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MULTI-FUNCTIONAL SURGICAL ROBOT FOR LAPARO-ENDOSCOPIC SINGLE-SITE COLECTOMIES

T. D. Wortman
University of Nebraska - Lincoln
Lincoln, NE

R. L. McCormick
University of Nebraska - Lincoln
Lincoln, NE

E. J. Markvicka
University of Nebraska - Lincoln
Lincoln, NE

T. P. Frederick
University of Nebraska - Lincoln
Lincoln, NE

S. M. Farritor
University of Nebraska - Lincoln
Lincoln, NE

D. Oleynikov
University of Nebraska
Medical Center
Omaha, NE

ABSTRACT

This paper presents work to develop a miniature in vivo robot for Laparo-Endoscopic Single-Site (LESS) colectomy. Currently, several complex surgical procedures are unable to be performed utilizing minimally invasive techniques. This is due to standard laparoscopic tools being non-intuitive and having multiple constraints, such as limited dexterity and imperfect visualization. Colon resections are generally not done laparoscopically and would benefit from a robotic platform that reduces the limitations that are currently encountered. By shifting colon resections from a standard open procedure to a minimally invasive procedure utilizing a robotic platform, several advantages will result. These advantages include reduced cost and hospital stay times, along with improved patient recovery and cosmetics. This paper looks at the workspace, forces, and speeds of a recently developed miniature in vivo surgical robot platform and analyzes the ability to perform a colon resection based on these criteria. This information is then compared to investigate the question of whether or not a robotic platform of this type is capable of colon surgeries. The robotic platform used in this study consists of a two armed robotic prototype and a remote surgeon interface. The robot is comprised of two four degree-of-freedom arms with shoulder and elbow joints. Each arm is equipped with specialized interchangeable end effectors. The robot has the ability to incorporate an on-board stereoscopic vision system or use a standard laparoscope. For the surgical procedure, each arm of the robot is inserted individually into a single five centimeter incision and then assembled within the abdominal cavity. The robot is then mated to a support rod and then grossly positioned so that the workspace best coincides with the portion of the colon that is being removed. A surgeon then utilizes a user interface that is remotely located within the operating room. The interface consists of a monitor, a foot pedal for locking and clutching the workspace, and two PHANTOM Omni controllers. The current robotic platform has not yet been demonstrated in an in vivo procedure, however, initial analysis and benchtop testing shows that this method will be feasible for future colon resections.

INTRODUCTION

As more surgical procedures transition from open procedures to laparoscopy, additional patients are able to experience the advantages of quicker recovery times, improved cosmetics, and decreased cost. The use of long instruments inserted through small incisions in the abdominal wall increases the complexity of the procedure in exchange for the added benefits. Such complexities include unintuitive control along with limited dexterity and vision. Because of this complexity, colon resections as well as other procedures are rarely performed laparoscopically. Out of the 240,000 colon resections performed in the United States annually, only ten percent are performed as laparoscopic procedures. The size and shape of the colon makes it difficult to reach and visualize when using traditional laparoscopic techniques and tools. Another difficulty occurs once the colon is mobilized, as an extra 3-4 cm incision is required for specimen extraction.

Another minimally invasive surgical technique is Laparo-Endoscopic Single-Site (LESS) surgery. LESS surgery is performed by utilizing multiple articulating, bent, or flexible

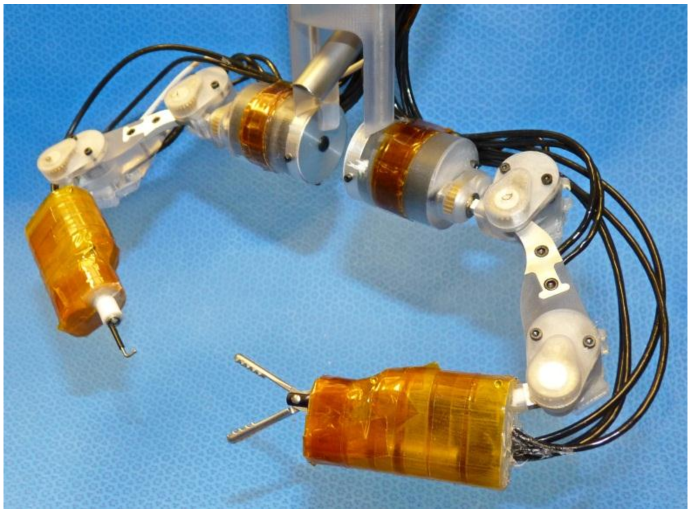

FIGURE 1. MULTI-FUNCTIONAL SURGICAL ROBOT

laparoscopic tools inserted through a single specialized port through the abdominal wall. By using one incision in or around the umbilicus instead of multiple small incisions, cosmetics can be improved and recovery time and cost can be reduced. This technique is particularly attractive for colectomies due to the 3-4 cm incision being the only incision needed, eliminating the additional small incisions needed for traditional laparoscopic colectomies. By performing colectomies utilizing a LESS procedure instead of an open procedure, hospital stays can be reduced from 4-6 days to 1-2 days [1]. However, current LESS techniques involve crossing the bent tools, resulting in the right end effector being controlled by the left hand, and vice versa. This adds to the already unintuitive control motions of traditional laparoscopic tools.

Various robots are currently being developed capable of robotic assisted laparoscopic surgery. The commercially available *da Vinci Surgical System®* (Intuitive Surgical) is currently used in hospitals around the world. This system allows for a surgeon located at a remote workstation to control laparoscopic tools working through incisions in the abdominal wall. Advantages of this system, as compared to traditional laparoscopic surgery, include wrist articulating end effectors, tremor filtering, and more natural control [2-4]. Despite the advantages of this system, its use is limited to its large size and high cost. Research is being performed to develop more compact laparoscopic surgery robots that also control long tools inserted through the abdominal wall. Examples include the Raven [5] and COBRASurge [6]. Due to the fact that all of these robotic systems still face the constraints of end effector position being controlled from outside the abdominal wall, their ability to work in multiple quadrants of the abdominal cavity is limited. This ability becomes increasingly important for colectomies due to the size and shape of the colon.

Robotic platforms for use in LESS procedures are also being developed. The *da Vinci* robotic system has been used to perform various LESS surgeries, including a right colectomy [7]. *Da Vinci* LESS procedures are still relatively new and are much rarer than traditional robot-assisted laparoscopic procedures. In addition to high cost and large size of this system, the redocking time to perform multiple quadrant surgery also limits its use for multi-quadrant colectomies.

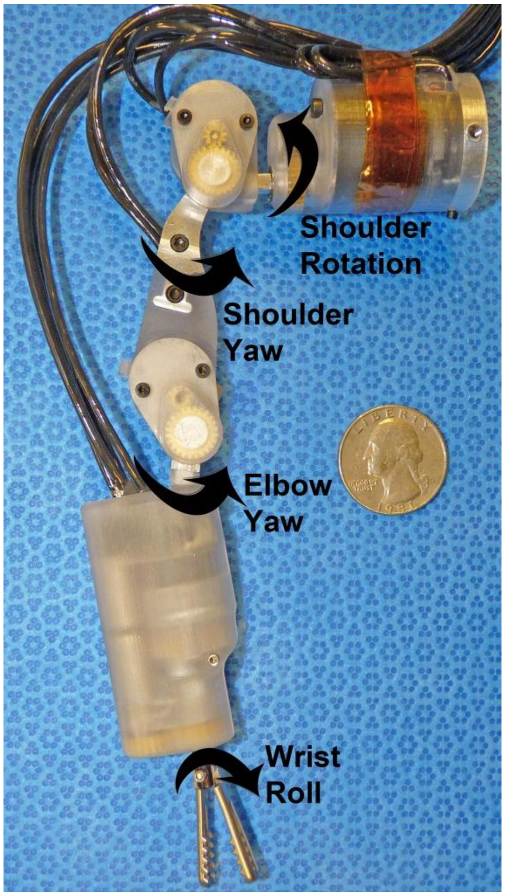

FIGURE 2. SEPARATED ROBOTIC ARM

Previous work within this research group has demonstrated the feasibility of using a two-armed dexterous *in vivo* surgical robot through multiple gall bladder removals, or cholecystectomies, and a partial colectomy through open procedures on live porcine models. Additionally, the ability to completely insert a miniature robot into the abdominal cavity through a single incision of a live porcine model and manipulate tissue in all quadrants through repositioning has been performed [8].

In this paper, a four degree-of-freedom surgical robot designed for LESS colectomies is presented. The robotic platform design, including robotic prototype and remote user interface will be discussed. Analysis of theoretical forces, speeds, and manipulability of the robot over its workspace will also be presented. Finally, *in vivo* results will demonstrate the feasibility of this prototype.

SURGICAL ROBOT PLATFORM DESIGN

Previous research within our group has demonstrated the feasibility of using a completely insertable robotic platform to address the limitations associated with LESS colectomies. A

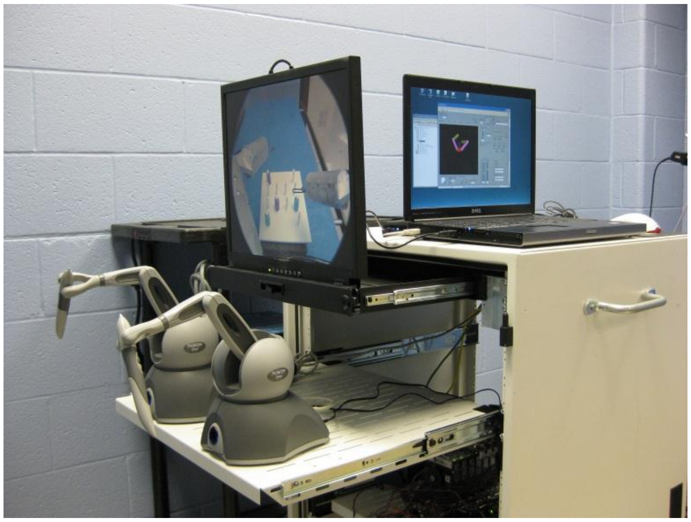

FIGURE 3. SURGICAL USER INTERFACE

platform utilizing this previous knowledge while making additional improvements has been designed and built. These improvements include a change in kinematics, smaller size, and increased joint limits. This platform consists of a two-armed miniature *in vivo* robot and a remote surgeon interface.

Robotic Prototype

The basic robot design consists of two four degree-of-freedom arms (Fig. 1). This robot is designed to be inserted into a single five centimeter incision and be completely contained within the abdominal cavity. The symmetric arms can be separated for insertion and then mated to a support rod once inside. Control rods are used to line up each arm and a custom mating piece and fasteners are used to lock the robot to the support rod. This support rod provides gross positioning of the robot once inside. The task of inserting and assembling the robot within the abdomen takes an average of five minutes to complete.

Each arm of the robot is made up of a torso, upper arm, and forearm. A two degree-of-freedom shoulder joint, located between the torso and the upper arm, provides yaw and pitch. A one degree-of-freedom elbow joint also provides yaw. A single arm with labeled degrees-of-freedom can be seen in Fig. 2. Specialized, interchangeable end effectors are available for use on both forearms. These end effectors provide tissue manipulation, monopolar cautery, and intracorporeal suturing capabilities. Each end effector has a rotational degree-of-freedom, along with open/close actuation if necessary.

Each robot joint is actuated using coreless permanent magnet direct current motors with magnetic encoders. The motors are housed in sealed cavities within the body and arms of the robot to prevent the electrical components from short circuiting in the moist environment. The motors are independently controlled using a proportional-integral-derivative (PID) control method. This is implemented using LabVIEW (National Instruments) software and two Compact RIO devices with NI 9505 motor modules. The software determines desired motor positions based on the inverse kinematics of the surgical robot. This information is then used by the Compact RIO motor drivers to move the motors to the desired positions in real time.

The robot has the ability to incorporate an on-board stereoscopic vision system or use a standard laparoscope. This gives the robot “eyes” and a light source within the abdominal cavity.

User Interface

The surgeon interface, located remotely within the operating room, consists of a video display, foot pedals, and two PHANTOM Omni (Sensable) controllers. This set up can be seen in Fig. 3. The video display is a high definition monitor that provides vision feedback from the on-board vision system or the laparoscope. The foot pedals are a triple action switch that allows for individual locking of both the left and right robotic arms, as well as clutching for resetting the position of the controllers within the workspace.

The two PHANTOM Omni’s are used to control the motion of the robot. The motion of these controllers is captured using a laptop and then mapped to the associated motor angles. These controllers and associated software provide different benefits that can be used to improve a surgeon’s experience. The controllers provide three degree-of-freedom force feedback. This haptic control is harnessed to limit the surgeons commands to the workspace and reduce hand tremor. The control architecture that is implemented allows for scaling. Scaling gives the surgeon the ability to change the precision of his/her movements within a single surgery.

WORKSPACE

Robotic workspace is defined as the volume of space that the end effector of each arm can reach. Workspace can be found mathematically by using the kinematic equations and the joint limits. For a four degree-of-freedom robotic arm, the workspace volume can be more easily calculated by finding the maximum and minimum reach and then revolving about the joint axes.

Surgical robots must have a large workspace so that the robot will not need to be grossly repositioned several times during a surgical procedure. Ideally, the workspace will encompass the entire volume that is involved in the surgical task. Workspace is dependent on link lengths and joint limits; therefore, because the robot must be small, the joint limit range must be maximized.

Furthermore, in the case of surgical robotics, just because a pair of arms has a large workspace does not mean they are ideal. The intersecting workspace, or workspace that both arms can reach, must be maximized. This is required so that the arms can cooperatively work together.

The intersecting workspace for the previously described robot was modeled along with a large intestine. This workspace along with the robot and colon can be seen in Fig. 4. The side and top view of this model show the workspace

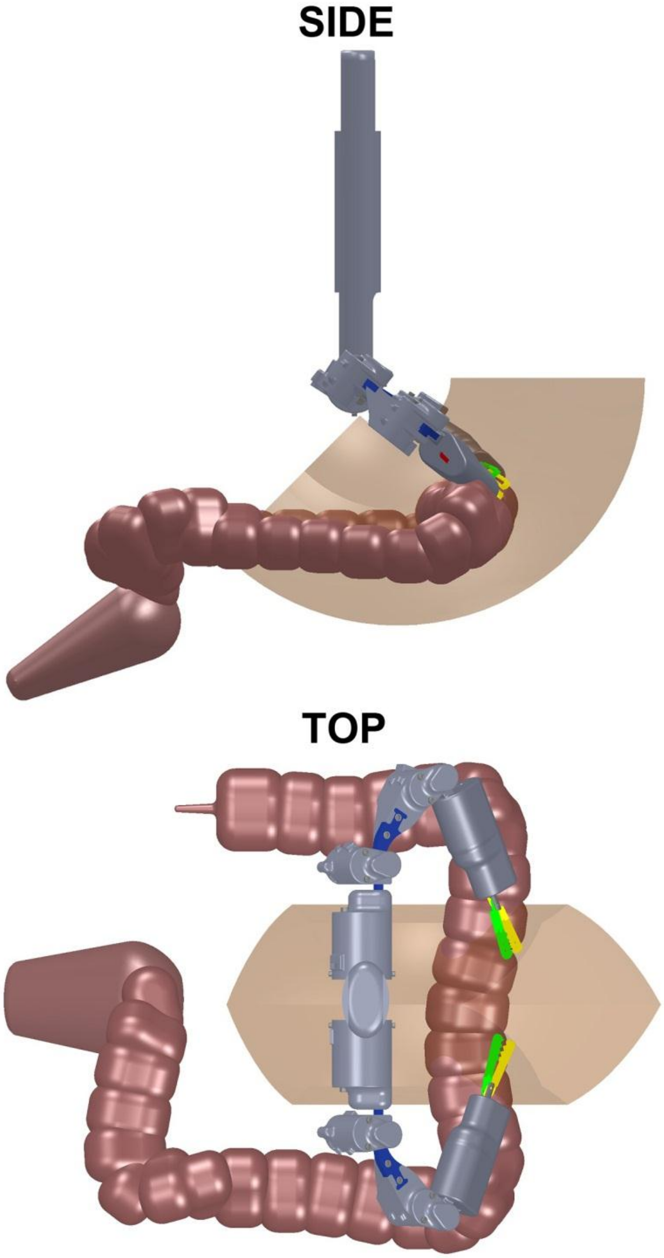

FIGURE 4. ROBOT WITH INTERSECTING WORKSPACE AND COLON

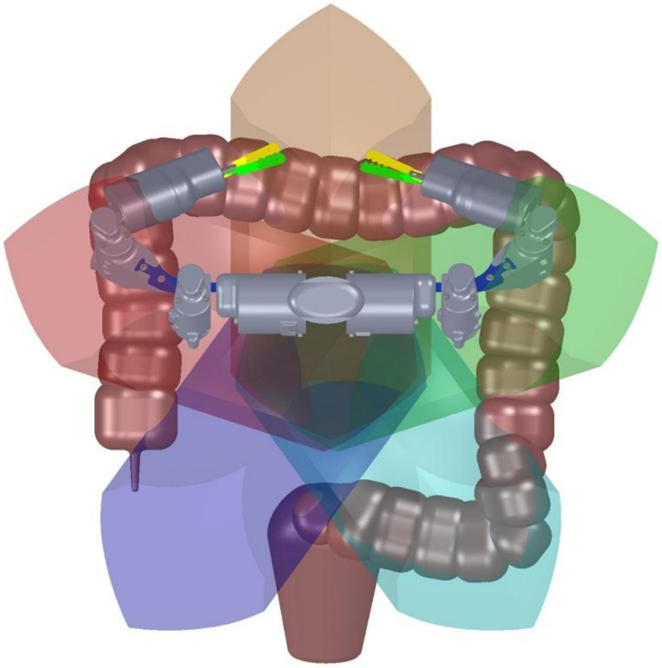

FIGURE 5. ROBOT WITH ROTATED INTERSECTING WORKSPACES

volume completely encompassing a section of the colon. The intersecting workspace essentially is a 9.5 cm square revolved around the body of the robot where the minimum and maximum reach is 50.8 and 132.2 mm, respectively.

For some colectomy procedures a large portion of the colon must be removed. This is where the advantage of a maneuverable support rod comes into play. By rotating the rod, all four quadrants of the abdominal cavity can be accessible. In order to remove an entire section of the colon, such as the ascending or transverse colon, it is assumed that three to four repositionings will need to occur. In previous *in vivo* studies, repositioning of the robot could be completed in under 30 seconds.

Figure 5 shows a top view of the robot, colon, and workspaces. There are five workspaces that demonstrate where the intersecting workspace would be if the robot was rotated about its central axis. With only rotation and no translation of the support rod, the entire colon is within reach of both arms of the workspace. This ability is extremely beneficial when attempting to perform a robotic colectomy.

FORCES AND SPEEDS

The exact forces and speeds required to perform colon procedures, along with other surgical procedures, is unknown at this time. The University of Washington has performed research trying to determine the forces and speeds using during laparoscopic procedures [9-10]. Their experiments don't relate as well to an *in vivo* robot because they measure the force applied by a surgeon to the laparoscopic tool and not the forces applied to the tissue.

The robot discussed in this paper was designed using knowledge gained from previous similar robots performing *in vivo* surgical tasks. Specifically, the motors used were selected based on the analysis of previous non-survival animal model experiments. By testing these motors, they have proven to possess the required forces and speeds. Through kinematic analysis we are able to determine where the worst case forces and speeds occur within the workspace.

Denavit-Hartenberg parameters were used to calculate the transformation matrix of the robot from the base frame to the endpoint frame. Three equations were then extracted from the transformation matrix to give the forward kinematics of the

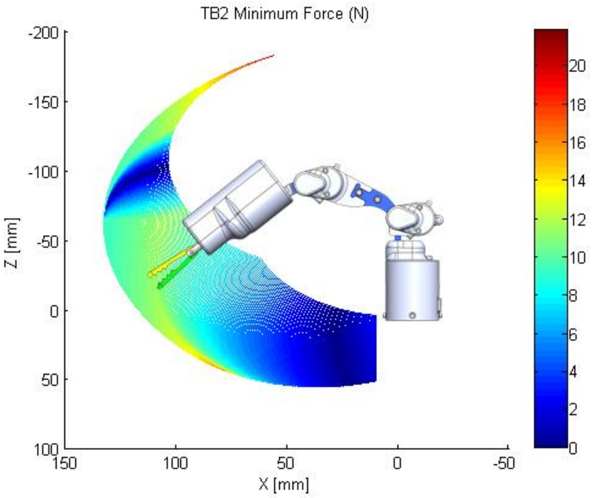

FIGURE 6. MINIMUM FORCE ACROSS THE WORKSPACE

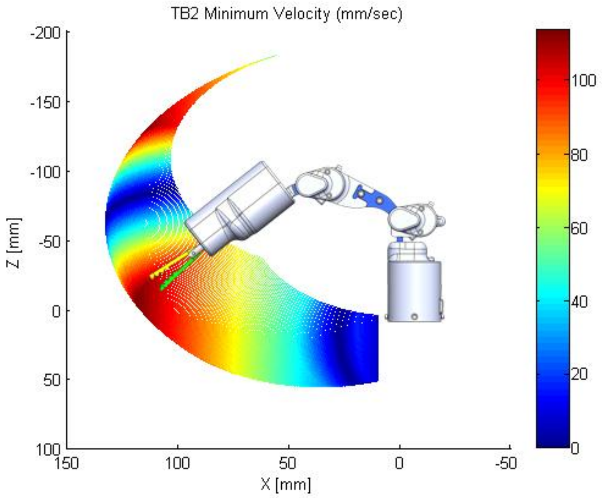

FIGURE 7. MINIMUM SPEED ACROSS THE WORKSPACE

robot. The forward kinematics equations can be seen in Eqns. 1, 2, 3.

$$X = 81.4c_1c_2c_3 - 81.4c_1s_2s_3 + 50.8c_1c_2 \tag{1}$$
$$Y = 81.4s_1c_2c_3 - 81.4s_1s_2s_3 + 50.8s_1c_2 \tag{2}$$
$$Z = -81.4s_2c_3 - 81.4c_2s_3 - 61.9 - 50.8s_2 \tag{3}$$
$$where\ c_n = \cos(\theta_n)\ and\ s_n = \sin(\theta_n)$$

These forward kinematic equations can be used to calculate the Jacobian matrix of the robotic arms. The Jacobian matrix relates the endpoint speeds to angular joint speeds and the transpose of the Jacobian matrix relates the endpoint forces to the joint torques. The angular joint speeds and joint torques are specified by the motor specifications and the output gearing used. Because we know these values, the endpoint forces and speeds can be calculated across the robotic workspace using a iterative mathematical process. The equation used to calculate the base frame Jacobian from the forward kinematics is shown in Eqn. 4, while the equations relating joint speed to endpoint speed and joint torque to endpoint torque can be seen in Eqns. 5 and 6, respectively.

$${}^0J(\theta) = \frac{\delta(X,Y,Z)}{\delta\theta} \tag{4}$$

$${}^0V = {}^0J(\theta)\dot{\theta} \tag{5}$$

$$\tau = {}^0J^T(\theta)F \tag{6}$$

Using these equations and the known motor values, the force and speed along the principle Cartesian axes was calculated. This type of analysis assumes no gravity and massless arms. In order to better analyze this theoretical data, the minimum force and speed value from the X, Y, and Z directions was recorded and then plotted. A mesh was then formed and a gradient of the force and speed values is shown across the workspace. The plots of minimum force and speed can be seen in Figs. 6 and 7, respectively. These plots are shown in 2-D to better see what is going on. A 3-D plot could be formed by rotating these plots around the torso of the robot.

Analyzing these plots it is seen that the minimum forces and speeds attained occur close to the body of the robot and when the arm is reaching slightly outward. The intersecting workspace of the robot, which is located in front of the torso away from the body, has the highest amount of forces and speeds generated. This is ideal because this is the area of the workspace that will be most utilized by surgeons when performing surgical tasks.

MANIPULABILITY

Workspace was previously defined as the region that a robot arm can reach, however just because it can reach a position does not mean it is able to perform specific tasks at that position. Manipulability is a concept that works to correct that problem. Manipulability is the measure of the tool tip's ability to move. Yoshikawa [11] introduced a method of quantifying the manipulability of a robot by using the Jacobian matrix previously discussed. His manipulability measure is defined in Eqn. 7.

$$W = \sqrt{\det(J(\theta)J^T(\theta))} \tag{7}$$

In order to analyze this robots ability within the abdominal cavity, the manipulability was calculated throughout the workspace of the robot. A plot of a single arms manipulability measure can be seen in Fig. 8.

The manipulability has been normalized in order to simplify the analysis. The plot shows that the highest manipulability values are directly in front of the robot. This area coincides with the majority of the intersecting workspace of both arms. It is promising that the area of highest manipulability is within the intersecting workspace of the robot This is the area that will be utilized the most by surgeons for colon resection procedures.

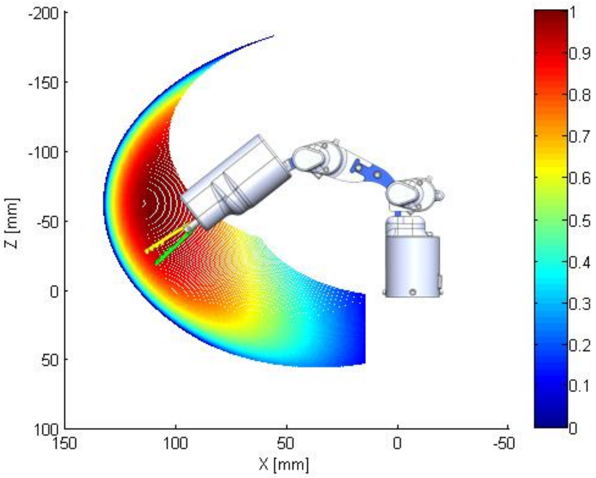

FIGURE 8. MANIPULABILITY ACROSS THE WORKSPACE

IN VIVO RESULTS

A surgical robot very similar to the one described in this paper has been tested in several non-survival animal model surgical procedures. To test the proof of concept of this idea multiple open cholecystectomy procedures were completed. This demonstrated the ability to use a miniature robotic platform to perform laparoscopic surgery. More recently, an insertion protocol was devised and implemented with great success. Additional extensive testing with this robotic model will be necessary to determine this robots ability to perform LESS colon resections.

CONCLUSIONS AND FUTURE WORK

In this paper, several aspects of a miniature *in vivo* surgical robotic prototype designed specifically for colon resections were analyzed. The workspace, forces, speeds, and manipulability of this robot were analyzed and it was found that the robotic prototype described in this paper will be an effective method of performing LESS colon resections. The intersecting workspace of the robot was shown to encompass a large portion of the colon, while the forces, speeds, and manipulability of the robot was shown to be maximal when in the area where most of the colon resection procedure would occur.

In the future, more *in vivo* testing will be done to demonstrate the efficacy of this robot. Further benchtop testing will be performed to compare the theoretical results found in this paper to experimental data. Design optimizations are continually occurring with the goal of the robot to be robust and efficient enough to perform a colectomy procedure on a human.

ACKNOWLEDGMENTS

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