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Semi-autonomous Surgical Tasks Using a Miniature In vivo Surgical Robot

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Abstract— **Natural Orifice Translumenal Endoscopic Surgery (NOTES) is potentially the next step in minimally invasive surgery. This type of procedure could reduce patient trauma through eliminating external incisions, but poses many surgical challenges that are not sufficiently overcome with current flexible endoscopy tools. A robotic platform that attempts to emulate a laparoscopic interface for performing NOTES procedures is being developed to address these challenges. These robots are capable of entering the peritoneal cavity through the upper gastrointestinal tract, and once inserted are not constrained by incisions, allowing for visualization and manipulations throughout the cavity. In addition to using these miniature *in vivo* robots for NOTES procedures, these devices can also be used to perform semi-autonomous surgical tasks. Such tasks could be useful in situations where the patient is in a location far from a trained surgeon. A surgeon at a remote location could control the robot even if the communication link between surgeon and patient has low bandwidth or very high latency. This paper details work towards using the miniature robot to perform simple surgical tasks autonomously.**

I. INTRODUCTION

Advances in surgical methods have allowed surgery to become less invasive. Open procedures are being replaced with laparoscopic surgery, thereby reducing patient trauma and improving patient recovery time. However, replacing the large incisions of open surgery with small incisions limits the visualization and manipulation capabilities of the surgeon. Specialized tools and instruments have allowed surgeons to overcome these limitations, making laparoscopy the preferred method for many procedures. Natural Orifice Translumenal Endoscopic Surgery (NOTES) is a step further in making surgery less invasive by completely eliminating external incisions through accessing the peritoneal cavity using a natural orifice, such as the upper gastrointestinal tract.

The transition from laparoscopy to NOTES potentially offers many of the same advantages as the transition from open procedures to laparoscopy, including reducing pain and improving patient recovery time. This transition, however, is limited by the constraints imposed by the size of the natural orifice and the requirement that instruments be flexible to traverse the natural lumen. Most NOTES procedures use flexible endoscopy tools to address these constraints, but this platform severely limits tissue manipulation and visualization, making a new approach to NOTES beneficial.

A robotic platform that attempts to emulate laparoscopic surgery for NOTES procedures is being developed. This paper details the work towards using this robotic platform to perform simple routine surgical tasks autonomously, enabling a surgeon at a remote location to control the robot even if the communication link has low bandwidth or has very high latency.

II. BACKGROUND

Laparoscopy has become the preferred method for many routinely performed surgeries. Studies have shown that laparoscopic procedures compare favorably to traditional open surgery by reducing pain, hospital stays, and speeding recovery [1]. While the move from traditional open surgery to laparoscopic surgery greatly reduces the invasiveness surgery, emphasis remains on making procedures less traumatic.

Accessing a surgical site through a natural orifice, as in NOTES, may be the next step in the evolution of minimally invasive surgery. NOTES feasibility was first demonstrated by Kalloo et al. using a transgastric approach in animal models [2]. Many studies demonstrating the feasibility of a transgastric and other approaches in animal models have followed, e.g. [3], [4]. NOTES procedures have also been successfully performed in multiple human cases including hybrid transvaginal laparoscopically-assisted cholecystectomies [5], and transvaginal and transgastric cholecystectomies [6], [7].

While these studies have demonstrated the feasibility of using a NOTES approach for performing surgical procedures, significant limitations have also been identified. It is difficult to determine spatial orientation, apply off-axis forces, and pass multiple tools through a single entrance point [8]. Many of the approaches for addressing these limitations are based on a flexible endoscopy platform such as the TransPort system from USGI Medical [9].

If completely *in vivo* devices are designed, multiple robots can be deployed through a single entrance point to provide vision or task assistance. The Magnetic Anchoring and Guidance System (MAGS) has been developed that includes an intra-abdominal camera, and instruments such as retractors and cautery that can be introduced into the peritoneal cavity through a single insertion point and held to the interior abdominal wall with an external magnet [10]. Similarly, an imaging device with multiple degrees of freedom has

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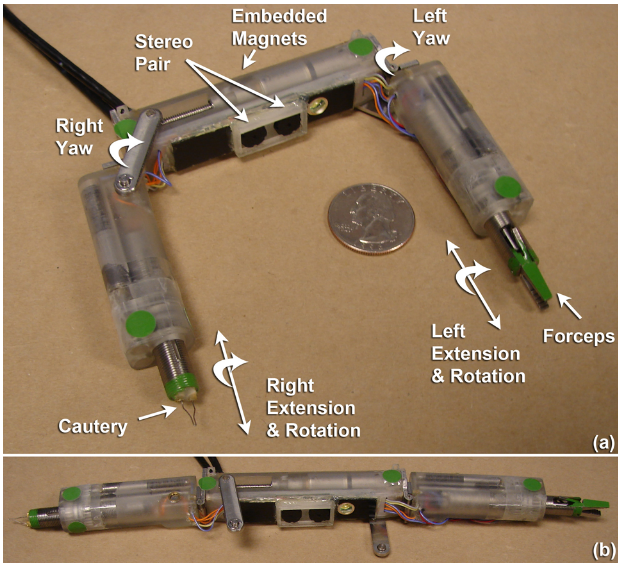

Fig. 1. Prototype NOTES Robot

been developed and demonstrated in animal model studies [11]. Eickoff, et al describe the results of the first human clinial trial of the NeoGuide Endoscopy System, a computer controlled colonoscope which automatically changes shape to avoid looping of the colonoscope [12].

A. *Visual Servoing*

Further efforts are directed towards the development of surgical robots for the automation of low-level, routinely performed tasks. Much of the work in application of visual servoing for minimally invasive surgery focuses on automatic positioning of a laparoscope. Some of the earliest work in this area was by Casals, et al. This system used laparoscopic tools with line and ring marks added to them to facilitate tracking by a computer vision system [13]. Wei, et al, implemented a laparoscope positioning system using color image segmentation to track the position of the laparoscope in real time [14]. Another method being developed for the automatic tracking of laparoscopic instruments is based on the measurement of the three-dimensional position of the instrument insertion points and simple models of the instruments [15] or markers [16]. A visual servoing system is also being developed that automatically brings the laparoscopic instruments into the center of the endoscopic image by means of laser pointers and optical instruments [18].

III. MINIATURE IN VIVO ROBOT FOR NOTES

In order to move the *in vivo* robots from surgical assistants to a platform that enables NOTES, a new design approach is needed that provides a stable platform for manipulation and visualization within the surgical environment, while also allowing flexibility for insertion. The miniature *in vivo* robot for NOTES, shown in Figure 1, consists of two prismatic arms connected to a central body by rotational shoulder joints. The linkage used for articulation of the shoulder joint can be disconnected, allowing flexibility at the shoulder joint for insertion. The left arm has a forceps end effector and the right has a cautery end effector. The body contains a stereo camera pair for visual feedback and magnets for attachment to the interior of the abdominal wall. Colored markers on the robot are used for real-time position tracking. Iterations of this NOTES robot design have been demonstrated in multiple surgeries in a porcine model including peritoneal exploration and partial cholecystectomy [19].

IV. SEMI-AUTONOMOUS TASKS WITH A NOTES ROBOT

In addition to using these robots for NOTES, these devices can also be used to perform semi-autonomous surgical tasks. Such tasks could be useful in situations where the patient is in a location far from a trained surgeon. A surgeon at a remote location could control the robot even if the communication link between surgeon and patient is of low bandwidth or has very high latency. In order to do this, the robot would need to be able to perform simple tasks autonomously. To investigate this, a system was designed using an existing NOTES robot prototype, seen in Figure 1. This system has three main components: visual tracker, controller, and stereo vision. The user is presented with a video capture from the robot. The user then selects a point on the image for the robot to move to (e.g. a piece of tissue to grasp or cut). The system then uses a stereo correspondence algorithm to compute the location of this point in 3D space. Once this point is verified by the user as correct, the controller moves the appropriate end effector to the desired position. This process is repeated until the desired task is completed.

A. *Tracker*

Joint position is found by visual tracking of several colored markers placed on the robot. Software on a PC equipped with frame grabbers analyses images from a camera located above the robot to locate these markers, Figure 2.

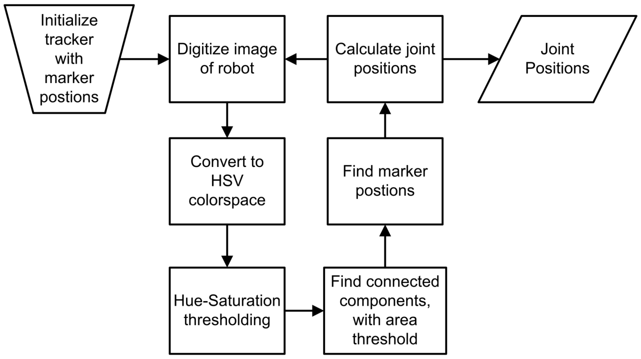

Fig. 2. Tracker Operation

At system startup, the tracker is initialized with starting marker positions either from an initialization file or by the user. A Sensoray Model 611 PCI framegrabber [20] is used to digitize an image from a camera. This image is then converted to HSV (Hue-Saturation-Value) color space where a thresholding of hue and saturation values is performed to isolate the pixels in the image that correspond to markers on the robot. A connected components algorithm is run on the resultant binary image to find the locations of markers in the image (Figure 3). The new marker positions are then found using previous known marker positions and the locations of markers in the image. Using the geometry of the robot, the joint positions and locations of the end effectors can be found.

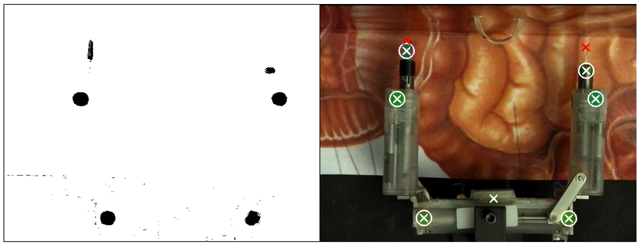

Fig. 3. Binary Threshold Image (left) and Marker Locations (right)

In the prototype system, the software tracks position using an overhead camera. The cameras on the robot did not provide a large enough field of view to enable tracking both end effectors over the entire workspace of the object. Rather than redesigning the robot, it was decided to first implement the tracker using the overhead view. In future devices, the tracker algorithm will be modified to track end effector positions from the cameras on the robot.

B. Controller

A PID controller was used for position control of each joint on the robot. First, each joint was modeled by analyzing the recorded response of each joint to a step input. A model for each joint was created. Initially, a proportional only controller was implemented, but with only proportional control, the amount of steady state error was unacceptable. With the addition of integral control, the steady state error was reduced to less than 0.5mm on the wrist joints and less than 0.5° on the shoulder joints. Each joint had a separate controller, all with an update rate of 5Hz.

C. Stereo Vision

The stereo vision component of the system is used to compute the desired end effector position based on user input. The user is presented with one of two images from the stereo imager pair on the robot, where he or she selects a piece of tissue to grasp or dissect. The software then uses a stereo correspondence algorithm to find the corresponding point in the image from the other stereo imager. Using the locations of these two points and the geometry of the cameras, the three dimensional coordinates of the point are calculated which are then confirmed by the user and used as input to the controller. Due to time constraints and the complexity of stereo correspondence algorithms, it was decided to use an existing algorithm from [21], rather than designing an algorithm specific to this application.

V. RESULTS

Several benchtop tests of the system were conducted. The robot was placed in a mount to keep it stationary. A piece of rubber band was placed in a separate mount in the middle of the robot's workspace to simulate a piece of tissue. A digital camcorder was mounted above the robot and tissue model. Each test was a simulated stretch and dissect task:

1) User selected location on tissue model to grasp.
2) Robot moved forceps arm to selected location.
3) User manually activated forceps.
4) Forceps arm was translated back to stretch tissue.
5) User selected point to cut with cautery arm.
6) Robot moved cautery arm to selected location.
7) Both arms moved back to starting position.

All images and data were saved for later analysis. Figure 4 shows positional data from the cautery end effector during the movement in step 6 of the task, calculated after the test from saved data. A graph of the tracker positional error over this movement is shown in Figure 5. The maximum measured error during tracking was 0.7mm, with a mean error of 0.3mm. These figures are typical of all movements over both arms.

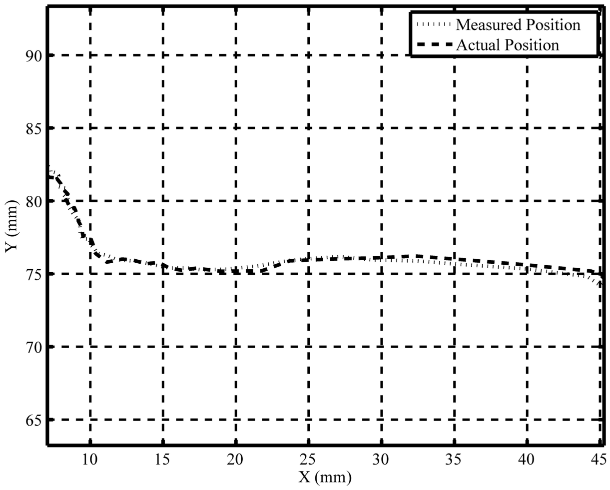

Fig. 4. End Effector Position

The performance of the digital controller is illustrated in Figure 6. This shows a graph of command angle and actual angle of the gripper arm during the movement in step 1 of the task. The steady state error of this response is 0.26°, or 0.1%.

VI. CONCLUSION

This paper presents a miniature *in vivo* robotic device for NOTES. This robot was used to develop a system capable of semi-autonomous task completion. The system uses an overhead camera for tracking the position of the robot in real time and a PI controller for position control of each of the robot's joints. A stereo correspondence algorithm computes joint positions based on user input. The tracker and controller functioned well during several benchtop tests.

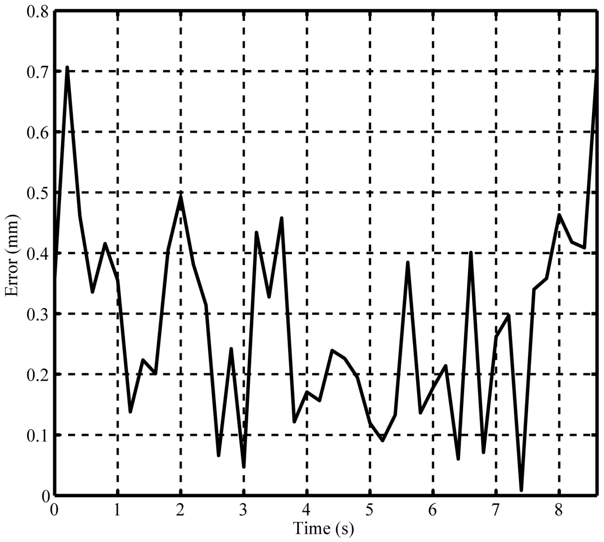

Fig. 5. Positional Error

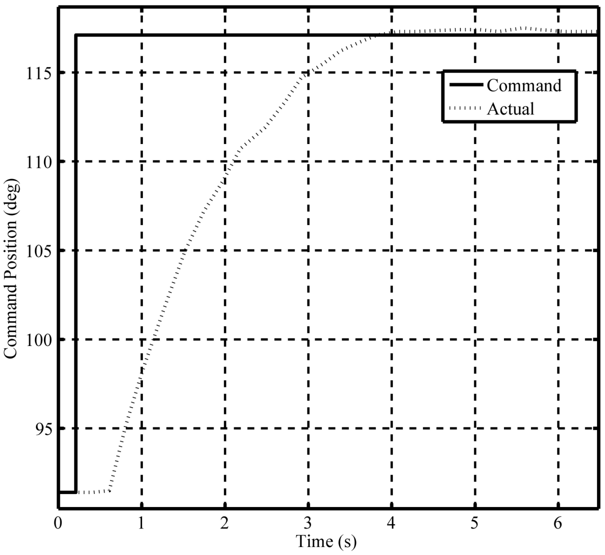

Fig. 6. Controller Performance

Future work on this project will include modifying the tracker to use images from the stereo pair on the robot for real time tracking. This would eliminate the need for the overhead camera, which is obviously not feasible in an *in vivo* situation. This system could also be adapted to current and future *in vivo* robotic devices, which are faster and provide more degrees of freedom than the device described here, which has a response time that is much to slow for surgical procedures (see Figure 6). A stereo correspondence algorithm specifically designed for this application will also be developed.

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