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Force/Position-based Modular System for Minimally Invasive Surgery

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***Abstract*—The limitations of minimally invasive surgery include the inability to sense forces exerted by the instruments on tissue and the limited visual cues available through the endoscope. A modular laparoscopic instrument capable of measuring force and position has been designed to address these limitations. Novel image-based position tracking software has been developed and integrated within a graphical user interface. This modular system is low cost, versatile, and could be used for training, localization of critical features or for guidance during surgical procedures.**

I. Introduction

THE benefits to patients of performing surgery through small incisions have been widely proven. Minimally Invasive Surgery (MIS), however, presents several difficulties for the surgeon. The one that has proven to be the hardest to solve is that the forces at the handle of the instruments do not reflect the forces acting at the tip, which causes the surgeon to lose the ability to sense how much force is being applied on tissue. The consequences of this limitation include: an inability to palpate tissue to identify differences in tissue stiffness [1], the risk of applying too much force causing tissue damage, or not enough force leading to slippage during grasping, loose knots, or the inability to effectively perform a task [2]. Furthermore, the limited view of the surgical area through a two-dimensional (2D) monitor can lead to disorientation or potentially unsafe conditions if the instruments are near critical areas.

Since tactile and force information is no longer available to surgeons performing MIS, they must compensate by using visual cues to estimate the amount of force being applied [3]. The limited visual cues available through a monitor impair this ability. Extensive research has been directed at providing force and position information to the user in MIS.

A. Position Sensing

There exist a number of commercially available systems that can track the position and orientation of an object in real time using specialized sensors. The most popular tracking systems are optical and electromagnetic (EM). EM tracking systems are often selected for medical applications since they do not require an unobstructed line-of-sight between the tracked object and the sensor. The main drawbacks of using EM trackers is their high cost, that they generate EM noise which can affect other sensing modalities, and that they can suffer from magnetic distortions in the presence of certain metals within their working volume.

One solution to the problem of surgical instrument tracking is to use only the images acquired by the camera. Most of the current techniques found in the literature that use digital image processing for tracking instruments provide only 2D information [4] or require the use of stereoscopic cameras [5]. An exception is the work detailed in [6], which places a colored marker on an instrument and relies only on the endoscopic image to track the instrument tip in three-dimensional (3D) space. Although promising, this approach is still limited in its ability to obtain real-time measurements and track more than one instrument at once.

B. Force Sensing in MIS

It is common to find sensorized MIS instruments or master-slave systems where forces are sensed outside the location where the instrument enters the patient's body [7-11]. However, it has been shown that tool-tissue interaction forces are very different to those acting at the instrument handle with a non-linear relationship between them [12].

Some sensorized instruments are capable of measuring grip forces [13-14], or forces at the tip in 3D using optical fibers [15] or strain gauges [16]. A sensorized master-slave system capable of providing feedback in 5 degrees of freedom (DOFs) is proposed in [17-18]. Furthermore, a force sensor capable of measuring forces in all 6 DOFs is presented in [19]. A 10 mm diameter sensor based on a Stewart Platform is combined with a 2 DOF cable driven joint for MIS. Finally, [20-21] presents the design of an MIS instrument for skills assessment and training, capable of measuring 5-DOF tip forces and 6 DOF position using EM trackers.

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C. *Motivation and Objectives*

The state of the art shows clear advances in force sensing and position tracking of MIS instruments. However, a fully integrated, compact system that can be used in any minimally-invasive surgical or training scenario, which incorporates accurate tissue-instrument force sensing in multiple DOFs and uses only the endoscopic image for 6-DOF visual tracking of the instrument tip, is still lacking.

The goal of this project was to design and develop a highly versatile system that can be used in *real surgical procedures* and that provides force and position information through novel design features and image-based position tracking software. Such an instrument offers several benefits to practitioners of MIS: force information can warn of excessive forces being applied on delicate tissue or insufficient forces applied when grasping or cutting; force data can aid in characterizing tissue stiffness and identifying the diseased areas such as tumors or calcifications; force and position information can be used to provide warnings about the application of damaging forces when the instruments are out of the field of view; force and position trajectories when performing standardized tasks can be used for training and skills assessment; instrument position data can be used to provide warnings when entering high risk areas; or it could be merged with preoperative or intraoperative images to provide additional guidance to the surgeon.

II. System Development

A prototype system was developed, building on the work presented in [20-21], with the following characteristics: (i) overall appearance and weight similar to MIS instruments; (ii) can measure forces and torques acting in all 5 DOFs available during MIS (3D tip forces, actuation force, and torque about the shaft axis); (iii) use of interchangeable tips and handles to increase versatility and reduce cost; (iv) can measure tip position and orientation using image-based tracking software; and (v) is able to interface with software to record force and position data in real-time. The details of the design and software development are presented below.

A. *Mechanical Design*

The instrument is formed by three shafts: an inner shaft connects the handle and the tip of the instruments to open and close the tool (scissors, grippers or needle drivers); the middle shaft connects the fixed elements on the handle and the tip and provides rigidity; the outer shaft protects the sensing elements and seals the inside of the instrument. Fig. 1 shows a picture of the completed prototypes. Depending on the task that needs to be performed, different tips can be screwed in and out of the distal end of the instrument. The needle driver model requires a different handle as well as different tips. In order to change the handles, a quick connect mechanism was designed, shown in Fig. 2. A flat spring (shown in red) ensures that the two connecting parts remain together when using the instrument.

Fig. 1. Prototypes showing the different types of handles and tips that can be used.

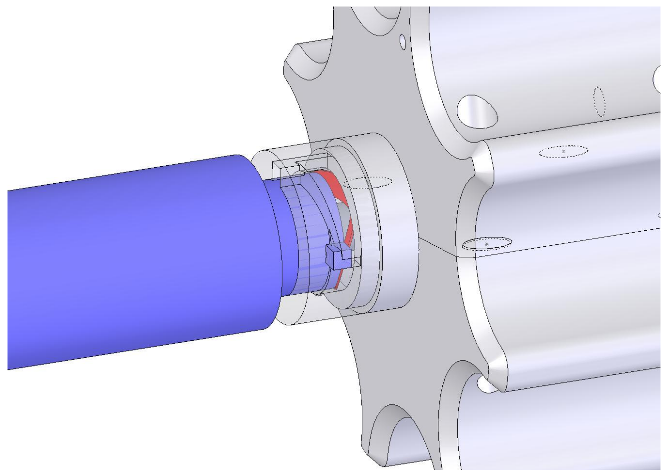

Fig. 2. CAD model of the quick connect mechanism for the handles.

1) Actuation force: The actuation force refers to the gripping or cutting force acting as the tool is opened and closed. This force is measured through 4 strain gauges attached to the inner shaft in a type III full Wheatstone bridge configuration. As the handle is closed to apply an actuation force, an axial force acts on the inner shaft and its corresponding deformation is sensed by the strain gauges.

In order to increase the deformation and for ease of strain gauge installation, a 1-mm thick flat section was machined on the shaft. To minimize the coupling between the bending forces and the actuation forces, a joint was added on the inner shaft, as shown in Fig. 3. When bending moments act on the instrument, the joint relieves the stresses on the inner shaft minimizing the coupling between the signals.

2) Bending moments: To measure the forces acting in the x and y directions, two pairs of strain gauges were mounted on opposite sides of the middle shaft in a half bridge type II configuration. Two 2.5 mm holes were drilled through the middle shaft at 90° angles in order to localize the deformation around the areas where the strain gauges were placed and increase the magnitude of the signal.

3) Torsion: Measurement of the torsional forces acting about the instrument shaft required two sets of two-element rosettes connected in a full torsion bridge configuration. Each rosette contains two gauges placed at 90° with respect to each other at a 45° angle from the centre of the gauge.

4) Axial: A structural element was developed to maximize and decouple the signal used to measure axial forces. This involved a specialized element with a thin wall section perpendicular to the instrument axis, with four small slots. Fig. 4 shows the structural element and its deformation when axial forces are applied. Strain gauges placed between the slots measure this deformation while cancelling other forces. Two dummy gauges placed on the main shaft allow the gauges to be connected in a type III full bridge configuration to maximize the signal, cancel noise and compensate for variations in temperature.

B. *Software Design*

Customized software was implemented to capture, process, and record sensor information obtained from the strain gauges and to acquire video streams from an video scope for the purpose of vision-based tracking of the instruments.

The software interface was developed in C++ using the Qt GUI library and presents two dynamically rescaling real-time plots; a tree of checkboxes used to enable or disable the plotting of various strain, force, position, and orientation signals on these plots; a table through which various parameters that influence signal processing tasks carried out by the software may be modified; an interface that facilitates force calibration of the MIS instruments; a video display on which the geometric features extracted from the video stream are overlaid and presented; and a log to which status messages and force calculation parameters are written. A view of the graphical user interface is shown in Fig. 5.

C. *Vision-Based Tracking*

The method by which position and orientation information is determined through analysis of an incoming video stream, thus eliminating the need for EM localizers, is based on a prior implementation by Tonet *et al.* [6]. In this prior work, a colored cylindrical strip is placed on the tip of an MIS instrument, and geometric analysis is performed on the color-coded region to obtain position and orientation readings for the instrument with 5 DOFs.

Herein, this procedure was enhanced and extended to support the simultaneous tracking of multiple instruments, as well as extract readings for a 6^{th} DOF. Tracking of multiple instruments was implemented through the placement of a second colored cylindrical strip, of a distinct hue from the first, on the tip of a second instrument and reprocessing each captured frame from the camera to extract the relevant geometric features necessary for localizing the instrument.

The 6^{th} DOF, roll, was acquired through the usage of two pairs of colored rectangular strips, each of distinct hues from the cylindrical strips. As a result, four distinct hues are necessary for performing the localization of 2 instruments with 6 DOFs. The strips are placed 180° apart on the shafts of the instruments, such that at most one of the rectangular strips on each instrument is observable by the camera at any given time. One rectangular strip hue corresponds to a roll angle of 0° to 179°, while the other corresponds to a roll angle of 180° to 359°. By determining the distance of the centroid of these strips from the sides of the instruments through geometric analysis, the roll angle of each instrument may be estimated. A close-up view of the position-tracking window is shown in Fig. 6.

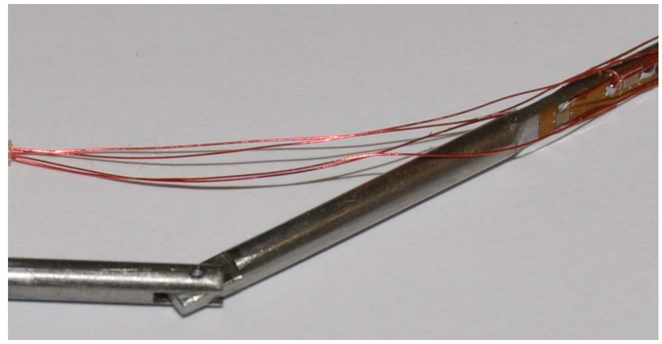

Fig. 3. Inner shaft showing inner joint used to minimize signal coupling.

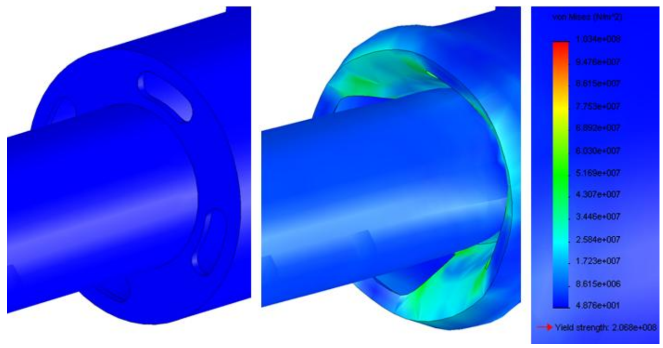

Fig. 4. Axial stress concentration diagrams at 0 N (*left*) and 20 N (*right*).

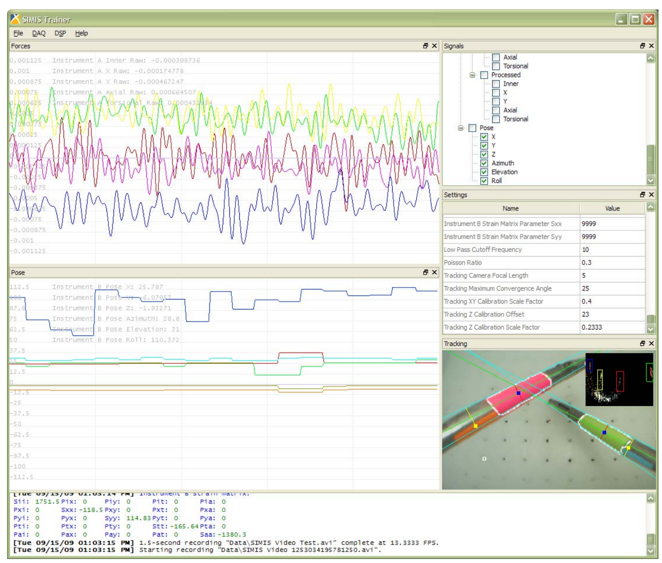

Fig. 5. Graphical user interface showing: force data (*top left*); position data (*middle left*); window to select which signals to display (*top right*); window to enter key parameters, scaling factors and other constants (*middle right*); instrument tracking display (*lower right*); and status information (*bottom*).

III. Calibration

In order to obtain reliable measures of force and position, the system must first be calibrated, as outlined below.

A. Force Calibration

Force calibration is required to establish the relationship between the measured voltages and the forces acting on the instruments. The calibration jig, shown in Fig. 7, allows weights to be placed in each of the directions being calibrated. The x and y moments were calibrated by applying weights at the tip while the instrument was held in a cantilever configuration. For the torsional moments, the instrument was supported at three points through the shaft length and weights were applied to the tip of the open gripper. The axial forces were calibrated by holding the instrument in a perfectly vertical position and applying weights at its tip. For the inner forces, a customized balance was designed. Weights were applied on one side of the balance while the instrument jaws were used to hold the balance at a predefined angle.

A preliminary analysis of the effect of coupling, i.e., the effect of the forces acting in each direction on the other signals, showed that the only signals that were significantly coupled were the axial and the actuation signals. A decoupling factor was added into the calculation of the inner forces, to eliminate the effect of coupling.

B. Position Calibration

Calibration of the Cartesian axes of the vision-based tracking system involved the use of one instrument with the colored strips attached, a rectangular plastic grid with points spaced 10 mm apart, and a plastic block 7 mm high. The grid was placed within the field of view of the camera such that the designated origin on the grid corresponded with the center of the camera's field of view.

To calibrate the x and y axes, the raw x and y coordinate readings reported by the instrument when pointing to the origin on the grid were recorded. The instrument was then pointed at a point on the grid known to be located 10 mm along the $+x$ axis, and 10 mm along the $+y$ axis. The x and y coordinate readings reported by the instrument were then recorded, and used to calculate scale factors for the x and y coordinates, respectively, such that multiplication by these scale factors resulted in the instrument reporting an x coordinate reading and a y coordinate reading of 10 mm when pointing to the marked point.

To calibrate the z axis, the raw z coordinate reading reported by the instruments when pointing to the origin on the grid was recorded. This reading was used as an offset for the z coordinates, such that the instrument reported a z coordinate reading of 0 mm when pointing to the origin. The plastic block was then used to raise the grid towards the camera by 7 mm. The z coordinate reading reported by the instrument was then recorded again and used to calculate a scale factor for the z coordinates such that multiplication by this factor resulted in the instrument reporting a z coordinate reading of 7 mm when pointing to the raised origin.

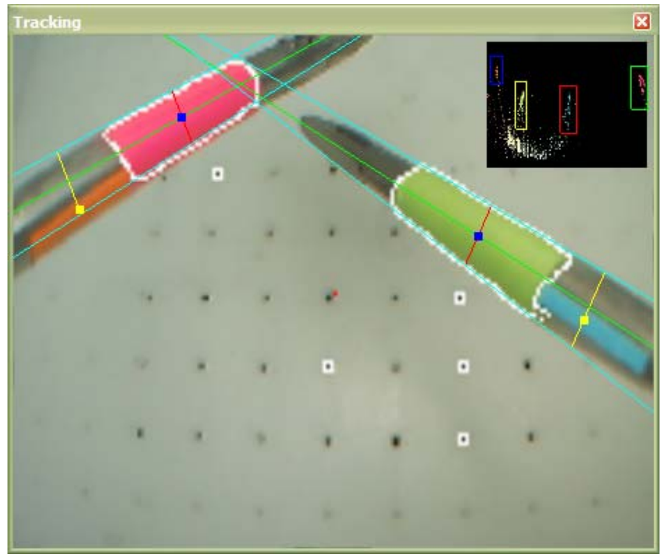

Fig. 6. Position tracking window showing both instruments with the colored strips attached, as well as a view of the processed image overlaid with the calculated geometric features and the hue selection histogram.

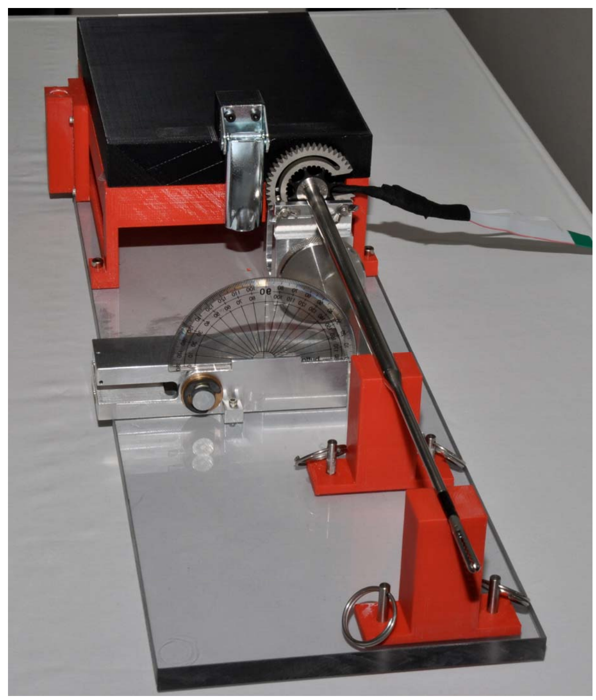

Fig. 7. Test bench for calibrating the forces in the individual directions.

IV. Performance Assessment

A. Force Calibration Assessment

A series of experiments were performed to evaluate the performance of the force sensors when forces were applied at the tip of the instrument, as follows:

1) Accuracy: To assess the accuracy of each signal, the instrument was placed in the calibration test bench while weights were applied from 0 to 500 g in 100 g increments in each direction. This process was repeated 3 times. The accuracy was calculated as the root mean squares (RMS) of the differences between the measured forces and the theoretical forces.

2) Repeatability: With the same data obtained for accuracy, repeatability was determined by calculating the maximum standard deviation (σ) observed during all of the trials.
3) Hysteresis: To assess the effect of hysteresis, weights were applied in each direction from 0 g to 500 g and back to 0 g in 100 g increments. The values at each weight level were then compared and the RMS error was calculated.
4) Signal drift and noise: Data were recorded for 10 seconds to measure signal noise and for 10 minutes to measure drift.
5) Coupling: the effect that each force has on the other forces was measured as the maximum deviation in all other signals when applying a force of 5 N in each direction.

The evaluation results are presented in Tables II and III.

B. Position Calibration Assessment

Other experiments were performed to assess the accuracy of the vision-based tracking system. Timing tests were performed to determine that the average acquisition speed of the vision-based tracking system is 10 frames per second. A 92 ms latency was measured from the time a frame was received from the frame grabber to when all processing of the frame is complete and is ready to be displayed. Although not ideal, this speed is sufficient for a human to react to the information being provided.

To evaluate the accuracy of the position readings, the rectangular plastic grid used during calibration was marked at the origin and at four further points up to 20 mm away from the origin along the x or y axes, all with a z coordinate of 0 mm. The coordinates reported by one of the instruments when pointed at these five locations were then recorded and compared to the theoretical locations. The recordings were repeated at distances of 7 mm and 14 mm along the z axis, facilitated by raising the plastic grid towards the camera using up to two of the plastic blocks used during calibration.

Angular accuracy was assessed by comparing the angular position of the instrument with that observed on a protractor placed at various orientations. Roll was assessed every 60° from 0° to 300°, sweep was assessed from 30° to 130° at four angular positions, and azimuth was evaluated from 0° to 180° at five angular positions. This process was repeated twice. Similar to the force measurements, the accuracy was calculated as the root mean squares (RMS) of the differences between the measured positions and the theoretical positions. Measurement repeatability was determined by calculating the maximum standard deviation (σ) observed at each position during the trials. The results of the position calibration assessment are presented in Table IV.

TABLE II
STRAIN GAUGE CALIBRATION ASSESSMENT

	RMS error	Max σ	Hysteresis	Noise / Drift
Actuation (N)	0.31	0.18	0.28	0.013 / 0.058
x axis (N)	0.08	0.04	0.10	0.015 / 0.057
y axis (N)	0.06	0.06	0.21	0.021 / 0.054
Torsion (N·cm)	0.07	0.12	0.10	0.004 / 0.027
Axial (N)	0.14	0.13	0.14	0.039 / 0.030

TABLE III
MAXIMUM DEVIATION FROM THEORETICAL ZERO CAUSED BY COUPLING

Caused by:	Effect on: Actuation (N)	x forces (N)	y forces (N)	Torsion (N·cm)	Axial (N)
Actuation	—	0.07	0.06	0.12	0.50
Bending	0.21	0.06 (y)	0.14 (x)	0.57	0.04
Torsion	0.03	0.03	0.30	—	0.65
Axial	0.1	0.05	0.05	0.11	—

TABLE IV
POSITION CALIBRATION ASSESSMENT

	RMS error	Max σ
x (mm)	1.3	1.43
y (mm)	1.5	1.85
z (mm)	2.9	3.09
Roll (°)	2.7	4.95
Sweep (°)	1.6	1.41
Azimuth (°)	3.8	5.09

V. CONCLUSIONS AND FUTURE WORK

A modular system has been designed and built that is capable of measuring forces in 5 DOFs and position in 6 DOFs. Novel design elements allow for good force sensing accuracy and signal decoupling. A new image-based tracking software has been developed to track both instruments simultaneously in all 6 DOFs using only the existing endoscopic video feed.

The accuracy of the position tracking system is comparable in x and y to that of EM tracking systems. Further refinements to the software are required to improve tracking accuracy in the z direction as well as the angular measurements. However, the most significant advantage of this system is how cost-effective and portable the system can become. 2D video images must always be acquired during MIS in order to provide a view of the surgical site. The utilization of these images to further provide 6-DOF information on instrument location and orientation is of great benefit and could be extended to many different areas and applications.

There are limitations to the use of visual images for position tracking. The position measured is with respect to a local frame of reference on the camera. As the camera moves, so does the coordinate frame, which limits the quality of the information obtained. Other inaccuracies are caused by occlusion of the markers by the other instrument or the tissue itself, or by staining of the markers by debris or fluids. Further work in this area is focusing on methods for tracking camera motion to provide position tracking in a world coordinate frame and complementing the visual images through the use of inertial sensors.

The force calibration assessment has been performed within the range of 0 to 5 N. This is considered to be a typical range of forces applied by MIS instruments, except for the grip forces, where the mean of the forces when driving needles could be 4 to 5 times higher. Within this range, accuracy measured was between 0.06 and 0.31 N, repeatability was between 0.04 and 0.18 N, and hysteresis was between 0.1 and 0.28. All of these measures are considered to be excellent compared to other existing technologies [22], allowing the developed instruments to effectively measure forces in all DOFs present in MIS.

It is unknown what level of resolution is required in actual surgical procedures. Depending on the type of procedure and the type of task being performed, the required force resolution might be quite different. However, having instruments capable of accurately sensing forces might allow further research to focus on determining the level of resolution required for different tasks and procedures.

The key to accurate axial force sensing was the design of the axial sensing element. Having a specialized element allowed the bending moments, torsion and axial forces to be completely decoupled. Coupling with the actuation force was inevitable with the current design, since the closing of the handle creates tension on the inner shaft, leading to compression of the middle shaft. To completely eliminate the coupling of these signals, future work will focus on devising a method to measure the actuation forces right at the tip of the instrument, which could be further enhanced by incorporating tactile sensors into the gripper.

These instruments will be used to collect force and position data while surgeons perform different procedures, with the goal of determining the best way of providing force feedback in real surgery and assessing the level of force sensing resolution required for different procedures.

It has been recognized that the future of MIS will be impacted by the development of smart surgical tools that can restore (or enhance) sensory capabilities [13]. The system presented above could have a significant impact on how MIS procedures are performed, potentially increasing the number of procedures that could be performed in a minimally invasive manner. The modularity of the system and the image-based tracking software make the system highly versatile and of low cost. It could be used for MIS training and skills assessment, for tissue characterization, to assist in the localization of diseased tissue or critical anatomical features, or for guidance near delicate areas.

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