 410, 424, 427, 437, 443; 606/1 (keyword delimited)

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

Orbit, Google Patents, Google, Google Scholar

Search terms used: laparoscopic, navigation, real time, 3D construction, annotating, liver, reference points, spatial coordinates, second reconstruction, obtaining distance, camera, laser, acoustic wave, increasing pixel, autofocus, hepatic arteries, port

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages     | Relevant to claim No. |
|-----------|----------------------------------------------------------------------------------------|-----------------------|
| X         | US 8,670,816 B2 (INNEROPTIC TECHNOLOGY INC) 11 March 2014 (11.03.2014) entire document | 1, 7-15               |
| Y         |                                                                                        | 2, 3, 16, 17          |
| Y         | US 8,027,710 B1 (DANNAN) 27 September 2011 (27.09.2011) entire document                | 2, 3, 16, 17          |
| A         | US 2007/0225553 A1 (SHAHIDI) 27 September 2007 (27.09.2007) entire document            | 1-20                  |
| A         | US 8,073,528 B2 (ZHAO et al) 06 December 2011 (06.12.2011) entire document             | 1-20                  |
| A         | US 8,554,307 B2 (RAZZAQUE et al) 08 October 2013 (08.10.2013) entire document          | 1-20                  |

☐ Further documents are listed in the continuation of Box C.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"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

"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

"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

"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

"&amp;" document member of the same patent family

Date of the actual completion of the international search

31 May 2015

Date of mailing of the international search report

25 JUN 2015

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