Proceedings of the
2005 IEEE Conference on Control Applications
Toronto, Canada, August 28-31, 2005

Control and User Interface Design for Compact Manipulators in Minimally-Invasive Surgery

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Abstract— **This paper describes the control system and user command interfaces developed for a lightweight, compact, endoscope camera manipulator prototype for robot-assisted minimally invasive surgery. A complete teleoperated minimally invasive surgical system in development is also based on using lightweight, compact manipulators with simple, reliable, and robust controllers.**

The endoscope manipulator is controlled by a single-board computer and individual motor controllers. The single-board computer processes user commands and generates control mode and analog velocity commands for the motor controllers. A miniature keypad attached to one of the surgical instruments and a voice recognition system with a foot pedal are used as user command interfaces.

I. INTRODUCTION

Minimally invasive surgical [MIS] procedures are performed through several small incisions using long, thin instruments. Compared to traditional open surgery, MIS procedures greatly reduce patient trauma and recovery time, yet the dexterity of the surgeon is reduced and the visibility of the tissues of the patient is limited. A rigid endoscope with an attached video camera must be partially inserted into the body of the patient during surgical procedures to display internal tissues and the tips of the instruments to the surgeon on an external video screen. As the surgeon generally needs to operate instruments with both hands during a procedure, the endoscope shaft must be held in place and oriented by an assistant to follow the work of the surgeon.

Various robotic assistants for MIS have been developed, either as a standalone manipulator to hold and orient the endoscope in desired positions [1], [2], [3], or as complete teleoperated master-slave systems in which a multi-armed robot system manipulates articulated instruments to perform a procedure on the patient while the surgeon controls the robotic motions seated at a teleoperation master console nearby. The *AESOP* [4], [5] system developed by Computer Motion Inc. is an endoscope manipulator which consists of a robotic arm with a cylindrical base clamped to the side of the operating table. The *EndoAssist* [6], [7] from Armstrong Healthcare is a floor-standing arm. Both manipulator arms include passive joints to allow the endoscope to pivot about its incision point as it is manipulated. Clinical trials [8], [9], [10], [11], [7] of these two endoscope manipulators are generally favorable as the lack of fatigue or tremor in the robot arms leads to a stable camera image and the safety and effectiveness of the surgery is not adversely affected.

Complete teleoperated surgical assistant systems which have been commercially sold and have obtained certifications in the United States and Europe include *Zeus* from Computer Motion, which uses instrument manipulator arms similar to the AESOP endoscope manipulator, and the *da Vinci* system [12] from Intuitive Surgical, Inc., which uses a large floor-standing robot with multiple arms.

II. THE LIGHT ENDOSCOPE ROBOT [LER]

The goal of our light endoscope robot work was to develop a prototype endoscope manipulator with at least the equivalent functionality and performance of the current state-of-the-art commercially available *AESOP* and *EndoAssist* systems, but much smaller, simpler, and easier to set up and use. The resulting light endoscope robot [LER], shown in Fig. 1, consists of a rotating base ring attached to a pivoting arch with a quick-release clamp to hold a trocar sleeve containing the endoscope shaft. The axes of rotation of the ring and arch intersect at the center of the mechanism, which is to be placed over the incision for the endoscope. The rotation of the ring and arch are actuated by two small motors and the insertion depth of the endoscope is actuated by a third motor which winds a cable which pulls against a compression spring on the endoscope shaft. The motion of each of the three degrees of freedom corresponds directly to the scaling and horizontal and vertical motion of the endoscope image.

The LER rests directly on the abdomen of the patient and it is typically held in place over the endoscope incision point by a lightweight arm clamped to a rail on the operating table. Straps, adhesives, or sutures can also be used to hold the device in place. Brushless DC motors[1] are used for actuation due to their reliability and high torque capacity in a small size. The motors, all cables and connectors, and all materials used are both sterilizable and waterproof so that the entire device can be autoclaved and immersed in cleaning solutions.

The potential advantages of the smaller, simplified design compared to more conventional large robot arm designs are

This work is sponsored by the RNTL and ANVAR through the MMM project. Support has also been provided by PRAXIM S.A. and CNRS.

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[1] Faulhaber 2036 024B K1155 motors with size 20/1, 86:1 ratio gear reductions

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that the LER is more reliable due to having fewer moving parts in the mechanism, safer due to its smaller mass and actuation forces, and easier to set up and use because it can be held in one hand. It does not restrict access to the patient from any direction, and it does not require any sterile drapes due to its sterilizability. The LER is less rigid and less capable of supporting heavy loads than conventional robot arms, however.

The latest LER prototype is described in more detail in [13] and [14]. Two earlier prototypes are described in [15] and [16]. Measured performance parameters and programmed controller parameters for the LER are given as follows:

Mass:	
LER	625 g
Endoscope and Camera	300-500 g typical
Backdrivability:	
Torque	0.45 N-m
Backdrive force on fully extended endoscope	1.5 N
Dimensions:	
Height	75 mm
Diameter	110 mm
Motion range:	
Azimuth rotation	360° continuous
Inclination	to 80° from vertical
Extension	160 mm
Maximum speed:	
Azimuth rotation	20 degrees/second
Inclination	20 degrees/second
Extension	25 mm/second
Maximum torque limit:	6 N-m
Maximum force on fully extended endoscope:	20 N
Actuation hysteresis:	0.38°

The 120 mm diameter refers to the outer diameter of the base ring and the 75 mm height to the maximum height of the pivoting arm which grips the endoscope trocar.

III. LER CONTROL SYSTEM

The control system for the LER is modular and consists of a single-board computer and three motor controllers. The control of the manipulator is independent of any processing required to respond to the user interface. The complete control system is shown schematically in Fig. 2.

A. High-Level Controller

The single-board computer[2] used for high-level control and communication is equipped with multiple channels of digital and analog input and output, and serial and ethernet ports for communication. A small LCD display and 7 key console is included on a daughter board. Data and program instructions are stored in flash memory.

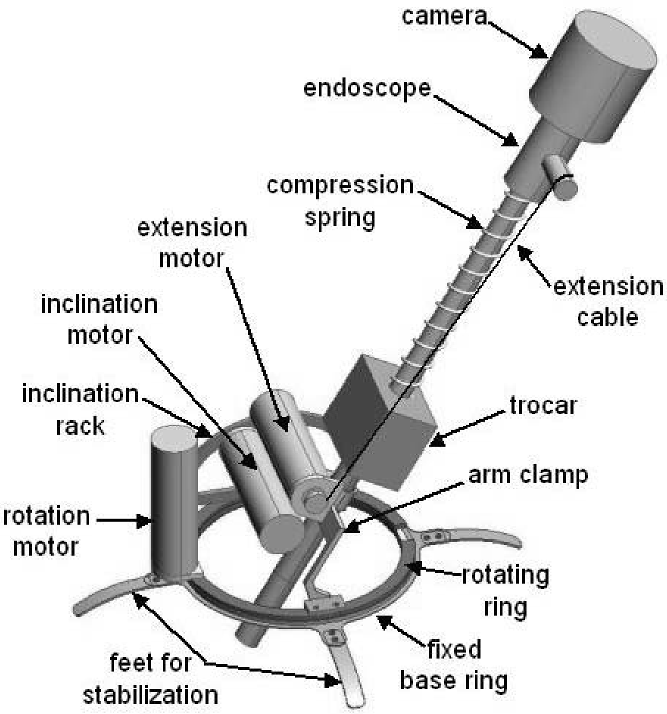

Fig. 1. Light Endoscope Robot

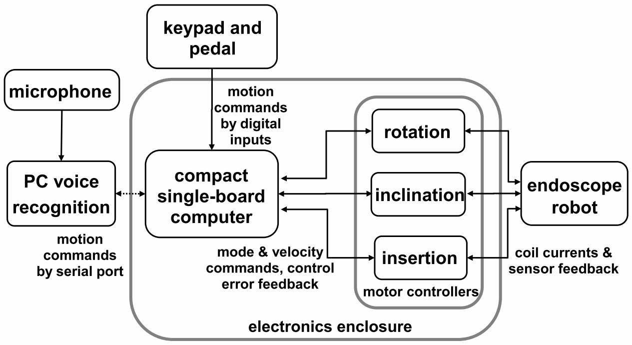

Fig. 2. Control system schematic

The single-board computer has been programmed to respond to commands from its serial port, console, or digital inputs by sending the appropriate control mode signals and analog velocity commands to the motor controllers. The speeds of each of the three motors can also be changed from the console during operation. As the motor directions directly correspond to commanded motions of the endoscope camera image, the high-level controller is not required to perform any kinematic calculations.

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[2] Zworld BL2100

B. Low-Level Motor Control

The three individual motor controllers[3] execute proportional-integral feedback gain control. The controllers can operate in velocity, position, and torque control modes, and commands may be given by analog voltage, pulse-width modulation [PWM], or serial port commands. Programs and control parameters can be transferred from a terminal and are stored in electrically-eraseable programmable read only memory [EEPROM]. To prevent any possibility of damage to internal tissues due to motions of the endoscope, the current limit of each motor controller is set to be only marginally more than necessary to actuate each degree of freedom under normal conditions.

The manipulator motor shafts are not equipped with encoders, as these are not available in sterilizeable versions. Instead, the linear outputs of the magnetic Hall effect sensors in the brushless motors are used to control motor shaft positions and velocities. No homing or initialization sequence is necessary and only relative position feedback is needed because the motor kinematics correspond directly to the motion of the endoscope image. No software motion limits are necessary as the mechanism structure has hard limits in the inclination and insertion motions.

Each motor controller was programmed to operate in velocity control, position control, or disabled modes according to a finite state machine, as shown in Fig. 3. When motion is commanded for one of the motors, the controller switches to velocity control mode, and when the motor is stopped the controller operates in position control mode. Switching between these two modes provides faster response, smoother motion, and better position holding than operating exclusively in either position or velocity control modes. Furthermore, erroneous motions are less likely to be generated as both an analog velocity command and a digital signal to switch to velocity control mode must be sent to a motor controller by the single board computer high-level controller to initiate motion.

The third motor controller mode in the finite state machine disables the motor currents. This mode allows the surgeon to reposition the endoscope manipulator by hand at any time during a procedure, as the actuator motors and gear reductions are backdrivable. This feature has been found in trials on cadavers and animals to be especially useful at the beginning and end of surgical procedures, when the surgeon has one or both hands free and it is simplest and most natural for the surgeon to move the endoscope by hand to perform a visual survey of the entire abdominal cavity.

C. Trajectory following Results

To enable the surgeon easily to move the endoscope to a desired location, the motion of the robot should be at a constant velocity with minimal response delay and no oscillation or overshoot, so that the endoscope camera image moves smoothly and the surgeon can visually track objects in the moving image without difficulty. Absolute positioning accuracy is a less important priority when all initiation and termination of the manipulator motion is under direct control of the surgeon.

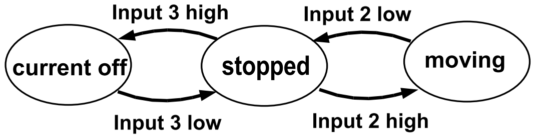

Fig. 3. Motor controller finite state machine

Trajectory responses in position and velocity are shown in Figs. 4 and 5. The command trajectories shown consist of constant velocity motions in both directions for each degree of freedom of manipulator. The orientation and insertion depth of the endoscope were recorded during each trajectory using an optical localizer[4] and infrared LEDs fixed to the eyepiece of the endoscope. Rotation trajectories were executed with the endoscope fully extended. Measured position in mm and velocity in mm/sec are shown for the insertion depth of the endoscope, and orientation and angular velocity measured in degrees are shown for the rotation and inclination. The position command trajectories in Fig. 4 are not shown for clarity.

The settling times of the current prototype manipulator velocity responses of Fig. 5 are approximately 0.5 seconds and position and angular errors are generally limited to less than 1.0 mm and 1.0 degrees during motion. Although the required accuracy of an endoscope robot is a subjective measure by the surgeon, it is certain that errors of less than 1.0 mm and 1.0 degrees cannot be achieved while holding an endoscope by hand due to human tremor and fatigue during operations which may last several hours.

The velocity and angular velocity responses exhibit small oscillatory errors with a period of 2-3 Hz. These errors are due to resonant vibration of the the endoscope camera, as the manipulator is supported by a 200 mm cantilevered bar and the endoscope camera extends an additional 200 mm when the the endoscope shaft is at full extension. Suppression of these small vibrations would require either more massive and rigid mounting of the manipulator to the operating table, or additional external position sensing and more sophisticated control. These vibrations during motions of the endoscope were found to be imperceptible to surgeons, however.

D. User Interfaces

Two primary user command interfaces were implemented for the LER, a standard voice recognition system and a

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[3] Faulhaber MCBL 2805

[4] Northern Digital POLARIS

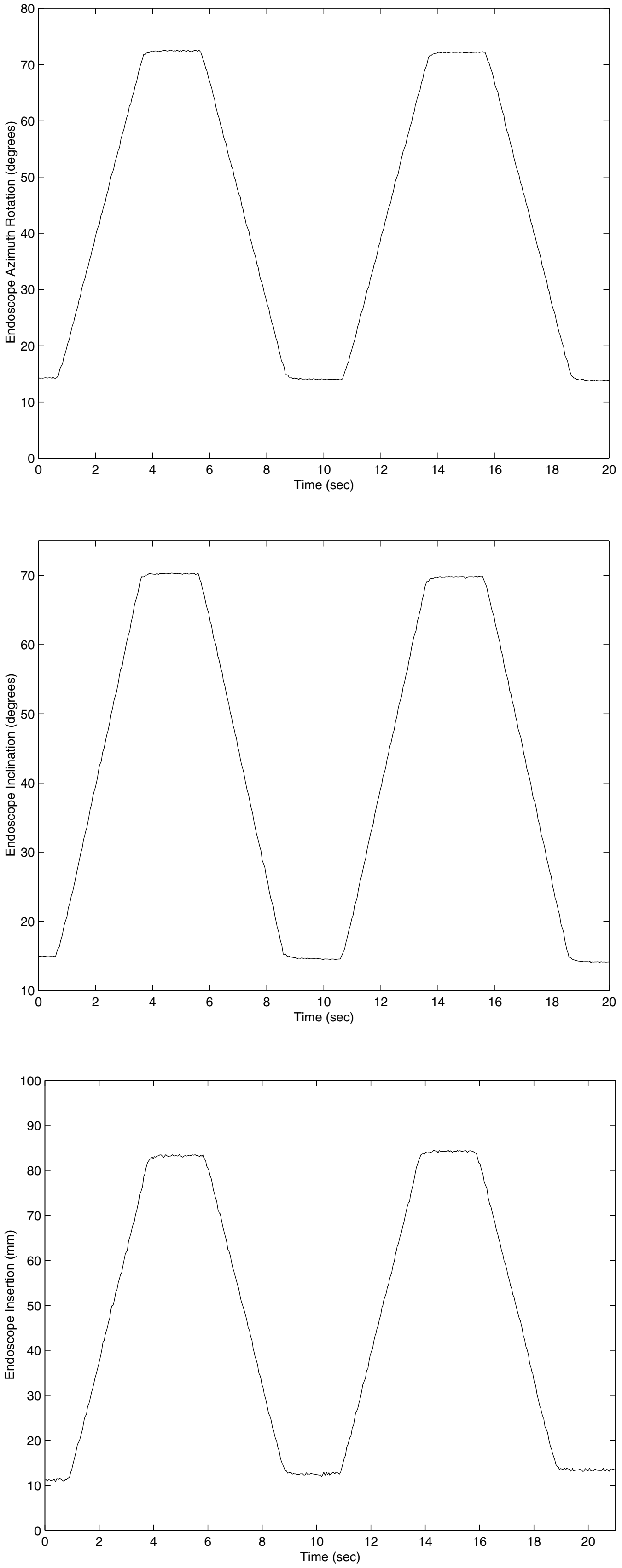

Fig. 4. Rotation, inclination, and insertion trajectory responses with LER

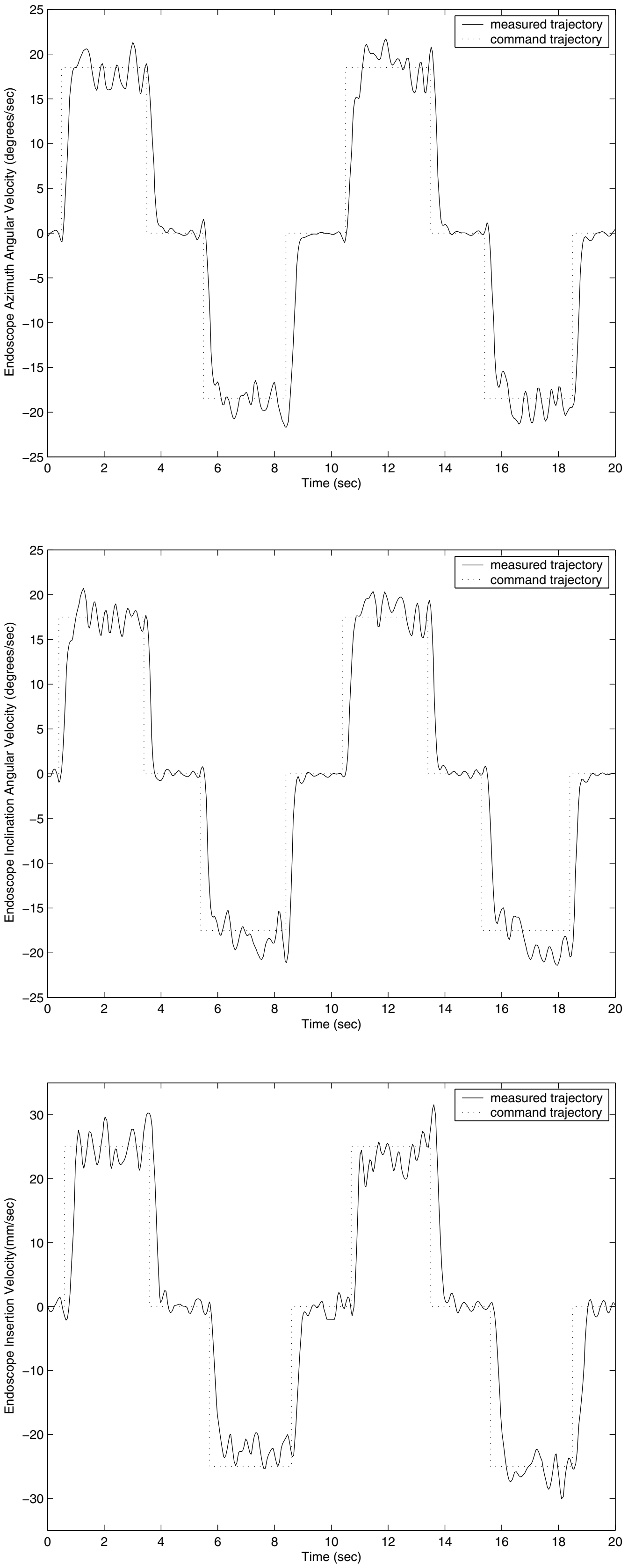

Fig. 5. Rotation, inclination, and insertion trajectory velocity with LER

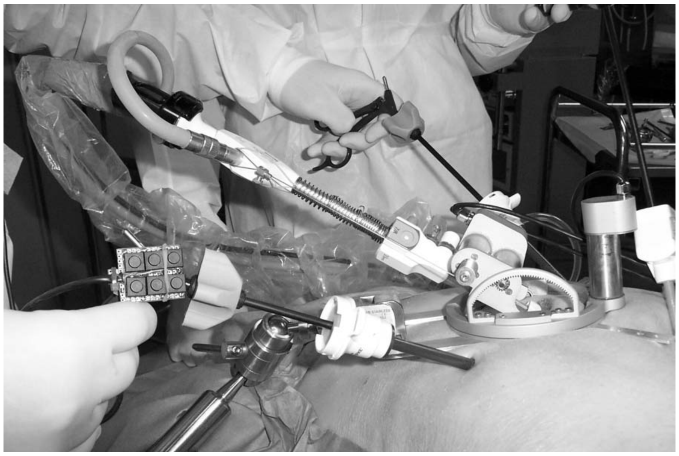

Fig. 6. Endoscope robot in surgery

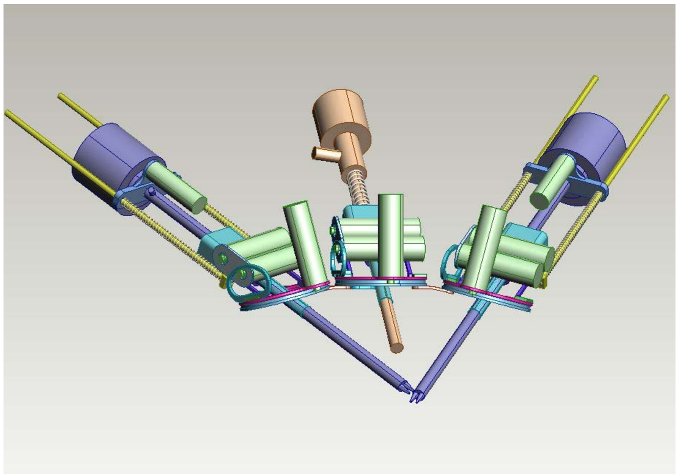

Fig. 7. Modular robotic surgery system

miniature keypad attached to one of the surgical instruments. The voice recognition system runs on a separate PC and uses a single pedal to confirm commands and stop the motion of the manipulator. Both interfaces operate concurrently and independently. Motion commands may also be given using the keys of the high-level controller single board computer console. These command interfaces are redundant so that the surgeon may use any command mode at any time. The keypad interface is shown with the LER while performing a surgical procedure on a cadaver in Fig. 6. The surgeons who tested the system showed a marked preference for the voice commands over the keypad interface, even though there was a slight processing delay to respond to the commands, and commands were occasionally incorrectly recognized in noisy environments.

In addition, the motors of the endoscope manipulator are backdrivable so that the endoscope may be positioned by hand whenever the motor controllers are disabled. This feature simplifies the initial setup of the robot system when the initial endoscope incision is made. Manual positioning of the robot is direct, simple, and intuitive, and is the easiest means for initial positioning of the robot before other instruments are introduced into the abdomen and when the surgeon has at least one hand free.

IV. TELEOPERATED SYSTEM

Due to the encouraging utility and performance shown by the LER, we are currently developing similar robot mechanisms for manipulation of articulated surgical instruments in a teleoperated minimally invasive surgical system. The principal modification of the LER necessary in order to develop an instrument manipulator is that the additional degree of freedom of the rotation of the instrument shaft must also be controlled. This fourth degree of freedom is not necessary in the LER because the vertical axis of the camera image automatically remains aligned with the vertical direction inside the abdomen, and if the surgeon ever wishes to rotate the camera image, the camera may be rotated by hand.

The design of an instrument manipulator based on the LER requires an additional motor to rotate the instrument shaft and additional rods to stabilize that rotation. A rack-and-pinion mechanism is used for the insertion depth of the instrument manipulator instead of the cable and compression spring in the LER due to the greater force and accuracy requirements of an instrument manipulator.

Figure 7 shows a modular teleoperated minimally invasive surgical system consisting of one endoscope manipulator and two instrument manipulators joined together. This system would be held in place on the abdomen by one or more articulated arms, in the same manner as the LER.

V. CONCLUSIONS AND FUTURE WORKS

Preliminary trials of the LER endoscope manipulator have confirmed the utility of simple, compact, lightweight devices as surgical assistant robots. The performance and convenience of the compact endoscope manipulator was the motivation to develop similar manipulators for the instruments in MIS as modules in a complete teleoperated surgical system.

A. Conclusion

The clinical environment of the operating room and the tasks in minimally invasive surgery impose strict requirements on the reliability and effectiveness of surgical assistant robots. Simplicity, compactness, and fail-safe operation were the primary priorities in the development of the mechanism, control, and user interfaces of the light endoscope robot we have developed.

The compactness of the mechanism leads to ease in setup and full access to the patient during use. A small mechanism is cleaned and sterilized more easily as well. A minimally simple design philosophy reduces the potential failure points as the number of interacting components is minimized. The direct kinematic relationship between the motion of the motors and the endoscope image eliminates the need for absolute position feedback and initialization of the controller. The use of simple, modular, high and low level control processors rather than a single centralized controller minimizes the startup time of the software when the system is enabled. The LER system was developed with redundant user command interfaces and communication signals inside the controller for reliability and fail-safe operation.

B. Future Works

To realize a complete prototype system for teleoperated robotic MIS, software and hardware system integration must be done for our existing endoscope and instrument manipulators and a teleoperation master command console. To match the capabilities of current teleoperated surgical systems it will also be necessary to develop dextrous, reliable, articulated wrists at the instrument tips. Finally, many cycles of evaluation and refinement of a prototype teleoperation system may be necessary to satisfy the stringent requirement of MIS.

VI. ACKNOWLEDGMENTS

The cooperation of the digestive and urological surgical staffs at the University Medical Center in Grenoble has been an essential contribution to this project. The robot mechanism was fabricated by Alpes Instruments S.A. of Meylan, France.

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