

Cooperative Robotic Assistant for Laparoscopic Surgery: CoBRASurge

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Abstract—Surgical robotic systems have a great impact on the application of laparoscopic surgeries in the operating room. The advent of externally operated surgical robots has prompted the first significant shift in general laparoscopic surgeries. Miniature *in vivo* robots that can be completely inserted in to the abdomen are also being studied to reduce patient trauma. Whereas external surgical robots have a constrained workspace but provide good speed and force capabilities; miniature surgical robots have good local workspace characteristics, but are generally slower and not as powerful. Current efforts to address these limitations include cooperatively using multiple surgical robots to increase dexterous manipulation capabilities, fault tolerance, and overall robustness. In this paper, a cooperative surgical robot system composed of an externally actuated, compact tool-positioning surgical robot, CoBRASurge (Compact Bevel-gear Robot for Advanced Surgery), and an *in vivo* fixed-base, task assistant Dexterous Robot, is presented to perform laparoscopic surgical procedures. The CoBRASurge functions as a gross end-effector positioning robot and the Dexterous Robot performs internal surgical tasks with fine accuracy, effectively increasing the flexibility of the robot system. The surgical procedure successfully demonstrates the feasibility of using CoBRASurge to provide the surgeon with stable and remotely adjustable repositioning of *in vivo* robots for laparoscopic procedures in the peritoneal cavity.

I. INTRODUCTION

MINIMALLY invasive surgical techniques continually develop towards reducing the invasiveness of many surgical procedures. Beginning in the 1990s, the development of new technologies, including advanced laparoscopes, clip appliers, and energy sources for

laparoscopy, provided a period of rapid development in minimally invasive surgery [1]. Minimally invasive abdominal surgery has become the treatment of choice for many routinely performed interventions, such as cholecystectomy [2]. Surgeries performed using laparoscopic techniques are generally safer, with quicker patient recovery, and improved cosmetic results as compared to general surgery. However, the surgeon's ability to visualize and manipulate the surgical target is limited by two-dimensional visualization and by working with long, rigid tools inserted through access points in the abdominal wall. These constraints have limited the expansion of laparoscopic techniques to complex procedures [3].

A. Externally Actuated Surgical Robots

The use of robotics to enhance the visualization and tissue manipulation capabilities is contributing to the advancement of minimally invasive surgery [4], [5]. The Automated Endoscopic System for Optimal Positioning (AESOP), introduced in the mid 1990s for control of a laparoscopic camera, was the first robotic device to receive Food and Drug Administration approval for use in laparoscopy [4]. More advanced telerobotic systems, such as the commercially available da Vinci® (Intuitive Surgical®, Sunnyvale, CA) provide additional capabilities including stereoscopic visualization, improved distal tip dexterity, and motion scaling [4]. However, the widespread use of the da Vinci® system for laparoscopic surgery has remained limited due to its high cost and large size.

Current efforts are focused on the continued development of externally actuated robots with improved mobility and sensing with reduced complexity and cost. For example, a master-slave telerobotic system with enhanced sensing and dexterity using millimeter-scale robotic manipulators is being developed [6]. Further work is directed towards the development of smaller telerobotic systems. For example, The RAVEN robot system is a seven degree of freedom (DOF) cable-actuated surgical manipulator that provides the same degrees of freedom as manual laparoscopy as well as wrist joints at the end effector [7]. Also, the CoBRASurge robot is a four-DOF remotely controlled surgical manipulator, with a configuration based on the spherical bevel-gear mechanism that is particularly compact and highly portable [8]. Other research on compact surgical robots includes a basic system for teleoperated robotic surgery with a modular configuration [9] and a surgical robot with force control [10].

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B. *In Vivo* Surgical Robots

In contrast to externally actuated robots, *in vivo* surgical robots are completely inserted into the peritoneal cavity through a single incision. These robots can be used inside the peritoneum without the typical constraints of an externally actuated device. The robots can be positioned to provide visualization and tissue manipulation within each quadrant of the peritoneal cavity. Further, multiple *in vivo* robots can be placed inside the peritoneal cavity through a single incision, with the number of devices not limited by the small diameter of the insertion incision.

Prototype systems of a transabdominal Magnetic Anchoring and Guidance System (MAGS) for minimally invasive surgery, including an intra-abdominal camera and multiple instruments, have been developed. An initial working prototype of the MAGS system consisting of passive tissue retractors and a camera with magnets that could be deployed into an insufflated abdomen has been demonstrated [11]. Two non-survival porcine laparoscopic nephrectomies were successfully performed using this prototype MAGS system and a 5-mm conventional trocar. In a subsequent study, a prototype three degree of freedom pneumatically controlled robotic arm with hook cautery was developed and used to assist in two non-survival porcine left laparoscopic nephrectomies [12]. The MAGS system was further demonstrated in four non-survival transvaginal Natural Orifice Translumenal Endoscopic Surgery (NOTES) cholecystectomies, also in a porcine model [13].

Insertable surgical imaging devices with multiple degrees of freedom for minimally invasive surgery are also being developed. The base system consists of a camera package, control interface driver, PC, and joystick controller. These devices have been demonstrated in multiple *in vivo* tests in a porcine model, including cholecystectomy, simulated appendectomy, running the bowel, suturing and nephrectomy [14]-[16]. For these procedures, the device was secured to the interior abdominal wall using sutures. Other methods of attachment, including an external holding mechanism and magnetic anchoring were also considered.

Further, *in vivo* robots with either a mobile or peritoneum-mounted platform have been developed. Mobile robots provide vision and task assistance using a remotely controlled wheeled platform that maneuvers on the pelvic organs. Prototypes with a mobile platform have provided visual feedback for laparoscopic cholecystectomy and biopsy in non-survival porcine procedures [17], [18]. Peritoneum-mounted robots use magnetic coupling to attach and grossly position the robot within the peritoneal cavity. Prototypes of this type of robot include an imaging robot with a tilting camera and LED lighting, and a retraction robot [19]. A dexterous peritoneum-mounted robot with stereo vision capabilities has also been developed to improve visualization and tissue manipulation for performing NOTES procedures in the peritoneal cavity [20]. The basic design of this robot consists of two prismatic “arms” with either a cautery or grasper end effector each connected to a

central “body.” The robot has a flexible configuration for insertion and an articulation configuration for visualization and tissue manipulation within the peritoneal cavity. The Dexterous Robot successfully demonstrated various capabilities including exploration, tissue manipulation, and cholecystectomy in non-survival porcine procedures.

C. *Cooperative Surgical Robots*

Whereas the above studies show that robotics has a significant impact on the advancement of laparoscopic surgery, the application of robotics to enhance the surgeon’s ability to visualize and dexterously manipulate the surgical target are still challenging. Recent activity is being directed toward achieving systems of cooperative robots engaged in one laparoscopic procedure. Such systems are of interest to better accomplish complex tasks and to provide a cheaper, less complex alternative to existing externally actuated robotic systems.

A series of laparoscopic animal-model surgeries have been performed using multiple miniature *in vivo* robots in cooperation with existing laparoscopy and endoscopy tools as well as the daVinci® surgical system. These procedures demonstrated that cooperative robots can address visualization constraints and provide task assistance from arbitrary orientations within the peritoneal cavity [19]. A six-DOF cooperative robot-assisted surgery system has also been developed for spinal fusion surgery [21]. This cooperative robot system successfully addressed two main limitations in existing laparoscopic spinal fusion surgery: limited manipulation capabilities provided by traditional surgical robots and the loosening problem.

In a previous study [22], the CoBRASurge was used as a surgical robotic assistant for manipulating laparoscopes in a porcine model. This study was performed to demonstrate the feasibility of providing the surgeon with a stable platform for dexterous manipulation. Its compactness allowed increased space around the operating table, and the robot was remotely manipulated by joystick. It also could be combined with other simple robotic tools for grasping, cautery, etc.

In this study, we propose a cooperative robot-assisted surgery system, CoBRASurge-Dexterous Robot, as shown in Fig. 1. It is a macro-micro cooperative robot system: the CoBRASurge is used as an external gross positioning robot, cooperating with a miniature *in vivo* robot, Dexterous Robot, that can perform both grasping and cautery tasks through a single incision.

II. DESIGN OF THE COBRASURGE

CoBRASurge was designed for controlling the position and orientation of an end-effector during laparoscopic surgery. The end-effector could be a laparoscope or other laparoscopic instrument. Based on the limitation of small incisions during laparoscopic surgery, this robot was designed to have a mechanically constrained remote center of motion (RCM) [23] collocated with the abdominal

incision.

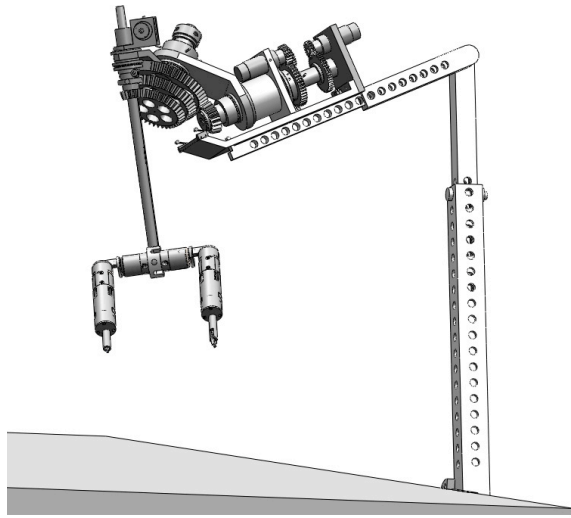


Fig. 1. Overall structure of the CoBRASurge-Dexterous Robot

A. Description

The CoBRASurge, shown in Fig. 2(a), uses a spatial bevel-gear mechanism to achieve a mechanically constrained RCM, functioning as a virtual spherical joint. This allows the tools to rotate freely about the entry port. It has a four-DOF motion space including three spatial rotational DOFs and one translational DOF along the tool axis. The three rotational DOFs are powered by DC servomotors that are mounted remotely to help reduce mass and dynamic effects.

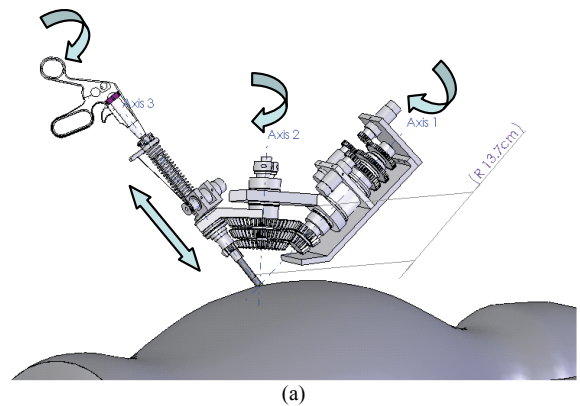
The fourth translational DOF uses a fourth DC servomotor that drives a cable-pulley in opposition to a compression spring along the surgical instrument shaft. A surgical tool is fixed within the cable-driven sleeve, located at the end of the articulated linkage. This method of actuation has limitations including a non-constant stiffness within the joint range, and additional motor torque requirements for pretension of the spring. Other actuation methods, including a closed loop cable drive, friction drive, or cog rail could be implemented with this system.

With the dimensional parameters optimized [8], the design only occupies a space bounded by a hemisphere of radius 13.7 cm. Due to its compactness and unique way of achieving the RCM, CoBRASurge is able to be easily suspended above the patient by a table-mounted clamp arm.

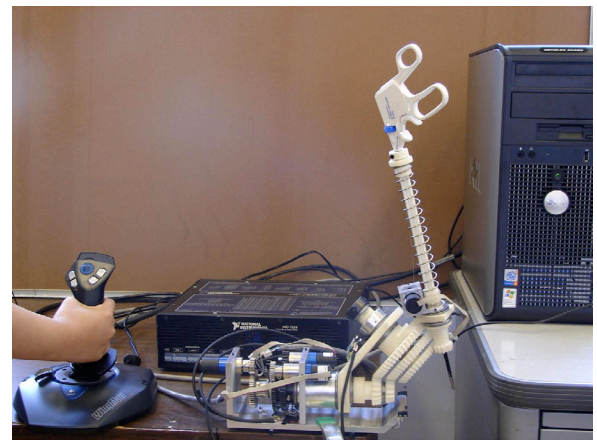
The workspace of the CoBRASurge encloses a cone with vertex angle of 65° , exceeding the dexterous workspace required for laparoscopic procedures (a cone with vertex angle of 60°) [24]. Further, it features a motion range of 150 mm for the insertion depth. Detailed design specifications of the CoBRASurge can be found in [8].

B. Attachment Methods with End Effectors

The sliding sleeve of the CoBRASurge used for holding the end effector, has an inside diameter of 10 mm. This is a typical diameter for laparoscopes and surgical tools. The upper end of the sleeve is integrated with a set screw shaft collar to tighten the end effector. For those tools with a diameter smaller than 10mm, a clamp-on shaft adapter can be used for attachment between the sleeve and the tool. In this study, a 10-mm rod threaded at one end was used for attachment to the Dexterous Robot. The threaded end was mated with a collar attached to the body of the Dexterous Robot. This attachment mechanism provides a simple way to attach the Dexterous Robot or other robots by using modular collars.



(a)



(b)

Fig. 2. CoBRASurge: (a) CAD model of the CoBRASurge, (b) Prototype of the CoBRASurge.

C. Surgeon-in-the-Loop Control

The control system for the CoBRASurge is a master-slave velocity control system such that the surgeon remotely controls the initiation and termination of the CoBRASurge actions using intuitive joystick motions that correspond to roll, pitch, and yaw of the tool. The translation is controlled using a slider on the joystick. The control system, shown in Figure 2(b), includes the user interface, PC, motion

controller, servo driver and the CoBRASurge prototype. The joystick interface provides three-DOFs as well as buttons and sliders that can be used for control of additional DOFs. The PC is programmed using LabVIEW (National Instruments, Austin, TX) to sample the joystick motion; and to perform kinematic transformations for converting the motion commands from the joint space coordinates to the robot's local spherical coordinates. The motion controller can operate in multiple control modes (e.g. velocity, absolute/relative position) based on PID control.

The maximum speed is limited by the controller to 0.2 revolutions/second and 2 mm/second for the rotational and translational DOFs, respectively. The maximum torque is at least 0.6 Nm according to motors and gear reduction specifications, and the maximum force in the insertion direction is 120 N as calculated using a pulley diameter of 10 mm. These torques and forces are more than sufficient to actuate various surgical instruments or *in vivo* robots. Maximum motor currents can also be limited by the controller during operation to be only slightly more than necessary to actuate each axis, for safe tissue interaction.

D. Performance Test of the CoBRASurge as Camera Guidance Assistant

In a previous non-survival study in a porcine model [22], the CoBRASurge was used as a portable camera-positioning robot for telesurgery to demonstrate the feasibility of providing the surgeon with a stable platform for dexterous tissue manipulation. The camera trajectories, based on encoder values, were recorded at 125 Hz using the known robot kinematics. A limitation of this method is that this plot neglects vibration of the robot links.

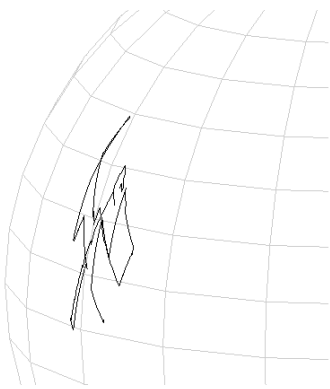


Fig. 3. Trajectory of the camera (in spherical coordinates, gridlines spaced at 10-degree increments) guided by CoBRASurge in a clinical experiment on a porcine model.

A portion of the laparoscope motion is shown in Fig. 3. The piecewise-smooth lines show that the CoBRASurge is able to guide the camera smoothly. Moreover, its compactness allowed increased space around the operating table, and the robot was remotely manipulated by joystick.

III. DESIGN OF THE DEXTEROUS ROBOT

The *in vivo* miniature Dexterous Robot [25] consists of two arms each connected to a central body at a two-DOF rotational shoulder joint, as shown in Fig. 4. The left and right robot arms are fitted with a grasper and cautery end effector, respectively, that translates 36 mm and rotates 360 degrees at an elbow joint. The shoulder joints and elbow joints combined give a total of four-DOFs for each arm. The distal shoulder joint has a range of motion from zero degrees, where the body and arm are aligned, to 135 degrees. The proximal joint has a range of rotation from zero to 180 degrees. The workspace of the Dexterous Robot is much smaller than that of the CoBRASurge Robot discussed previously. These two robots together provide redundant coverage of large areas.

Independent joint PID control is implemented with this robot. Permanent magnet DC motors with encoders are used to actuate each degree of freedom. This robot is designed to apply at least 10N along the end effector axis, and 5N perpendicular to this axis. The diameter of this prototype robot shown is approximately 26mm.

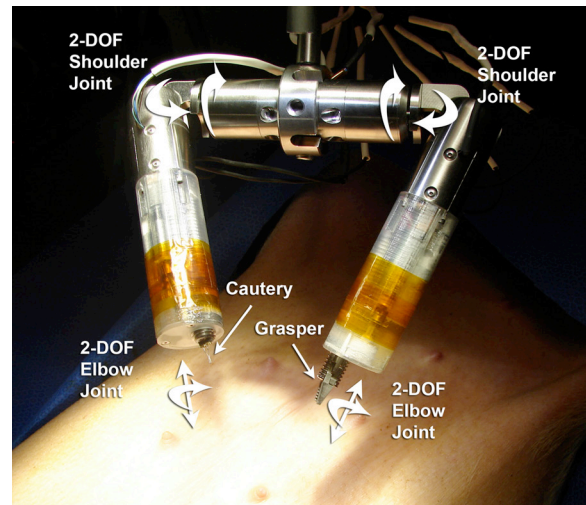


Fig. 4. Developed prototype of the Dexterous Robot

The surgeon controls the robot using a console located within the operating room. The console consists of a monitor for displaying video from the robot, and two joysticks that provide the primary user interface for control of the robot. For this study, a shaft was connected to the body of the robot using a collar. This shaft provided the mating interface with the CoBRASurge system. The robot was tethered for power and communication. Various versions of the Dexterous Robot have previously been used independently of the CoBRASurge system to perform natural orifice and single incision surgery in porcine model [20,25].

IV. EXPERIMENT

The Dexterous Robot was used cooperatively with the CoBRASurge to perform a non-survival surgical procedure

in a porcine model. The CoBRASurge and Dexterous Robot were used as a macro-micro cooperative robot system. The CoBRASurge was used for gross positioning and the Dexterous Robot performed tissue manipulation. The CoBRASurge initially positioned the Dexterous Robot within the surgical workspace and maintained a motionless state while the Dexterous Robot performed surgical tasks. The Dexterous Robot was repositioned as needed throughout the procedure. A laparoscope was used as the primary visual feedback to the surgeon interface.

For laparoscopic surgery, the intended setup using the CoBRASurge-Dexterous Robot is as follows: The CoBRASurge is positioned above the porcine model using a table-mounted arm as per normal procedure. Two incisions are made in the abdominal wall. The arms of the Dexterous Robot are placed into a linear position, and the Dexterous Robot is then inserted into the peritoneal cavity through an incision slightly larger than the robot. The CoBRASurge is inserted through this same incision and is mated with the Dexterous Robot using the collar mechanism described previously. The second trocar is used initially with a laparoscope to assist in mating the Dexterous Robot with the CoBRASurge, and is later used with standard laparoscopic tools to assist in tissue retraction. While the incision used for insertion of the Dexterous Robot is larger than typical incisions for laparoscopy, the use of the robot allows for the number of typical number of incisions to be reduced because the robot arms function as two tools inserted through a single incision.

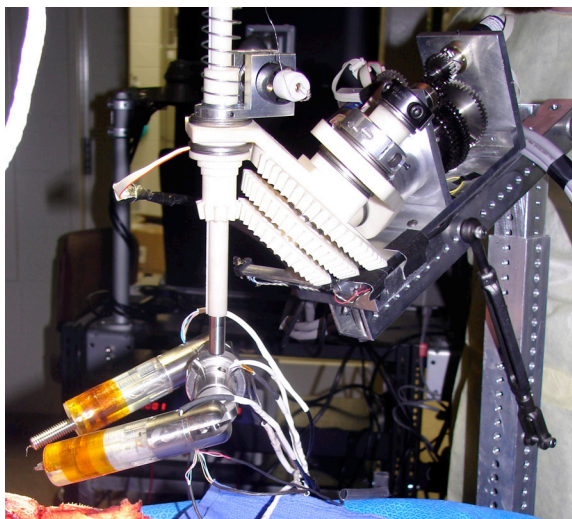


Fig. 5. Cooperative laparoscopic procedure using the CoBRASurge-Dexterous Robot.

The surgeon then uses the CoBRASurge to grossly position the Dexterous Robot within a suitable workspace for performing surgical tasks. The CoBRASurge maintains the Dexterous Robot's body in a static state until repositioning is needed. After the procedure, the CoBRASurge is detached from the Dexterous Robot, moved back through the trocar, the abdomen deflated, and then the Dexterous Robot is retracted through the incision.

To better understand the interactions between the CoBRASurge and the Dexterous Robot for this initial feasibility study, an open surgery was performed using the cooperative CoBRASurge-Dexterous Robot, as shown in Figure 5.

V. RESULTS

The feasibility of using the CoBRASurge-Dexterous Robot system has been demonstrated in a non-survival porcine model procedure. The coupled dexterous workspace enabled the surgeon to remotely position the Dexterous Robot using the CoBRASurge while the manipulation capabilities of the Dexterous Robot allowed the surgeon to perform stretch and dissect tasks within the peritoneal cavity, as shown in Fig. 6. Positioning of the Dexterous Robot using the CoBRASurge, provided an additional four-DOF, and mitigated the need for additional incisions or manual positioning of the Dexterous Robot.

Furthermore, this study suggests that the number of incisions for laparoscopic procedures can be reduced using this system. By inserting the Dexterous Robot fully into the peritoneal cavity through a single trocar, the robot arms provide essentially two tools working through a single incision. The reduction of the number of incisions required for performing a typical surgical procedure may further improve patient recovery.

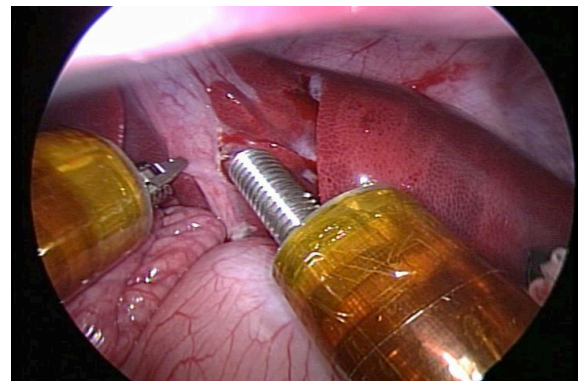


Fig. 6. In vivo view of cooperative laparoscopic procedure using the CoBRASurge-Dexterous Robot in a porcine model.

This procedure demonstrates the feasibility of using miniature *in vivo* robots cooperatively with externally actuated surgical robots to perform surgical procedures. The CoBRASurge element of the cooperative robot system provided a stable mounting platform, with smooth repositioning of the Dexterous Robot. These capabilities are important to the surgeon's ability to explore and manipulate tissue within the peritoneal cavity. Because this initial procedure was performed as an open surgery, there are potential limitations to this system that will be addressed in future designs. One limitation is the coupling method between the Dexterous Robot and the CoBRASurge Robot. For this procedure, the two robots were coupled externally. In future designs, a quick-coupling method will be

developed to allow for easier assembly.

VI. CONCLUSION

The CoBRASurge Robot and the Dexterous Robot are independent robotic systems that have been used separately in multiple animal model procedures as discussed previously. This procedure is the first procedure performed using these two robotic systems cooperatively. This cooperative robot procedure demonstrated the feasibility of using the CoBRASurge externally actuated surgical robot to provide the surgeon with a stable and remotely adjustable platform for positioning of an *in vivo* robot for laparoscopic procedures in the peritoneal cavity. The CoBRASurge can hold *in vivo* robots externally through trocars and reposition them remotely and smoothly. The potential for reducing the number of abdominal incisions, thereby reduce surgical invasiveness, was also demonstrated. The use of cooperative surgical robots addresses significant constraints of existing methods for performing laparoscopic procedure and shows the potential for cooperative surgical robots to augment laparoscopic applications for complex abdominal procedures.

REFERENCES

- [1] S. Horgan, and D. Vanuno, "Robots in Laparoscopic Surgery," *Journal of Laparoendoscopic & Advanced Surgical Techniques*, vol. 11(6), pp. 415-419, 2001.
- [2] J. P. Ruurda, I. A. Broeders, R. P. Simmermacher, I. H. R. Borel, and T. J. V. Van, "Feasibility of Robot-Assisted Laparoscopic Surgery," *Surgical Laparoscopy, Endoscopy & Percutaneous Techniques*, vol. 12(1), pp. 41-45, 2002.
- [3] P. Lo, N. Ahmed, and N. H. Chung, "Which laparoscopic operations are the fastest growing in residency programs?" *Surgical Endoscopy*, vol. 15, Suppl1:S145, 2001.
- [4] R. M. Satava, "Surgical robotics: the early chronicles," *Surgical Laparoscopy, Endoscopy & Percutaneous Techniques*, vol. 12(1), pp.6-16, 2002.
- [5] G. H. Ballantyne, "Robotic surgery, telerobotic surgery, telepresence, and telementoring," *Surgical Endoscopy*, vol. 16, pp.1389-1402, 2002.
- [6] D. Choi, and C. Riviere, "Flexure-based manipulator for active handled microsurgical instrument," *In: Proceedings of the 27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, pp. 5085-5088, Sep. 2005.
- [7] J. Lum, D. Friedman, J. Rosen, G. Sankaranarayanan, H. King, K. Fodero, R. Leuschke, M. Sinanan, and B. Hannaford, "The RAVEN – design and validation of a telesurgery system," *International Journal of Robotics Research*, to be published, Jan. 2009.
- [8] X. Zhang, and C. A. Nelson, "Kinematic Analysis and Optimization of a Novel Robot for Surgical Tool Manipulation," *ASME J Med Devices*, vol. 2(2), 2008.
- [9] P. Berkman, and J. Ma, "A Compact, Modular, Teleoperated Robotic Minimally Invasive Surgery System," *IEEE International Conference on Biomedical Robotics and Biomechatronics*, Pisa, Italy, pp. 702-707, 2006.
- [10] N. Zemiti, T. Ortmaier, and G. Morel, "A New Robot for Force Control in Minimally Invasive Surgery," *Proc. IEEE Conference on Intelligent Robots and Systems*, Sendai, Japan, vol. 4, pp. 3643-3648, 2004.
- [11] S. Park, R. A. Bergs, R. Eberhart, L. Baker, R. Fernandez, and J. A. Cadeddu, "Trocator-less instrumentation for laparoscopy: magnetic positioning of intra-abdominal camera and retractor," *Ann Surg*, vol. 245(3), pp.379-384, 2007.
- [12] I. S. Zeltser, R. Bergs, R. Fernandez, L. Baker, R. Eberhart, and J. A. Cadeddu, "Single trocar laparoscopic nephrectomy using magnetic anchoring and guidance system in the porcine model," *Journal of Urology*, vol. 178, pp. 288-291, 2007.
- [13] D. J. Scott, S. J. Tang, R. Fernandez, R. Bergs, M. T. Goova, I. Zeltser, F. J. Kehdy, and J. A. Cadeddu, "Completely transvaginal NOTES cholecystectomy using magnetically anchored instruments," *Surg Endosc*, vol. 21(12), pp. 2308-2316, 2007.
- [14] T. Hu, P. K. Allen, R. Goldman, N. J. Hogle, and D. L. Fowler, "In vivo pan/tilt endoscope with integrated light source, zoom auto-focusing," *Medicine Meets Virtual Reality 16*, Long Beach, CA, pp. 174-179, Feb. 2008.
- [15] T. Hu, P. K. Allen, R. Goldman, N. J. Hogle, and D. L. Fowler, "Insertable surgical imaging device with pan, tilt, zoom, and lighting," *IEEE International Conference on Robotics and Automation*, Pasadena, CA, pp. 2948-2953, May 2008.
- [16] N. J. Hogle, T. Hu, P. K. Allen, and D. L. Fowler, "Comparison of monoscopic insertable, remotely controlled imaging device with a standard laparoscope in a porcine model," *Surgical Innovation*, vol. 15(4), pp. 271-276, 2008.
- [17] M. Rentschler, J. Dumpert, S. Platt, S. Farritor, D. Oleynikov, "Mobile in vivo camera robots provide sole visual feedback for abdominal exploration and cholecystectomy," *Surg Endosc*, vol. 20(1), pp. 135-138, 2008.
- [18] M. Rentschler, J. Dumpert, S. Platt, K. Iagnemma, D. Oleynikov, and S. Farritor, "An in vivo mobile robot for surgical vision and task assistance," *ASME J Med Devices*, vol. 1(1), pp.23-29, 2007.
- [19] A. C. Lehman, K. A. Berg, J. Dumpert, N. A. Wood, A. Q. Visty, M. E. Rentschler, S. Platt, and S. Farritor, and D. Oleynikov, "Surgery with cooperative robots," *Computer Aided Surgery*, vol. 13(2), pp. 95-105, 2008.
- [20] A. C. Lehman, J. Dumpert, N. A. Wood, L. Redden, A. Q. Visty, S. Farritor, B. Varnell, D. Oleynikov, "Natural Orifice Cholecystectomy Using a Miniature Robot," *Surgical Endoscopy*, vol. 23(2), pp. 260-266, 2009.
- [21] J. Lee, K. Kim, W. K. Chung, S. Choi, and S. Y. Kim, "Huamnguided surgical robot system for spinal fusion surgery: CoRASS," *IEEE International conference on Robotics and Automation*, Pasadena, CA, USA, May 19-23, 2008.
- [22] C. A. Nelson, X. Zhang, B. C. Shah, R. M. Goede, and D. Oleynikov, "Multipurpose Surgical Robot as a Laparoscope Assistant," *Society of American Gastrointestinal and Endoscopic Surgeons Annual Meeting*, Phoenix, AZ, Apr. 22-25, 2009.
- [23] R. H. Taylor, and D. Stoianovici, "Medical Robotics in Computer-Integrated Surgery," *IEEE Transactions on Robotics and Automation*, vol. 19(5), pp. 765-780, 2003.
- [24] J. Lum, J. Rosen, M. N. Sinanan, and B. Hannaford, "Optimization of a Spherical Mechanism for a Minimally Invasive Surgical Robot: Theoretical and Experimental Approaches," *IEEE Transactions on Biomedical Engineering*, vol. 53(7), pp. 1440-1445, 2006.
- [25] A.C. Lehman, N.A. Wood, S.M. Farritor, M.R. Goede, and D. Oleynikov, "Dexterous robot for single incision advanced minimally invasive surgery," *Presented at the 2009 Scientific Session of the Society Session of the SAGES Posters of distinction, Surgical Endoscopy*, vol. 23 (Suppl 1), pp. S203.