**Proceedings of the ASME 2013 International Design Engineering
Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2013
August 4-7, 2013, Portland, Oregon, USA**

DETC2013-13161

MULTI-QUADRANT SURGICAL ROBOT FOR SINGLE INCISION LAPAROSCOPIC COLECTOMY

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

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

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

J. R. Bartels
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

Colorectal surgery is an area of active research within general surgery. However, over 80% of these procedures currently require an open surgery based on the size and location of the tumor. The current state-of-the-art surgical instruments are unintuitive, restricted by the incision site, and often require timely repositioning tasks during complex surgical procedures. A multi-quadrant miniature *in vivo* surgical robot has been developed to mitigate these limitations as well as the invasiveness of colorectal procedures. By reducing invasiveness, the patient benefits from improved cosmetics, decreased postoperative pain, faster recovery time, and reduced financial burden. A paradigm shift in invasiveness is often inversely proportional to surgeon benefits. Yet, through the use of a robotic device, the surgeon benefits from improved ergonomics, intuitive control, and fewer required repositioning tasks. This paper presents a two armed robotic device that can be controlled from a remote surgical interface. Each arm has six internally actuated degrees of freedom, decoupling the system from the incision site. Each arm is also equipped with a specialized interchangeable end effector. For the surgical procedure, visual feedback is provided through the use of a standard laparoscope with incorporated light source. The robotic device is introduced into the abdominal cavity through a hand-assisted laparoscopic surgery (HALS) port that is placed within the navel. The device is then grossly positioned to the site of interest within the abdominal cavity through the use of a protruding rod that is rigidly attached to each arm. The surgeon can then begin to manipulate tissue through the use of the surgical interface that is remotely located within the operating room. This interface is comprised of a monitor to provide visual feedback, foot pedals to control the operational state of the device, and two haptic devices to control the end point location of each arm and state of the end effectors.

INTRODUCTION

Throughout history, general surgical procedures have been transitioning from large open incisions to no external incisions. This transition has contributed to superior patient outcomes, manifested as quicker recovery times, improved cosmetics, and decreased cost [1]. However, this shift of invasiveness has resulted in poor ergonomics, increased operative time, and poor visualization and triangulation of the surgical site. Due to these complexities, complex surgical procedures such as colectomies, often require a large open incision. Yet, some experienced laparoscopic colorectal surgeons have shown that single incision laparoscopic total colectomy using standard laparoscopic tools is a feasible and safe method for benign disease in selected patients [2]. Single incision laparoscopic surgery is an attractive technique for colon resection, which requires a 3-5 cm incision for specimen extraction once the colon is mobilized.

Robotic minimally invasive surgery is an advantageous method that is used to augment the surgeon's abilities. The current commercially available surgical robot, the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA, USA),

Copyright © 20xx by ASME

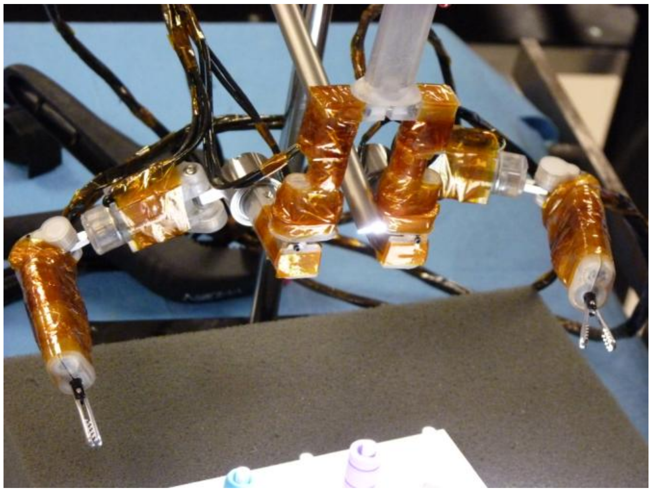

Figure 1. Multi-Quadrant Surgical Robot.

provides a stable three-dimensional view, improved dexterity with an increased range of motion, reduced tremor, and enhanced ergonomics [3]. This robotic system primarily mimics the surgeon's movements through the control of laparoscopic tools with articulated end effectors. Consequently, this architecture is restricted to the incision site, similar to standard laparoscopic tools. Furthermore, its use is also limited due to its large size and high cost. Single incision semi-rigid tools that can be inserted through curved cannula have also been developed for the da Vinci Surgical System [4]. Unlike the standard EndoWrist instruments, they do not have a wrist at the distal end but the curved cannula effectively re-creates the triangulation of a standard laparoscopic procedure. The specialized instruments also reduce the occurrence of collisions during the procedure. Other researchers are currently working to develop an inexpensive, compact robot that similarly controls laparoscopic tools with articulating end effectors [5], [6].

Other robotic research includes devices which are partially or entirely inserted into the body. The simplest of these devices have been mechanisms that transverse the gastrointestinal tract. These devices include an untethered pill that is swallowed which captures frequent images as the capsule passively moves through the digestive tract [7]. Other researchers have developed robotic colonoscopes to examine the colon [8], [9]. More complex devices that are partially inserted include IREP, a two armed snake-like device, that can be inserted through a 15mm diameter single incision and is capable of covering a workspace of 50x50x50mm [10]. All degrees of freedom of IREP are externally actuated. SPRINT, a bimanual robotic system, can be inserted through a 30mm diameter single incision [11]. The first two degrees of freedom of each arm of the SPRINT robot is externally actuated. Additionally, no end effectors have been developed for the SPRINT system.

Previous research within our lab has developed a succession of miniature *in vivo* robots that could be entirely inserted into the abdominal cavity. A family of modular robots was developed that provided vision, sensory, and task assistance during minimally invasive surgical procedures [12]. A two armed planer miniature *in vivo* robot was also developed that was introduced via the esophagus [13]. Most recently, a two armed multi-functional robot was developed that could be inserted through a single incision [14]. Each of these platforms demonstrated the feasibility of an entirely insertable robotic platform for general surgery.

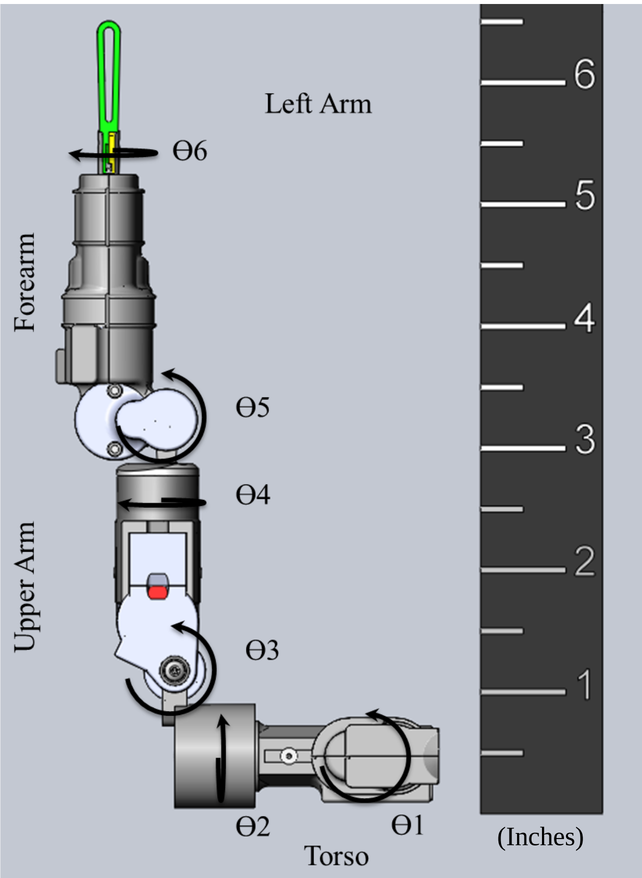

Figure 2. Kinematic Layout of the Multi-Quadrant Surgical Robot.

This paper presents our current progress towards developing a highly dexterous miniature *in vivo* robot that can be inserted through a single incision. Once inserted, the device can reach multiple quadrants of the cavity with high dexterity.

ROBOT DESIGN

The prototype of the multi-quadrant surgical robot consists of two, symmetric six degree of freedom arms (Fig. 1). The device was designed to be entirely inserted into the abdominal cavity through a single incision. For insertion, each arm of the device is detached from the central insertion rod and individually inserted through a commercially available hand assisted laparoscopic surgery (HALS) port to effectively reduce the incision size. Once the first arm is inserted, only a 3mm rod and the communication and power cables pass through the incision. After the second arm is safely inserted, both arms of the device are rigidly coupled using mating geometry.

Figure 3. Surgical Interface Remotely Located Within the Operating Room.

The central insertion rod is then rigidly attached to each of the arms and can be used to grossly position the device throughout the cavity. The insertion process takes an average of five minutes.

Each arm is comprised of six degrees of freedom (DOF) with end effector actuator (Fig. 2). The device has three sections, from proximal to distal tip: torso, upper arm, and forearm. The device has a three DOF shoulder between the torso and the upper arm providing shoulder yaw, pitch, and yaw, a two DOF elbow between the upper arm and forearm providing elbow roll and yaw, and a one DOF wrist providing end effector roll. The forearm also houses the motor that provides end effector actuation. The end effectors can be interchanged based on the surgical procedure. Available end effectors include a grasper, needle driver, and a monopolar cautery.

Each degree of freedom was actuated using a coreless DC motor with integrated gearhead and encoder. A spur gear set was then used to transmit the rotational motion from the motor to the next link. A proportional integral derivative (PID) controller was used to independently control each of the motors with an outer current limiting loop. The control software was implemented using LabVIEW (National Instruments) software and two Compact RIO devices with NI 9505 motor modules. The software determined the desired motor position based on the target position provided by the surgeon using the inverse kinematics of the robot. These motor set points were then used by the Compact RIO motor drivers to provide commutation to each of the motors in real time.

REMOTE SURGICAL INTERFACE

A remote surgical interface was developed to control the prototype of the multi-quadrant surgical robot. The interface included a scaled kinematically matched master-slave controller, a monitor to provide visual feedback, and foot pedals to individually lock or unlock the right and left arm of the device (Fig. 3).

An enlarged kinematically matched master-slave controller was first used to simplify the control, eliminating the need to compute the inverse kinematics of the robot at every time step and provide immediate feedback on the design. An analog to digital converter was used to read potentiometers that were fixed to each of the controller's joints. These values were used as the motor set points within the control software. Additionally, the master-slave controller provided a visual representation of the commanded location and allowed the surgeon to control each joint location instead of just the end effector location.

To allow this device to be controlled by other researchers at remote locations, a custom kinematically matched master-slave controller was not a viable option. The PHANTOM Omni (Sensable) was selected as a secondary controller based on its acceptance among researchers and its ability to provide haptic feedback [5], [6], and [14]. For this application, the haptic feedback was primarily used to prevent the user from reaching the robot's workspace boundary. Two inverse kinematic solutions were derived based on the PHANTOM Omni controllers.

The first inverse kinematic solution mapped the intersection of the axes of the stylus gimbal to the end effector of the robot and the orientation of the stylus gimbal to θ_4, θ_5, and θ_6. However, only the positional degrees of freedom of the PHANTOM Omni provided force feedback and the range of the gimbal angles could not be limited. Small changes in the gimbal angles at the extent of the robots workspace caused the solution to diverge. This problem was avoided with the kinematically matched master-slave controller by adding mechanical limits to each joint.

The second solution mapped the intersection of the axes of the stylus gimbal to the elbow of the robot, the intersection of θ_4 and θ_5. Similarly, the gimbal orientation was mapped to θ_4, θ_5, and θ_6 This mapping allowed the elbow's workspace to be haptically defined by the PHANTOM Omni and therefore the range of θ_4 and θ_5 does not dynamically change throughout the Omni's workspace, mitigating the problem encountered during the original mapping.

For the PHANTOM Omni control solution a third foot pedal was added to allow the surgeon to clutch and reposition the controller within its workspace. Additionally, a scaling

Copyright © 20xx by ASME

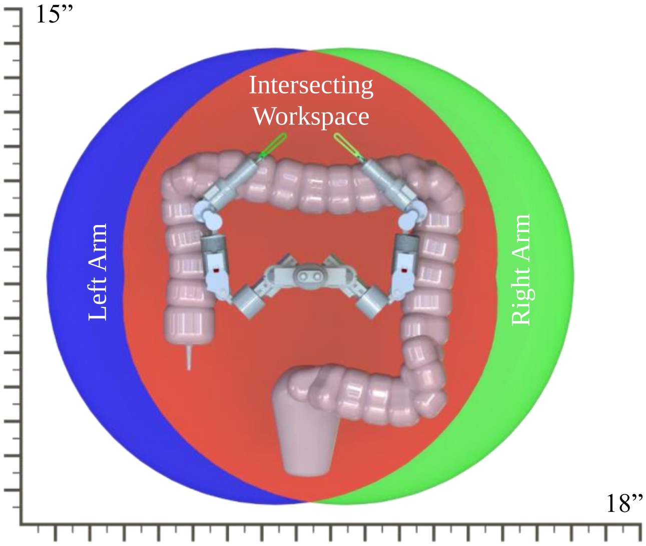

Figure 4. Reachable Workspace of the Multi-Quadrant Surgical Device (Blue: Workspace of the Left Arm Only, Green: Workspace of the Right Arm Only, Red: Intersecting Workspace of the Right and Left Arm).

factor and tremor reduction was provided to allow the surgeon to customize the interface and improve the user’s experience.

WORKSPACE

Traditionally, the workspace of a manipulator is defined by the points that the end effector can reach. However, within surgical applications both instruments often work closely together throughout the procedure. For example, when dissecting the mesentery during a colectomy procedure, multiple stretch and dissect tasks are completed that requires close interaction between the grasper and cautery device. For this robotic prototype the intersecting workspace, which is the points that both arms can reach, was maximized. The workspace of each arm was geometrically derived and an anatomically correct model of the human colon was overlaid upon the workspace. The robotic prototype was then overlaid upon this image, to show the relative size compared to the colon (Fig. 4). The intersecting workspace completely encompasses the entire colon. Based on this preliminary analysis, this robotic prototype can reach every section of the colon.

BENCHTOP TESTING

The abdominal cavity has been determined to be at a times an unknown and aqueous environment. This environment has proven to be hazardous to robotic prototypes during insertion and throughout the surgical procedure. To mitigate these previously encountered problems, a sealing solution and a series of testing methods have been developed.

The first benchtop test required the surgeon to complete the fundamental of laparoscopic skills peg transfer task (Fig. 5). The task was used strictly for training and to familiarize the surgeon with the prototypes capabilities. The time to complete the task was not recorded but observed to be slower than standard laparoscopic tools. This test provided valuable feedback on the efficacy of the device.

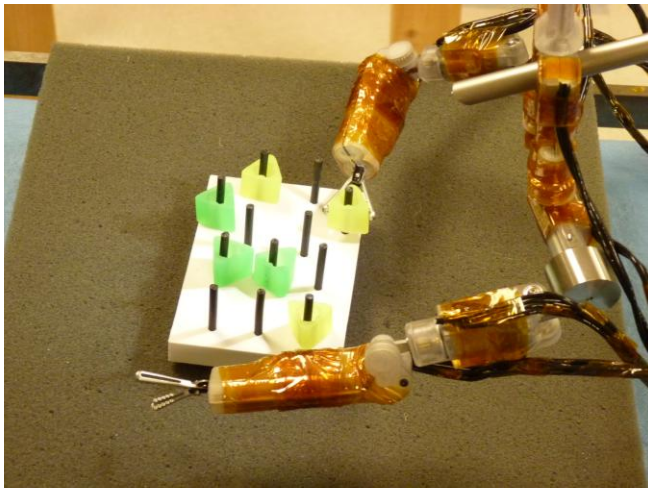

Figure 5. Benchtop Testing: Fundamentals of Laparoscopic Skills Peg Transfer Task.

Figure 6. Benchtop Testing: Dampened Paper Towels Used to Simulate to a Semi-Aqueous Surgical Environment.

The second benchtop test required the surgeon to manipulate and cauterize dampened paper towels (Fig 6). This task closely simulated a semi-aqueous surgical environment. The experiment thoroughly tested the monopolar cautery device and stressed the passive circuit that was used to filter the electrocautery noise from the control circuitry. Additionally, the robotic prototype was required to be water resistant for this test and future *in vivo* testing. The sealing method for this prototype consisted of a commercially available cut-to-length bag that was placed over each segment of the prototype that contained sensitive items. The bag was secured at each end with elastomeric bands with matching groves and self-fusing tape. Additionally, each end effector was packed with an FDA approved lubricant to prevent the ingress of fluid into the actuators motor housing. To date, no failures have occurred due to improper sealing with this prototype.

Copyright © 20xx by ASME

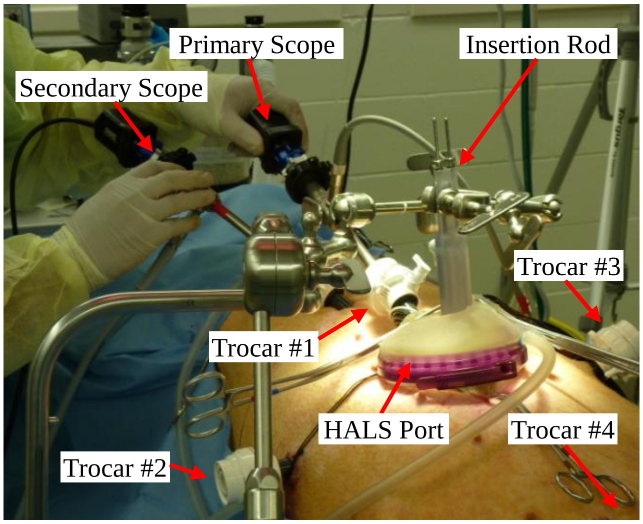

Figure 7. Intraoperative Image of the Surgical Device Entirely Within the Abdominal Cavity.

Each benchtop test was completed with both the scaled kinematically matched master-slave controller and PHANTOM Omni controller using the second inverse kinematic solution. Both controllers were seen to be a viable control platform. For each test, visual feedback was provided by a Karl Storz 30 degree laparoscope.

IN VIVO TESTING

After rigorous benchtop testing of the robotic prototype *in vivo* testing proceeded to determine the validity of this device. A live porcine model was used to quantify the surgical abilities of the multi-quadrant surgical device. The experiment was performed at the University of Nebraska Medical Center. The experimental protocol was approved by the institutional review board.

Each arm of the surgical device was individually inserted into the abdominal cavity through a single incision, approximately 50mm in length or 31.8mm in diameter if the incision could be stretched to a perfectly circular shape. This incision length is comparable to other single incision robotic devices and the incision required to extract the colon after resection. Both arms were then mated together using the central insertion rod. The hand assisted laparoscopic surgery (HALS) port was then placed around the insertion rod and the cavity was insufflated (Fig. 7).

During the procedure two laparoscopes were used to provide visual feedback. The primary scope was inserted through the single incision HALS port and placed between the torso of the right and left arm (Fig. 1, Fig. 7). This video stream was displayed on the monitor within the surgical user interface. In addition to the HALS port, four additional 10mm trocars were equally spaced along the abdominal wall for the secondary scope. This video stream was used by the surgical staff to ensure no traumatic collisions occurred throughout the experimental procedure.

For this procedure, the right arm of the robotic prototype was equipped with a monopolar electrocautery device and the left arm with a grasper. During the procedure, the sigmoid colon was mobilized. To fully mobilize the colon, the following process was completed multiple times throughout the procedure: 1) the colon was secured using the grasper, 2) tension was applied to the mesentery, 3) large vessels were then located within the tissue plane, and 4) all connecting tissue was dissected on both sides of the large vessel that was located using the monopolar electrocautery device. This process is shown in Figure 8a through Figure 8d. Supplementary tools, a LigaSure (Valleylab) and an Endo GIA Stapler (AutoSuture), were then introduced through the single incision to seal and separate the large vessels and the colon. The robotic prototype was used to apply tension to the large vessels and the colon. After the colon was fully separation from the live porcine model, the robotic prototype was removed and the colon was extracted through the single incision.

To perform this procedure, the scaled kinematically matched master-slave controller was used. This control method was selected based on its simplicity and the visual feedback of the commanded position that was provided by the control platform. This *in vivo* experiment has shown that this prototype is a viable method for completing complex colorectal surgical procedures.

An additional experiment was performed that used the PHANTOM Omni controllers using the second mapping solution to verify this control method. During the experiment,

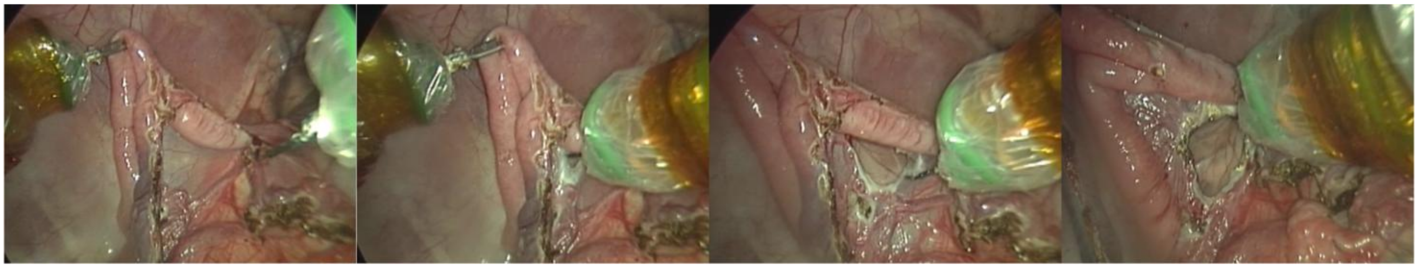
(a) (b) (c) (d)

Figure 8. Images from the Primary Laparoscope That Was Displayed Upon the Monitor Within the Surgical User Interface. From Left to Right: (a) The Colon was Secured by the Right End Effector, a grasper, (b) Tension was Applied to the Mesentery, (c) a Large Vessel was Located within the Tissue Plane, and (d) All Connecting Tissue was Dissected Using the Left End Effector, a Monopolar Electrocautery Device.

Copyright © 20xx by ASME

the surgeon concluded that the robotic device was not listening to the commands that were being relayed through the controllers. No other results were concluded from this experiment while using the PHANTOM Omni controllers.

CONCLUSIONS AND FUTURE WORK

A multi-quadrant surgical device was developed for colorectal surgery. Through preliminary analysis to experimental *in vivo* testing this platform has shown to be a feasible method for completing single incision laparoscopic total colectomy procedures. However, supplementary instruments were required for vessel and bowel sealing.

The prototype was entirely and safely inserted through a 50mm abdominal incision which is within the range of required extraction incisions for colorectal procedures [2]. The device was then grossly positioned to the surgical target using the protruding insertion rod. Two different control interfaces were then used to relay the surgeon's commands to the device. A scaled kinematically matched master-slave controller required minimal training and provided a visual cue of the commanded position. The second control interface used a commercially available joystick from Sensable, the PHANTOM Omni. The mapping of this interface to the robotic prototype seemed to become unintuitive and unnatural during experimental *in vivo* testing. The surgical device was also sealed using commercially available items. No failures due to ingress have been encountered.

Future work will continue to improve upon the devices abilities, patient benefits, and surgeon experience. Currently, additional specialized end effectors are being developed that can effectively seal and separate large vessels. Additional mapping solutions and more rigorous benchtop tests will also be required to mitigate the problems that were encountered during the experimental testing. Onboard cameras and sensing solutions are also being researched to eliminate both the primary and secondary laparoscopes.

ACKNOWLEDGMENTS

The material is based upon work support by the National Science Foundation Graduate Research Fellowship under grant number 25-1123-0009-001. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would also like to acknowledge NASA EPSCoR, Nebraska Research Initiative, Telemedicine and Advanced Technology Research Center, and the Nebraska Space Grant Consortium for their support of this work.

REFERENCES

[1] Mack, M. J. (2001). Minimally invasive and robotic surgery. *JAMA: the journal of the American Medical Association*, *285*(5), 568-572.

[2] Leblanc, F., Makhija, R., Champagne, B. J., & Delaney, C. P. (2011). Single incision laparoscopic total colectomy and proctocolectomy for benign disease: initial experience. *Colorectal Disease*, *13*(11), 1290-1293.

[3] Stein, R. J., White, W. M., Goel, R. K., Irwin, B. H., Haber, G. P., & Kaouk, J. H. (2010). Robotic laparoendoscopic single-site surgery using GelPort as the access platform. *European urology*, *57*(1), 132-137.

[4] Escobar, P. F., Kebria, M., & Falcone, T. (2011). Evaluation of a novel single-port robotic platform in the cadaver model for the performance of various procedures in gynecologic oncology. *Gynecologic oncology*, *120*(3), 380-384.

[5] Lum, M. J., Friedman, D. C., Sankaranarayanan, G., King, H., Fodero, K., Leuschke, R., ... & Sinanan, M. N. (2009). The raven: Design and validation of a telesurgery system. *The International Journal of Robotics Research*, *28*(9), 1183-1197.

[6] Nelson, C. A., Zhang, X., Shah, B. C., Goede, M. R., & Oleynikov, D. (2010). Multipurpose surgical robot as a laparoscope assistant. *Surgical endoscopy*,*24*(7), 1528-1532.

[7] Cavallotti, C., Piccigallo, M., Susilo, E., Valdastri, P., Menciassi, A., & Dario, P. (2009). An integrated vision system with autofocus for wireless capsular endoscopy. *Sensors and Actuators A: Physical*, *156*(1), 72-78.

[8] Dario, P., Carrozza, M. C., & Pietrabissa, A. (1999). Development and in vitro testing of a miniature robotic system for computer-assisted colonoscopy.*Computer Aided Surgery*, *4*(1), 1-14.

[9] Chen, G., Pham, M. T., & Redarce, T. (2006, October). Development and kinematic analysis of a silicone-rubber bending tip for colonoscopy. In*Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*(pp. 168-173). IEEE.

[10] Ding, J., Xu, K., Goldman, R., Allen, P., Fowler, D., & Simaan, N. (2010, May). Design, simulation and evaluation of kinematic alternatives for insertable robotic effectors platforms in single port access surgery. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on* (pp. 1053-1058). IEEE.

[11] Piccigallo, M., Scarfogliero, U., Quaglia, C., Petroni, G., Valdastri, P., Menciassi, A., & Dario, P. (2010). Design of a novel bimanual robotic system for single-port laparoscopy. *Mechatronics, IEEE/ASME Transactions on*, *15*(6), 871-878.

[12] Platt, S. R., Hawks, J. A., & Rentschler, M. E. (2009). Vision and task assistance using modular wireless in vivo surgical robots. *IEEE transactions on bio-medical engineering*, *56*(6), 1700.

[13] Lehman, A. C., Dumpert, J., Wood, N. A., Redden, L., Visty, A. Q., Farritor, S., Varnell, B., & Oleynikov, D. (2009). Natural orifice cholecystectomy using a miniature robot. *Surgical endoscopy*, *23*(2), 260-266.

[14] Wortman, T. D., McCormick, R. L., Markvicka, E. J., Frederick, T. P., Farritor, S. M., & Oleynikov, D. (2011). Multi-Functional Surgical Robot for Laparo-Endoscopic Single-Site Colectomies. ASME.

Copyright © 20xx by ASME