Design of a Compact Laparoscopic Assistant Robot : KaLAR

Yun-Ju Lee*, Jonathan Kim*, Seong-Young Ko*,
Woo-Jung Lee**, Dong-Soo Kwon*

* Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea
(Tel : +82-42-869-3082; Fax : +82-42-869-3095 ; E-mail: kwonds@ kaist.ac.kr)
** Yonsei University School of Medicine, Seoul, Korea (Tel : +82-11-9073-1012)

Abstract: This paper describes the development of a 3-DOF laparoscopic assistant robot system with motor-controlled bending and zooming mechanisms using the voice command motion control and auto-tracking control. The system is designed with two major criteria: safety and adaptability. To satisfy the safety criteria we designed the robot with optimized range of motion. For adaptability, the robot is designed with compact size to minimize interference with the staffs in the operating room. The required external motions were replaced by the bending mechanism within the abdomen using flexible laparoscope. The zooming of the robot is achieved through in and out motion at the port where the laparoscope is inserted. The robot is attachable to the bedside using a conventional laparoscope holder with multiple DOF joints and is compact enough for hand-carry. The voice-controlled command input and auto-tracking control is expected to enhance the overall performance of the system while reducing the control load imposed on the surgeon during a laparoscopic surgery. The proposed system is expected to have sufficient safety features and an easy-to-use interface to enhance the overall performance of current laparoscopy.

Keywords: Surgical Assistant Robot, Laparoscopic Surgery, Bending and Zooming Mechanism, Compact

1. INTRODUCTION

The advancement in modern medicine and science in the past several decades is moving toward the minimization or elimination of incision. This minimization of incision, so-called minimally invasive surgery (MIS), greatly enhances the outcome of surgery by shortening the recovery time and reducing the tissue/muscle damages incurred from incision. From these advantages, the MIS has become popular in the past 10 years and 60~80% of total open surgery in many countries is done in MIS today [1].

Laparoscopic surgery is a type of MIS conducted with long, slender surgical instruments and a laparoscope inserted through three to five openings called *ports* in the abdomen. The surgical site is viewed through a laparoscope equipped with a CCD camera. Despite the several advantages from the patient's perspective, the operating surgeons suffer from many limitations such as limited flexibility and range of motion, inability to "touch and feel" the organ of interest, and the lack of depth perception due to the projected image of the surgical site on a 2D monitor. To cope with these limitations many researchers have researched and sought solutions using robotic technology.

Laparoscopic robots have been actively developed during the past decade in two areas: teleoperation robots for laparoscopic surgery and assistant robots for maneuvering laparoscope. In 1994, Philips S. Green developed a telesurgery system [2]. Despite this system is not solely intended for MIS, he showed the possibility of teleoperation robot's performance reaching the performance of on-site open surgery. This system had two master manipulators with force reflection, one slave manipulator, stereovision and audio feedback for realistic telepresence. This telesurgery concept became the model for the *da Vinci* system from Intuitive Surgical [3]. In 1995, Russell H. Taylor and his colleagues developed a complete system including a remote-center-of-motion robot that holds a laparoscopic camera or other instrument [4]. This robot has 7 degrees of freedom (DOF) that is divided into three translations, two rotations, and two distal components. It used an instrument-mounted joystick. In the same year, the HISAR system, a 7-DOF ceiling-mounted surgical robot for laparoscopic camera navigation, is developed by IBM Research and Johns Hopkins Medical Center [5].

In vision system, A. Casals presented a camera control strategy to track the instruments during a surgical procedure based on the computer vision analysis of the laparoscopic image in 1996 [6]. Y. Wang developed the AESOP® at Computer Motion in 1996 [7]. The AESOP® was a 4-DOF robot for the control of a laparoscope and has a pedal and speech recognition system. It was the first robot approved by Food and Drug Administration (FDA) in laparoscopy and is widely used in many countries at present. In 1998 A. J. Madhani showed a teleoperated surgical instrument for MIS: the Black Falcon, which has an 8-DOF teleoperator slave including a 4-DOF wrist to operate in abdomen [8]. Later, it was improved and implanted as part of the *da Vinci* system.

For laparoscopic camera control, commercial surgical assistant robots such as the AESOP® and EndoAssist have been developed and used in real surgeries. However, these systems are known to take large space in the operation room, which is filled with surgeons and assistants, and may interfere with people. This bulky design of these robots is mainly due to modification of industrial robots to suit the medical application. To alleviate the problem, Berkelman et al. [9] have developed a compact laparoscopic endoscope manipulator, which is mounted on the surface of the patient's abdomen, using the McKibben artificial muscles. Although this system is compact, it covers large area in the abdomen and may cause interference with surgeons during a more complex surgery such as Hand-Assisted Laparoscopic Surgery (HALS).

In other to enhance the performance of surgery and to overcome disadvantage of conventional systems, we designed a laparoscopic assistant robot. The developed robot is called KAIST Laparoscopic Assistant Robot (KaLAR). KaLAR have a motor-controlled bending mechanism within the patient's abdomen and zooming mechanism using voice command motion control and auto-tracking control. KaLAR is designed for laparoscopic cholecystectomy, which is a standard procedure for managing symptomatic cholelithiasis [10]. It uses a CCD camera for imaging and optical fiber for transporting light from a light source. For sterilization purposes, the frontal portion is designed watertight so that it can be sterilized with antiseptic solution. KaLAR is a compact robot and is easily attachable to the bedside using a conventional laparoscope holder. As this system does not require a pivoting point for rotation, it is easily applicable for thyroidectomy, a resection of thyroid from underarm.

2. SYSTEM COMPONENTS

2.1 Background

A typical procedure for laparoscopic cholecystectomy is as follow. First, as a preparation stage, a surgeon cuts a small incision just below the navel or belly button, using a trocar. CO_2 gas is injected through this port, and the abdominal region is then inflated to create a workspace in which surgeon can manipulate tools. Thorough the trocar, a rod-like instrument equipped with CCD camera, called laparoscope, is inserted and used to monitor the surgical site. Two to four ports are made on the sides of the abdomen and surgical tools such as grasping forceps, dissecting tools, and electrocautery devices are inserted thorough these ports. During surgery, the primary surgeon monitors the inside of the patient while the assistant surgeon maneuvers the laparoscope at the primary surgeon's command. After preparation, the operation such as clipping, cutting, suturing and cautery is performed. Should the lens of laparoscope become cloudy by the debris from cautery or bloodstains during operation, the camera assistant pulls out the laparoscope from the abdomen and cleans the lens with water. The dissected gallbladder is removed out of the abdomen using a specimen bag.

2.2 Camera Assistant

The number and position of surgeons vary depending on surgical types and surgeon's techniques. Fig.1 shows a typical operating room for laparoscopy [11]. A patient is at supine positioning and the camera operator stands beside the primary surgeon and first assistant is on the opposite side the primary surgeon. The primary surgeon mainly operates and the first assistant surgeon supports the primary surgeon.

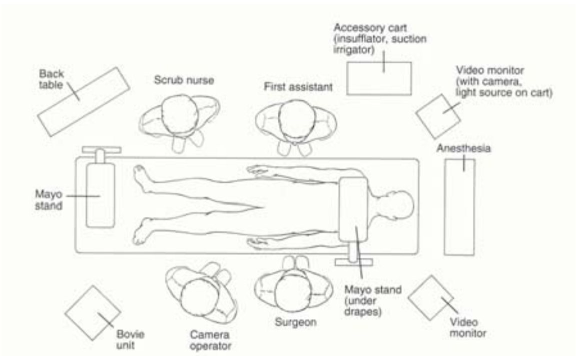

Fig. 1 The cholecystectomy operating room configuration

As can be seen in Fig.1, the operating room is very crowded. In real operation, this may be cause interference, as many surgeons have to work in a limited space. Fig.2 shows the complexity of working environment of a real operating room. Sometimes the camera operator needs to manipulate the laparoscope through a very small space such as the primary surgeon's underarm. Oftentimes, the position of the camera operator is changed, as different view is required.

If the camera operator is inexperienced, he or she is prone to project the image of wrong view, due to the *fulcrum effect*. Human factors such as tremor and fatigue are also critical factors that influence the outcome of the surgery. We would like to eliminate these issues and improve the outcome by adopting robotic technology.

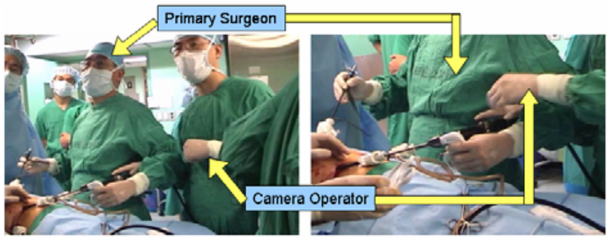

Fig. 2 Interference between the primary surgeon and camera operator in real operating room

3. DESIGN CONCEPT

Considering medical characteristics, surgical robots must be different from conventional industrial robots. Surgical robots would be more dangerous than industrial robots because surgical robots are directly in contact with human body. Therefore, safety is an important factor that must be considered in designing a surgical robot. Although AESOP® is used in many operating rooms nowadays, the robot has a problem in aspect of safety. Kobayashi pointed that this mechanism has a possibility of hitting the surgeons or patients [12]. Since the room is filled with surgeons and nurses, fully replacing the role of an assistant surgeon and occupying less space will enhance the operation performance. Hence KaLAR should be compact, simple and light.

The application of a novel system to a conventional surgical procedure is difficult. There are many things to consider such as adaptability for present surgical environment, sterilization, accuracy, safety, etc. In our design, we have focused on safety and adaptability.

3.1 Safety

Safety is one of the most important issues in the robotic surgery [13, 14]. Since a robot is a combined system with hardware and software, we must consider both aspects.

In the aspect of hardware, the workspace of a surgical robot has to be within the region where the endpoint of hardware cannot reach tissues/organs other than the affected tissue. A task-oriented/optimized workspace reduces possible damage in case of system failure. One method of reducing possible damage is to observe and analyze the required motions and to build the robot with specific range of motion. The can be done by either simply reducing actuating range or reducing degree of freedom (DOF). Using low-pressure pneumatic power also could minimize the danger of electrical actuation [15].

Safety features in software are also critical. Wrong commands may cause malfunction of robot. Hence it needs programmable software such as a filtering system against wrong commands.

3.2 Adaptability

For adaptability, the robot is designed with compact size to minimize the interference with the staffs in the operating room. For easy handling, the robot is designed so that it weighs less than 2 kg. The robot uses a conventional laparoscope holder for its fixation to the bedside. Since the holder has multiple degrees of freedom, the robot can be mounted and positioned at various locations of the patient's abdomen. Once it is fixed in the vicinity of the surgical site, it can bend and translate (forward and backward) within that region to provide necessary views at different time.

4. CONCEPTUAL DESIGN

In laparoscopic surgery, various types of instruments are used such as forceps, graspers, scissors, needle holders and retractors, etc. Basically these conventional laparoscopic instruments require 4-DOF as shown in Fig.3 [16, 17]. The same rule applies for the laparoscope. However, if the axial rotation about the laparoscope can be adjusted for proper viewing by software, 3-DOF motions are sufficient for controlling a laparoscope [9].

Fig. 3 The 4-DOF motions in conventional laparoscopic instruments

Many medical robots are modified or adapted from bulky industrial robots, and the generated motions create a large workspace, which causes interference between the robot and the surgeon. To reduce the motion range and size, we have adopted a flexible laparoscope with a bending mechanism within the abdominal cavity and with a zooming mechanism through in and out motion at the port.

KaLAR has 3-DOF that includes up/down, left/right and forward/backward movement. We have simulated the motion of KaLAR shown in Fig. 4. Fig. 4 (a) shows the commercial laparoscopic holder and (b) shows 3-DOF KaLAR. The end tip of the KaLAR has a CCD camera, optical fibers and the bending section for 2-DOF motions for up/down and right/left motions controlled by wire-driven mechanism. 1-DOF zooming mechanism makes forward/backward movement from the linear-stage controlled by motors. Motion of the rotation could be controlled by software.

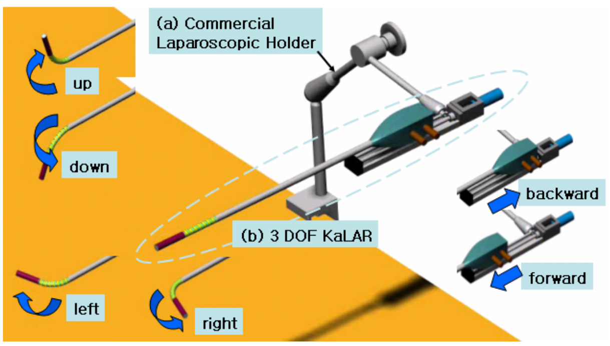

Fig. 4 Simulation of KaLAR in conceptual design

4.1 Surgical Workspace Analysis

To analyze the required range motion in laparoscopic cholecystectomy, we have observed whole procedures in several types of laparoscopic surgery and we have measured the workspace.

Particularly, in laparoscopic cholecystectomy, we found out that the workspace of laparoscope is limited and almost fixed, except for the time when the surgeon checks the entire abdomen during the preparation stage. The up/down and right/left movement region is limited between 10 to 50 degrees and forward/backward movement does not go beyond 100mm. Fig. 5 shows the surgical workspace and Table 1 shows the system requirement.

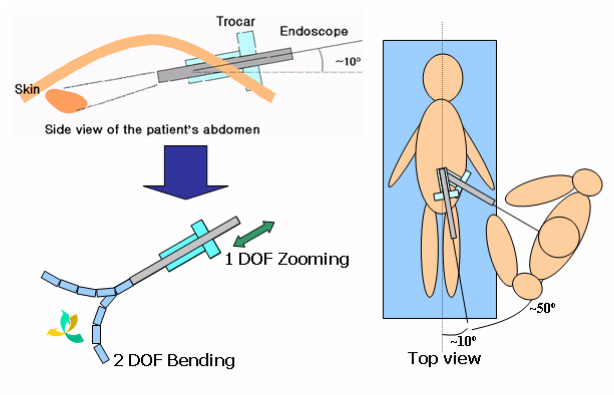

Fig. 5 Surgical workspace of the cholecystectomy

Table 1 Design concept and system requirement.

Issues	Requirement	Design Concept
Limited Surgical Space	Compact Size	3 DOF + Passive Arm
Range of motion: 10~50 degrees 100mm	Articulated joint might be sufficient	Wire-driven Flexible Endoscope Tip (2DOF) Zooming (1DOF)
Cleaning of the lens	Easily attachable and detachable	Quick and Stable Clamping

The surgeons in actual surgery require an assistant robot that is capable of visualizing the entire abdomen during the preparation stage, fully showing and the partially zooming or focusing the region of interest. Then we determined the workspace of KaLAR to satisfy the requirements of surgeons. The ranges of bending motion are from -90 to +90 degrees for each direction and the range of zooming motion is 130mm.

4.2 Bending Mechanism

In order to minimize the motion range and size, we have decider to adopt a flexible laparoscope. A flexible laparoscope is manipulated by a bending mechanism using a tendon-driven (wire-driven) system. The required torque and speed was determined empirically and appropriate motors were selected. The overall assembly of the bending mechanism is shown in Fig. 6 and Fig. 7.

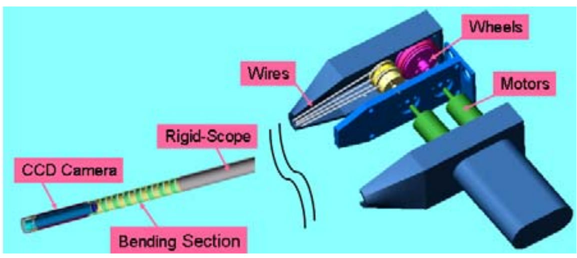

Fig. 6 Conceptual design of bending mechanism

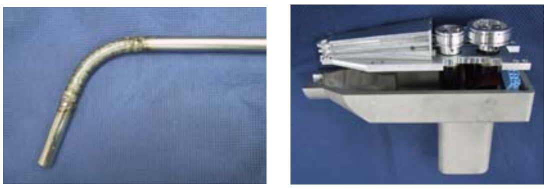

Fig. 7 Bending mechanism in KaLAR

For bending motion, we have applied a bending section from a commercial flexible laparoscope. The bending section is driven by two pairs of wires, each pair controlling one DOF. We have used two motors: one motor drives two wires for the up/down bending motion and the other motor drives two wires for the left/right bending motion. The wires are attached to rotating wheel by screws. A CCD camera and bundles of optical fiber are attached at the frontal end of the system for vision. This bending mechanism at the tip makes it possible to view wide area of internal organs without making wide motions in the operating room.

4.3 Zooming Mechanism

We had considered three mechanisms such as a linear-guide with a ball-screw, a rack-pinion, and wire-driven mechanism to drive the stroke of 130mm. Considering torque, weight, ease of disassembly (for cleansing), speed, backlash, and appearance, we have decided to use a linear-stage that consists of a linear-guide and a ball-screw as shown in Fig. 8 and Fig. 9. The focusing function of the CCD camera is not used as focusing can be easily adjusted by controlling the insertion depth through forward and backward motion.

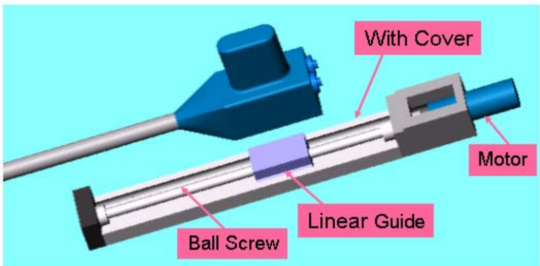

Fig. 8 Conceptual design of zooming mechanism

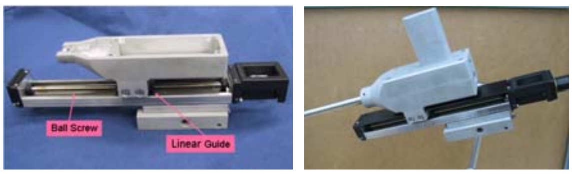

Fig. 9 Zooming mechanism in KaLAR

4.4 Attachment Mechanism

The lens of the laparoscope is constantly fogged by the debris from electrocautery and bloodstains, and requires constant cleaning as discussed in section 2.1. Therefore, it is necessary to remove the robot from the patient's abdomen after detaching it from the holder. To facilitate this process, we have built a linking block that binds the robot and the holder. The shape of block and its mechanism are shown in Fig. 10 and Fig 11.

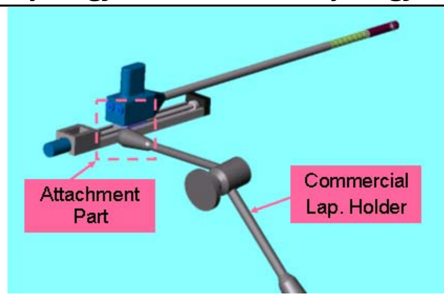

Fig. 10 Conceptual design of attachment mechanism

We have designed a spring-attached sliding mechanism to connect the linear-stage to the laparoscope holder. The attachment is easily separated and directly attachable by simply pushing the spring-attached knob and sliding the component as shown in Fig. 11. Pushing the tip disengages the robot from the commercial laparoscopic holder and the groove acts as a guide.

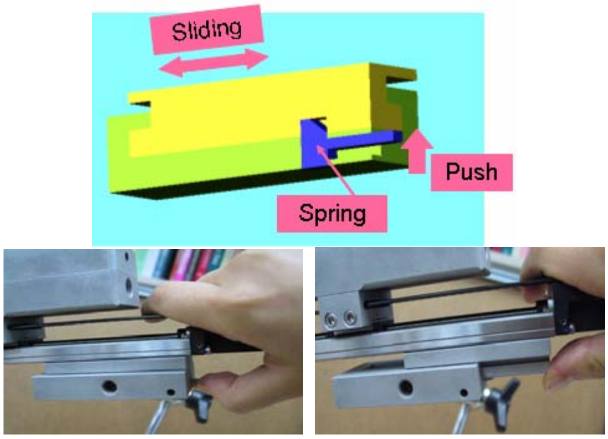

Fig.11 Simple attachment mechanism in KaLAR

5. CONTROL AND INTERFACE

5.1 Control

Fig. 12 shows the schematic diagram of the proposed surgical assistant robot system. The main controller runs under windows 2000. In order to grab the surgical image in real-time, Meteor-II board of Matrox Co. is used. The board acquires the image data from CCD camera on the tip of bending section. To control positions of motors, PD controller is used and the Sensoray 626 board is utilized. Intelligent control algorithm analyzes the image obtained from the grabbing board and generates proper viewpoints for low-level control.

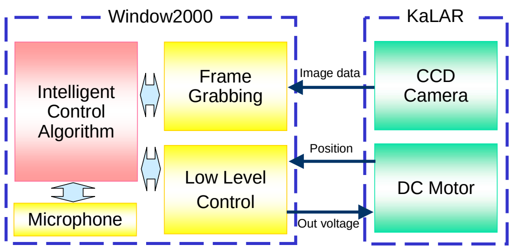

Fig. 12 Schematic diagram of KaLAR

5.2 Interface

Since the surgeon's two hands are occupied by surgical tools, voice command is one of the modalities that can be easily used. The voice commands such as "up", "down", "left" and "right" are used to control the surgical robot. Due to the nature of laparoscopic surgery, the viewpoint is changed continuously and this continuous change of viewpoints can make the surgeon fatigued. To overcome this disadvantage, we have studied an auto-tracking method that can track the tip of the surgical tools [18]. These two methods operate well, but the surgeon frequently wants to see other regions besides the tip of the surgical tool. We are working on developing an intelligent control mode that can swap between the voice-activated control mode and the auto-tracking mode. The overall system architecture including interfaces can be seen in Fig. 13.

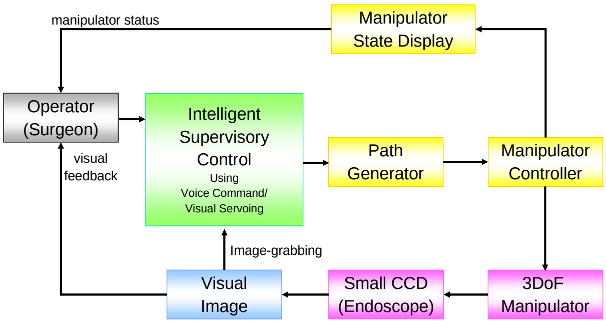

Fig. 13 System and interfaces architecture

6. SUMMARY AND FUTURE WORK

6.1 Summary

We have designed a novel, compact laparoscopic assistant robot called KaLAR. To overcome drawbacks of conventional systems such as AESOP® and to make it possible to apply in surgery, we have focused on two criteria: safety and adaptability. As a result of laparoscopic surgery observation, we have analyzed the workspace of laparoscope's motion and these parameters are reflected in the design. KaLAR have 3-DOF motions, which include 2-DOF for bending mechanism and 1-DOF for zooming mechanism. To minimize the size and the workspace and to avoid the interferences with surgeons, we have designed KaLAR with bending motion inside of the abdomen. KaLAR is equipped with an easy-to-assemble/disassemble feature, which facilitates the positioning, and cleaning of the robot. This robotic system eliminates the cause of degradation of surgical outcome by eliminating disadvantageous human factors such as hand tremor, fatigue, inaccuracy, and the confusion resulted from the *fulcrum effect*. Fig.14 shows the developed system.

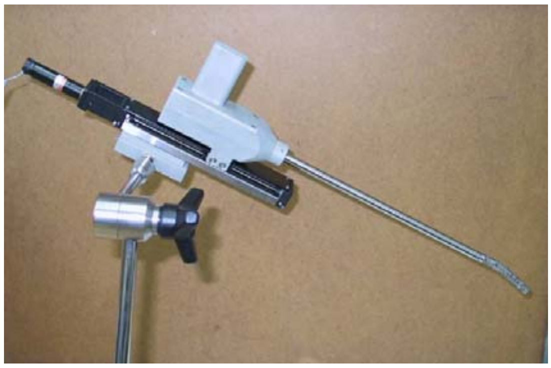

Fig.14 The developed system

6.2 Future Work

The ultimate objective of our research is to build a system that is usable in real operation. Even if the robot behaves well in the laboratory environment, it does not guarantee that it will do the same in real operation. It is our next objective to conduct many experiments in clinical environment to verify the safety and adaptability issues. More practical issues are expected to arise during these experiments and modifications will be made accordingly.

In our current system, the zooming mechanism only works in the vicinity of initial position and this limitation makes it difficult for its application in more complex laparoscopic surgery such as gastrectomy (resection of stomach). To allow more complex motions, fixing the robot with a conventional laparoscopic holder is not sufficient. More DOFs are required to allow viewing from all possible angles. This requires building of a motor-actuated replacement of the laparoscope holder. Our next design is expected to generate optimized external motions so that the system is applicable for more complex surgical procedures.

ACKNOWLEDGMENTS

This work has been supported by the Human-friendly Welfare Robot System Engineering Research Center (HWRS-ERC) at KAIST in Korea.

REFERENCES

[1] R. H. Taylor et al, "An overview of computer-integrated surgery at the IBM Thomas J. Watson Research Center," *IBM J. RES. DEVELOP.*, Vol.40, No.2, pp163-183, 1996

[2] J. W. Hill, P. S. Green, J. F. Jensen, Y. Gorfu, and A. S. Shah, "Telepresence surgery demonstration system," *Proc. of the Conf. on Robotics and Automation*, pp 2302-2307, 1994.

[3] G. S. Guthart and J. K. Alisbury Jr., "The Intuitive™ Telesurgery system : Overview and Application," *Proc. of the Conf. on Robotics and Automation*, pp 1477-1484, 2000.

[4] R.H. Taylor, J. Funda, B. Eldridge, K. Gruben, D. LaRose, S. Gomory, M. Talamini, L. Kavoussi, and J. Anderson, "A Telerobotic Assistant for Laparoscopic Surgery," *in IEEE EMBS Magazine Special Issue on Robotics in Surgery*, pp. 279-291, 1995.

[5] J. Funda et al, "Control and evaluation of a 7-axis surgical robot for laparoscopy," *Proc. of the Conf. on Robotics and Automation*, pp 1477-1484, 1995.

[6] A. Casals, J. Amat, and E. Lapote, "Automatic guiance of an assistant robot in laparoscopic surgery," *Proc. of the Conf. on Robotics and Automation,* pp 895-900, 1996.

[7] Y. F. Wang, D. R. Uecker, and Y. Wang, "Choreographed scope maneuvering in robotically-assisted laparoscopy with active vision guidance," *Proc. 3rd IEEE Workshop on Applications of Computer Vision,* pp. 187-192, 1996.

[8] A. J. Madhani, G. Niemeyer, and J. K. Salisbury Jr., "The Black Falcon: a teleoperated surgical instrument for minimally invasive surgery," *Proc. of the Conf. on Intelligent Robots and Systems,* pp 936-944, 1998.

[9] P. Berkelman, P. Cinquin, J. Troccaz, J. M. Ayoubi, C. Letoublon, and F. Bouchard, "A Compact, Compliant Laparoscopic Endoscope Manipulator," *Proc. of the Conf. on Robotics and Automation,* pp 1870-1875, 2002.

[10] M. E. Arregui, R. J. Fitzgibbons, Jr., N. Kikhouda, J. B. McKernan, H. Reich, *Principles of Laparoscopic Surgery*, Springer-Verlag, New York, 1995.

[11] B. V. MacFadyen and Jr. J. L. Ponsky, *Operative Laparoscopy and Thoracoscopy*, Lippincott-Raven, Philadelphia, 1996.

[12] E. Kobayashi, K. Masamune, I. Sakamura, T. Dohi, and D. Hashimoto, "A New Safe Laparoscopic manipulator System with a Five-bar Linkage Mechanism and an Optical Zoom," *Computer Aided Surgery*, Vol. 4, No. 4, pp.182-192, 1999.

[13] R. D. Howe and Y. Matsuoka, "Robotics For Surgery," Annual Review of Biomedical Engineering, Vol.1, pp. 211-240, 1999.

[14] V. F. Munoz et al, "Design and control of a robotic assistant for laparoscopic surgery," *Proc. of the International Symposium on Intelligent Robotic Systems,* 2001.

[15] A. B. Slatkin, J. Burdick, "The development of a robotic endoscope," *Proc. of the Conf. on Intelligent Robots and Systems,* pp162-171, 1995.

[16] M. C. Cavusoglu, M. Cohn, F. Tendick, S. S. Sastry, "Laparoascopic Telesurgical Workstation," *Proc. of the SPIE International Symp. on Biological Optics,* pp. 296-303, 1998.

[17] M. C. Cavusoglu, I. Villanueva, F. Tendick, "Workspace Analysis of Robotic Manipulators for a Teleoperated Suturing Task," *Proc. of the Conf. on Intelligent Robots and Systems,* 2001.

[18] M. S. Kim, "Real-time Visual Servoing for Laparoscopic Surgery," KAIST, Master's Thesis, 2003.