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Robotic Natural Orifice Translumenal Endoscopic Surgery

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Abstract— **Gaining access to the peritoneal cavity through a natural orifice is potentially the next paradigm shift in minimally invasive surgery. Natural Orifice Translumenal Endoscopic Surgery (NOTES) provides distinct patient advantages, but is surgically challenging. Access to the peritoneal cavity is limited by the size and complex geometry of the natural lumen, and existing tools do not adequately address these constraints. A miniature *in vivo* robot with two "arms" and a central "body" has been developed for NOTES. The robot can be advanced through the esophagus and into the peritoneal cavity using an overtube and endoscope. Once completely inserted, the robot provides a stable platform for visualization and dexterous manipulation from arbitrary orientations. *In vivo* testing of the NOTES robot in a porcine model has been successful. Using the robot, the surgeon was able to explore the abdominal cavity and perform small bowel dissection. In addition, benchtop testing has demonstrated the ability of the robot arm to follow a predetermined path in Cartesian space and shows good results towards future three-dimensional feedback control.**

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I. INTRODUCTION

The performance of surgeries through small incisions, such as in laparoscopy, reduces invasiveness as compared to open procedures. These procedures are generally safer, shorten patient recovery time, reduce expense, and improve cosmetic results as compared to general surgery. Natural Orifice Translumenal Endoscopic Surgery (NOTES) is a new approach to abdominal surgery that further reduces invasiveness by gaining access to the surgical target through a natural orifice. Theoretically, transgastric access to the peritoneal cavity through a natural orifice has several advantages over laparoscopy. While laparoscopy reduces the effects of penetrating the abdominal wall, access through a natural orifice requires no external incisions. This eliminates possible wound infections, further reduces pain, improves cosmetics, and speeds recovery. Also, the NOTES approach could allow the use of minimally invasive techniques on obese patients where the thickness of the abdominal wall prevents laparoscopy. A NOTES approach has the potential to again revolutionize general surgery.

While NOTES is very appealing from the patient's perspective, it is also surgically challenging. Access is limited to the size of the natural orifice making it difficult to have multiple instruments simultaneously passing through an orifice. The instruments must also be flexible throughout their entirety to traverse the natural lumen. Current endoscopic tools are inadequate. New technologies and tools are needed to overcome these challenges and improve the surgeon's ability to manipulate and visualize the surgical environment through a NOTES approach.

This paper presents the feasibility of using an *in vivo* miniature robot for NOTES. An *in vivo* miniature robot would be capable of being inserted through the lumen of the intestinal tract through the upper approach, as shown in Fig.1. Once fully inserted, the robot could be used inside the peritoneum without the typical constraints of an externally actuated endoscopic device, improving both the visualization and dexterity of the surgeon.

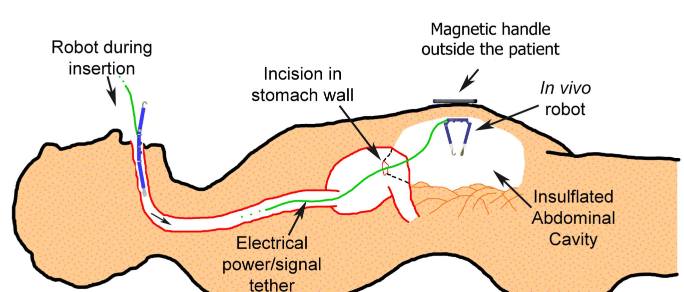

Fig. 1. Natural orifice surgery with miniature *in vivo* robot.

II. Background

A. Laparoscopic Surgery

Traditional open surgery requires incisions large enough for the surgeon to see and place fingers and instruments directly into the operating site. It is widely accepted that the trauma inflicted while gaining access to the area to perform a surgical procedure often causes additional injury to the patient, resulting in more pain, longer recovery times, and increased morbidity. Beginning in the early 1990s new technology (advanced laparoscopes, clip appliers, energy sources, and robotics) enabled a rapid period of development for minimally invasive surgery as an alternative to conventional surgery [1], prompting a paradigm shift in surgical methods [2]. Minimally invasive abdominal surgery (i.e. laparoscopy) has become the treatment of choice for several routinely performed interventions. Studies clearly show that laparoscopic procedures result in shorter hospital stays, less pain, more rapid return to the normal activities of daily living, and improved immunologic response [3].

B. Natural Orifice Translumenal Endoscopic Surgery

Many believe the next logical step in further minimizing the invasiveness of surgical procedures is to gain access to the surgical site through a natural orifice. The feasibility of Natural Orifice Translumenal Endoscopic Surgery (NOTES) has been evaluated in several animal-model laboratory experiments. The basic procedure and technical feasibility of a NOTES approach was first demonstrated by Kalloo [4]. This study included twelve nonsurvival and five survival examinations of the peritoneal cavity in an animal model utilizing natural orifice transgastric access. Subsequent studies evaluating the safety and feasibility of transgastric procedures include survival studies of ligation of fallopian tubes [5], peritoneal exploration and organ resection [6], gastrojejunostomy [7], partial hysterectomy [8], gastrojejunal anastomosis [9], lymphadenectomy [10], and oophorectomy and tubectomy [11]. Similarly, nonsurvival transgastric studies include cholecystectomy [12], splenectomy [13], and a feasibility study of diaphragm pacing [14].

Alternatively, the transvesical and transcolonic approach to peritoneal access have been evaluated. The transvesical approach to endoscopic peritoneoscopy of the abdomen and liver biopsy has been evaluated in an experiment including three nonsurvival and five survival animals [15]. Transcolonic abdominal exploration has also been demonstrated [16], with the first successful survival NOTES cholecystectomy in an animal model using the transcolonic approach [17]. Another study has assessed the feasibility of using a combined transgastric and transvesical approach to perform cholecystectomy [18].

The first transgastric appendectomy procedure in humans has been described by Rao et al, although no publications are yet available [19]. In March 2007, Marc Bessler (New York-Presbyterian Hospital/Columbia University Medical Center), performed the first transvaginal assisted gallbladder removal operation in the United States [20]. Subsequently, in June 2007, the first transgastric cholecystectomy in the United States was performed by Dr. Lee Swanstrom (Oregon Clinic) utilizing the EndoSurgical Operating System (USGI Medical) [21].

C. Instruments for NOTES

While the above studies were successful, they clearly show that a NOTES approach is surgically challenging. Conventional tools are not specifically designed to be used in a NOTES approach to surgical procedures, and many of the above researchers described the severe constraints of working with flexible tools through a natural orifice and long curved natural lumen. Constraints associated with the usage of conventional tools include maintaining spatial orientation and the development of a multitasking platform, as well as limited tissue manipulation due to small diameter tools and the constrained directionality of force application [19],[22], [23]. Clearly there is a need for new instruments for NOTES procedures. Technology, such as robotics, has significantly influenced laparoscopy and has potential to bring about a revolution in the application of NOTES by mitigating the complications of manipulation and visualization.

D. Robotic Assistants for Minimally Invasive Surgery

The use of robotics is currently recognized as having a significant impact on the advancement of minimally invasive surgery [24],[25]. The first robot to be used in clinical practice was the Automated Endoscopic System for Optimal Positioning (AESOP), a robotic camera holder that received FDA approval in 1994 [24],[25]. The da Vinci Surgical System (Intuitive Surgical), is a more advanced, commercially available telerobotic system that serves in a master-slave relationship with the surgeon where the robotic arms hold the surgical instruments. Advantages of more sophisticated telerobotic systems, such as da Vinci, include stereoscopic vision, tremor reduction, motion scaling, corrections for motion reversal, and articulating end-effectors [25].

Much effort is currently being directed toward the development of next-generation robots that improve sensing and mobility while reducing complexity and cost. For example, developments are focusing on force and tactile feedback for telesurgical applications [26], and canceling tremor in handheld surgical tools [27]. Smaller robots with force and tactile feedback are also being developed [28].

None of these robots can be directly applied to NOTES because they are not capable of navigating the complex curved geometry of the natural lumen. All of these systems are implemented from outside of the body, and will always be constrained to some degree by the entry incision.

E. In Vivo Robots for Minimally Invasive Surgery

Many medical robots have been developed in which all, or most, of the device enters the body. Maneuverable endoscopes and locomotion devices have been developed for exploration of hollow cavities such as the colon or esophagus [29]-[31]. Still another robot under development moves across the surface of a beating heart [32]. Miniature *in vivo* robots are also being developed to assist in laparoscopy. These robots are fully inserted through a laparoscopic trocar and are designed to provide vision and task assistance without the constraints of the entry incision [33],[34]. A miniature mobile robot has been used to successfully cross from the gastrointestinal tract into the peritoneal cavity [35]. There is a need for a new approach to NOTES procedures. As robotic technology has aided in the application of laparoscopy, there is a potential for robots to enable the use of a NOTES approach.

III. NOTES Robot

A. NOTES Robot Design Overview

A miniature *in vivo* robot with stereoscopic vision has been developed for insertion into the peritoneal cavity through the upper gastrointestinal tract approach. The basic design of the NOTES robot, as shown in Fig. 2, consists of two prismatic "arms" each connected to the central "body" by a rotational "shoulder" joint. The left and right arms have a forceps and cautery end-effector, respectively

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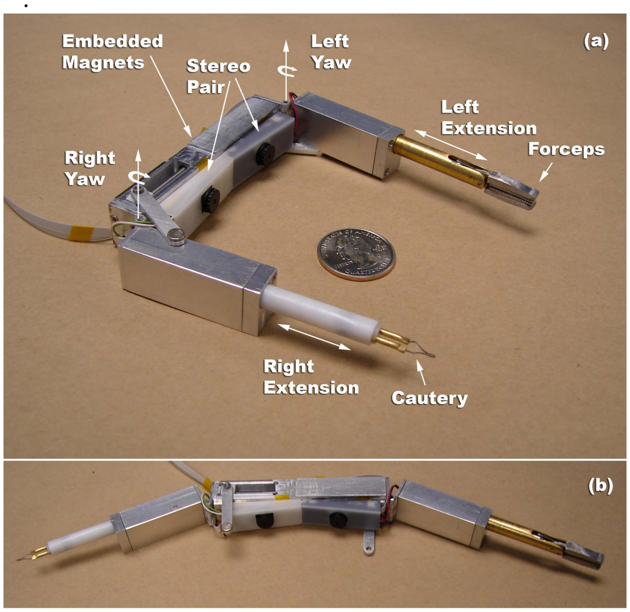

Fig. 2. NOTES robot in (a) articulation and (b) insertion configurations.

The body contains embedded magnets that interact with magnets housed in the external magnetic handle to attach the robot to the interior abdominal wall. Gross repositioning of the robot is accomplished through repositioning the external magnetic handle. This provides the surgeon with the ability to visualize and manipulate within the peritoneal cavity from different orientations throughout a procedure. The body also contains a stereo camera pair and the motors for articulation of the shoulder joints.

Two basic configuration of the NOTES robot enable flexibility for natural orifice insertion, and rigidity for visualization and tissue manipulation. In the insertion configuration, the linkage connecting each arm to the body is disconnected to allow the shoulder joints to freely rotate for insertion through the complex geometry of the natural lumen. Once fully inserted into the peritoneal cavity, each linkage is reconnected to provide a stable platform for visualization and application of significant off-axis forces.

B. NOTES Robot Kinematic Design and Modeling

A kinematic model of the NOTES robot is shown overlaid on the robot schematic in Fig. 3. The robot is a 2-DOF planar manipulator with a rotational shoulder joint and prismatic arm denoted by joint variables θ_2 and a_2 respectively.

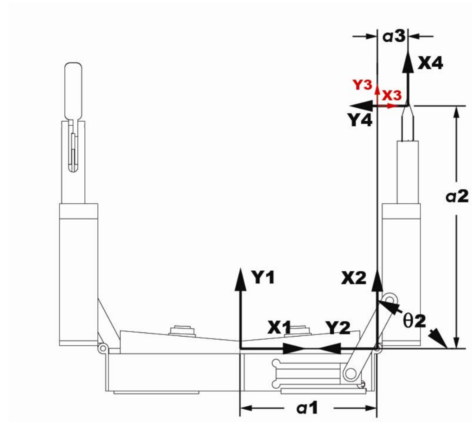

Fig. 3. Kinematic model of the NOTES robot.

The Denavit-Hartenberg parameters for the robot are shown in Table I. The parameter α_0 defines the angle of rotation of the robot with respect to a universal frame {0} that is used to introduce gravity. Parameters a_1 and a_3 are constants defining the body width and offset of the end-effector with respect to the axis of rotation of the shoulder joint, respectively.

TABLE 1
Denavit-Hartenberg Parameters

i	α_{i-1}	a_{i-1}	θ_i	d_i
1	α_0	0	0	0
2	0	a_1	θ_2	0
3	0	a_2	-90	0
4	0	a_3	90	0

Using the general kinematic model and the Denavit-Hartenberg parameters, the equations that describe the location of the end-effector in frame {1} are defined and used to derive the Jacobian of the robot as given in (2) - (3).

$$ {}^{1}P_{Org4} = \begin{bmatrix} c_{\theta_2} a_2 + s_{\theta_2} a_3 + a_1 \\ s_{\theta_2} a_2 - c_{\theta_2} a_3 \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{1} $$

$$ J(q_1, q_2) = J(\theta_2, a_2) = \frac{\partial}{\partial q_i} {}^{1}P_{Org4} \tag{2} $$

$$ {}^{1}J = \begin{bmatrix} -s_{\theta_2} a_2 + c_{\theta_2} a_3 & c_{\theta_2} \\ c_{\theta_2} a_2 + s_{\theta_2} a_3 & s_{\theta_2} \end{bmatrix} \tag{3} $$

Inverse kinematic equations for joint variables a_2 and θ_2 are obtained by solving (1).

$$a_2 = \sqrt{x^2 + y^2 - 2xa_1 + a_1^2 - a_3^2} \tag{4}$$

$$\theta_2 = \arctan 2(A, B) \tag{5}$$

$$A = \frac{xa_3 + ya_2 - a_1 a_3}{x^2 + y^2 - 2xa_1 + a_1^2} \tag{6}$$

$$B = \frac{a_2 \left(x - a_1 \right) - ya_3}{x^2 + y^2 - 2xa_1 + a_1^2} \tag{7}$$

The geometry of the shoulder joint is given by the kinematic model of an offset slider crank mechanism, shown in Fig. 4. Distance, *e*, is the offset distance from the line of action of the slider to the axis of rotation of the arm, and distance, *s*, is the location of the slider with respect to the axis of rotation.

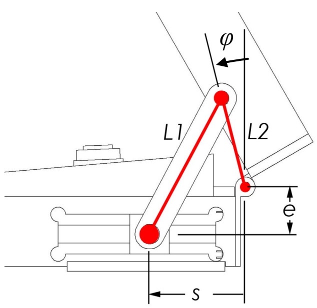

Fig. 4. Kinematic model of NOTES robot shoulder joint.

Position and velocity equations derived from the above configuration can be solved for slider position and velocity as functions of crank position, φ, and angular velocity.

$$s = L_2 \sin\varphi + L_1 \sqrt{1 - \left(\frac{e + L_2 \cos\varphi}{L_1} \right)^2} \tag{8}$$

$$\dot{s} = \dot{\varphi} \left[L_2 \cos\varphi + \frac{L_2 \sin\varphi}{L_1} \frac{\left(e + L_2 \cos\varphi \right)}{\sqrt{1 - \left(\frac{e + L_2 \cos\varphi}{L_1} \right)^2}} \right] \tag{9}$$

C. Robot Control

Open-loop control tests were performed with the NOTES robot for a Cartesian straight line path. Using a linear function with parabolic blends and assuming a maximum allowable velocity, a path was planned in Cartesian space. The Cartesian path was converted to joint space using the inverse kinematic relationships, and the inverse of the Jacobian.

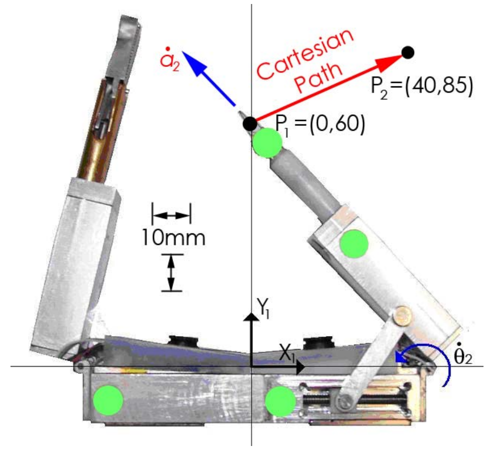

Fig. 5. Planned open-loop Cartesian straight line path.

A path from P1=(0,60) to P2=(40,85) (mm) in Cartesian space was generated, as shown in Fig. 5, and converted to joint space position and velocity traces, as shown in Fig. 6. Joint variable θ_2 was then converted to actuator space, where velocity is linearly related to motor speed, using the equations derived for the offset slider-crank mechanism.

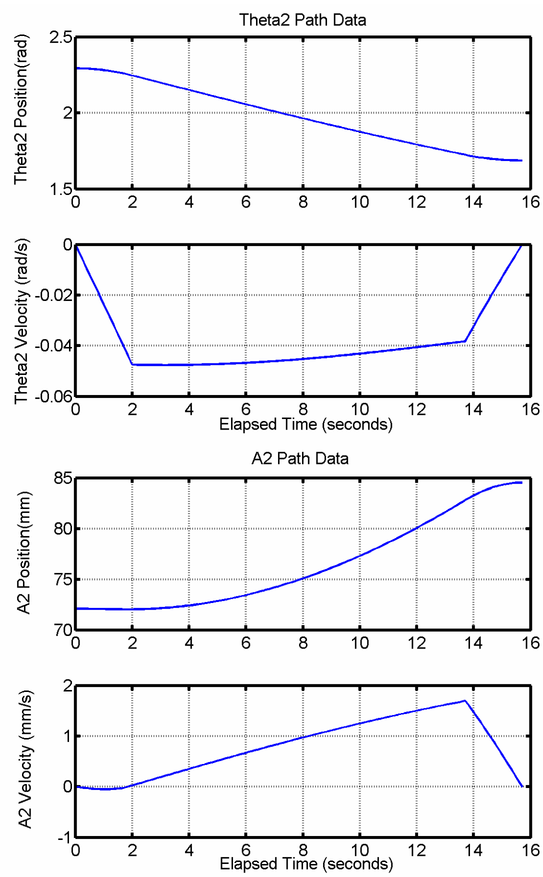

Fig. 6. Planned joint space position and velocity paths.

Using the generated actuator space velocity traces, six open-loop tests were performed. A comparison of the planned path and the actual paths is shown in Fig. 7. The mean of the actual paths is given as a dotted line with an envelope containing all paths. While the open-loop tests closely follow the desired path, feedback control will improve system performance. Path error as a function of distance along path for the open-loop tests is shown in Fig. 8. Mean error as well as deviations encompassing all six tests are shown. As expected error generally increases as the path is traversed.

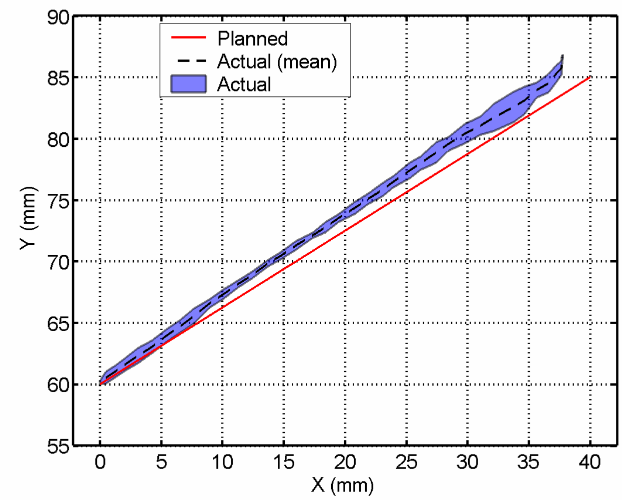

Fig. 7. Comparison of planned path and actual path.

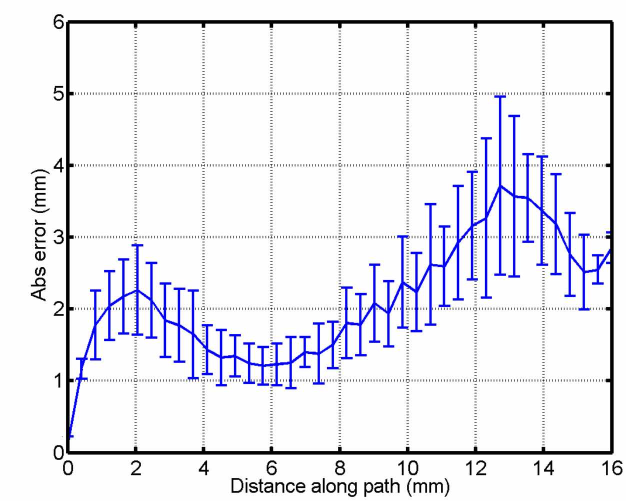

Fig. 8. Path error as a function of distance along the path.

IV. In Vivo Results

The NOTES robot successfully demonstrated various capabilities *in vivo* in a non-survivable porcine model. Prior to robot insertion, an overtube was advanced through the esophagus and into the peritoneal cavity through a transgastric incision using the endoscope. The robot, in its insertion configuration, was advanced using an endoscope through the overtube and into the peritoneal cavity, as shown in Fig. 9.

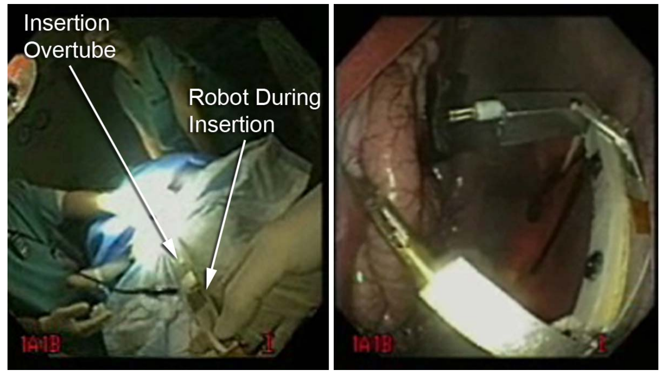

Fig. 9. NOTES robot shown being inserted through overtube (left) and manipulating within peritoneal cavity (right)

Once fully inserted, the robot was configured for articulation. The robot was then grossly positioned using the exterior magnetic handle to provide a suitable workspace for visualization and tissue manipulation. The on-board robot cameras were used to explore the peritoneal cavity and to visually guide the surgeon in the performance of the surgical tasks. The design of the robot enabled the surgeon to apply sufficient forces in arbitrary directions to successfully perform *in vivo* stretch and dissect tasks, as shown in Fig. 10. The stable visualization platform also enhanced the surgeon's understanding of the surgical environment.

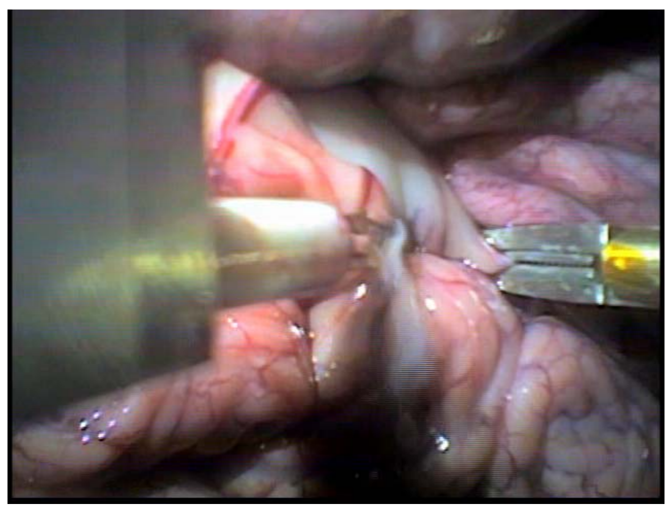

Fig. 10. NOTES robot performing small bowel dissection.

V. Conclusion

The successful *in vivo* demonstration of the NOTES robot suggests the feasibility of using miniature *in vivo* robots for performing natural orifice procedures in the peritoneal cavity. The design of the robot enabled flexibility for insertion through the natural lumen, and once deployed provided a stable platform for dexterous tissue manipulation from arbitrary orientations. The visual feedback provided by the on-board cameras, and the ability to easily reposition the robot enabled the surgeon to explore and manipulate within the peritoneal cavity. Further, benchtop testing has demonstrated the ability of the robot to follow a straight line path in Cartesian space.

Current work is focused on improving dexterity and control through increasing the degrees of freedom and developing feedback control capabilities in three dimensional space. These developments are important to enhancing the capability of *in vivo* miniature robots to further provide task assistance.

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