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Laparoscopic Telesurgical Workstation

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ABSTRACT

Robotic telesurgery is a promising application of robotics to medicine, aiming to enhance the dexterity and sensation of minimally invasive surgery through millimeter-scale manipulators under control of the surgeon. With appropriate communication links, it would also be possible to perform remote surgery for care in rural areas where specialty care is unavailable, or to provide emergency care en route to a hospital. The UC Berkeley/Endorobotics/UCSF Telesurgical Workstation is a master-slave telerobotic system, with two 6 degree of freedom (DOF) robotic manipulators, designed for laparoscopic surgery. The slave robot has a 2 DOF wrist inside the body to allow high dexterity manipulation in addition to the 4 DOF of motion possible through the entry port, which are actuated by an external gross motion platform. The kinematics and the controller of the system are designed to accommodate the force and movement requirements of complex tasks, including suturing and knot tying. The system has force feedback in 4 axes to improve the sensation of telesurgery. In this paper, the telesurgical system will be introduced with discussion of kinematic and control issues and presentation of in vitro test results.

Keywords: Robotic Telesurgery, Medical Robotics, Laparoscopy

1. INTRODUCTION

Medical robotics and computer assisted surgery are new and promising fields of study that aim to augment the capabilities of surgeons by taking the best from robots and humans.

In this joint project between the Robotics and Intelligent Machines Laboratory of the University of California Berkeley, Endorobotics Inc., and the Department of Surgery of the University of California San Francisco, a telesurgical workstation is being developed for use in laparoscopic surgery.[1] The current design is a 6 DOF manipulator, instrumented with a gripper, controlled by a 6 DOF master manipulator.

Research on medical robotics at UC Berkeley includes the development of an endoscopic manipulator,[2,3] early designs of millirobotic manipulators for laparoscopy,[4] studies on tactile sensing,[5–7] and development of a virtual reality training system for laparoscopic surgery.[8,9]

What is Laparoscopic Surgery?

Laparoscopic surgery is a revolutionary technique.[10] It is minimally invasive, i.e., the surgery is performed with instruments inserted through small incisions (less than 10mm in diameter) rather than by making a large incision to expose the operation site. The main advantage of this technique is the reduced trauma to healthy tissue, which is the major reason for post-operational pain and long hospital stay of the patient. The hospital stay and rest periods, and therefore the procedures' cost, are significantly reduced with minimally invasive surgery, at the expense of more difficult techniques performed by the surgeon.

Minimally invasive operations include laparoscopy (abdominal cavity), thoracoscopy (chest cavity), arthroscopy (joints), pelviscopy (pelvis), and angioscopy (blood vessels). The first major laparoscopic surgery, for cholecystectomy (removal of gall bladder), was performed in 1985 by Mühe in (West) Germany. In less than a decade, there was a quick shift from open surgery to laparoscopic surgery in relatively simple procedures, with 67% of cholecystectomies

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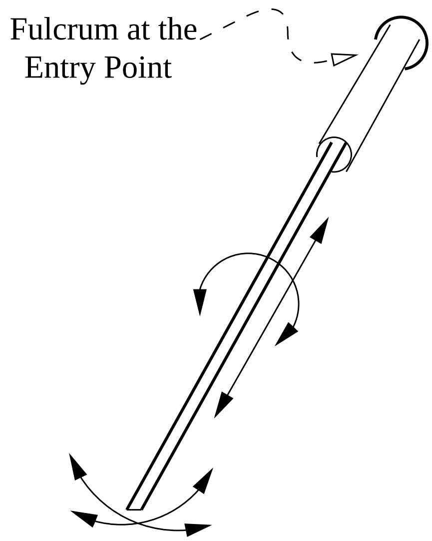

Figure 1. 4 DOF available in conventional laparoscopic instruments

performed laparoscopically in the US in 1993.[11] Adoption of laparoscopic techniques has been slower in more complex procedures, largely because of the greater difficulty due to the surgeon's reduced dexterity and perception.

In laparoscopic surgery, the abdominal cavity, which is expanded by pumping carbon dioxide inside to open a workspace, is observed with a laparoscope inserted through one of the incisions. Laparoscopes have fiber-optic channels to carry light to illuminate the abdominal cavity, and lens optics to transmit the images. A CCD camera is connected at the outer end of the laparoscope, and the monoscopic image of the operation site is displayed on a high resolution TV display. The instruments used for the operation are specially designed long and thin instruments with trigger-like handles. They are inserted through trocars put at the incision to air seal the abdomen. The instruments have only 4 DOF (see Fig. 1), preventing the ability to arbitrarily orient the instrument tip.[12] Dexterity is significantly reduced because of the lost DOF's and motion reversal due to the fulcrum at the entry point. Force feedback is reduced due to the friction at the air tight trocar and the stiffness of the inflated abdominal wall. There is no tactile sensing at all, on which surgeons highly depend in open surgery to locate arteries and tumors hidden in tissue.

Minimally invasive surgery itself is telemanipulation as the surgeon is physically separated from the workspace. Therefore, telerobotics is a natural tool to extend capabilities in laparoscopic surgery. In robotic telesurgery, the conventional instruments can be replaced with robotic manipulators controlled in a master-slave manner by the surgeon through a master manipulator. With the telesurgical workstation developed in this project, the goal is to restore the manipulation and sensation capabilities of the surgeon which were lost due to minimally invasive surgery. The 6 DOF slave manipulator controlled through a spatially consistent and intuitive master will restore the dexterity, the force feedback to the master will increase the fidelity of the manipulation, and the tactile feedback will restore the lost tactile sensation.

Actually, once the surgeon is physically separated from the workspace, it is also possible to geographically separate her from the operating room and perform remote telesurgery. A typical application of remote telesurgery is trauma care on battlefield. On the battlefield, an injured soldier often has only 30 minutes to an hour to survive before dying of blood loss. This period is often too short to find the soldier and transport him to a surgical unit where he can be stabilized. Battlefield surgical units mounted in armored vehicles have been proposed.[13] In order to protect valuable experienced surgeons, however, they would operate via telesurgery from a master located in a safe area. The battlefield units would only need a miniature operating room with slave surgical manipulators and staffed by medics. Other possible applications of remote telesurgery vary from urban trauma care to health care in the third world countries.

Other work in the literature on telesurgical systems for abdominal surgery include the telesurgical system for open

Figure 2. Slave manipulator of the Berkeley/Endorobotics/UCSF laparoscopic workstation

surgery with 4 DOF manipulators developed at SRI International[14] (a laparoscopic version is also being developed), the telerobotic assistant for laparoscopic surgery developed by Taylor et.al.,[15] and the telesurgery experiments performed between JPL, California, and Polytechnic University of Milan, Italy,[16] and between Nagoya and Tokyo in Japan.[17]

There are other successful medical applications of robotics including systems for orthopedic surgery,[18] microsurgery and stereotactic neurosurgery,[19] eye surgery,[20] and radiotherapy.[21] See Dario et.al.[22] and Taylor et.al.[23] for good reviews.

This paper will introduce the UC Berkeley/Endorobotics/UCSF Telesurgical Workstation, describe the implemented control algorithm, and present experimental results.

2. DESCRIPTION OF THE SYSTEM

The UC Berkeley/Endorobotics/UCSF Telesurgical Workstation is a master-slave teleoperation system with two 6 DOF robotic manipulators. The slave manipulator is composed of two parts. The first is the gross positioning stage located outside the body. It is responsible for positioning the millirobot, which is the second part. The gross stage controls the same 4 DOF as those available in conventional laparoscopic instruments. It has a parallel structure, where three linear joints hold a small platform that carries the tool arm and the motor rotating it. All four actuators of this part are DC servo motors. Power is transmitted by lead screws connected to the motors (Fig. 2).

The millirobot, located inside the body, has a 2 DOF wrist and a gripper (Fig. 3). It is 10 mm in diameter. The wrist to gripper length is 10 cm. The roll axis and the gripper of the millirobot are actuated with hydraulic actuators. The yaw axis is actuated by tendons driven by a DC servo motor located outside the body. The roll joint is actuated by a pair of bladders which are inflated with water. The water section is separated from the rest of the hydraulic circuit via a set of diaphragms. The millirobot is designed to be disposable, and the bladders will be driven by sterile saline solution to avoid problems in case of leaks.

Performance goals in the design of the millirobot are given in Table 1. These values are estimated for a suturing task, force and movement requirements for driving a needle through tissue and tying a knot. Table 2 gives the

Figure 3. Laparoscopic End-effector, with 2 DOF Wrist and Gripper

Table 1. Performance goals for the millirobot

Parameter	**Value**
Dimension: overall diameter	10-15 mm max
Dimension: wrist joint to grasper	100 mm max
Force: at the point of needle, for driving the needle through tissue	1.5 N min
Torque: about grasper axis, for driving needle (assumes curved needle, 15 mm from grasper to needle tip)	2.2 N-cm min
Force: gripping, while driving needle	5 N min
Force: knot tightening tension	2.2 N min
Range of motion: gripper jaw opening	2-3 mm min
Range of motion: rotation about grasper axis, to drive plus allowance for inclined work surface	180–270 degrees min
Range of motion: wrist flexion, for driving needle	90 degrees min
Range of motion: wrist pronation	180 degrees min
Bandwidth	5 Hz min

experimental results with the actual robot, which exceed all design goals except wrist roll range. The specifications adopted for the second version of the system are given in Table 3.*

The master manipulator is a 6 DOF serial robot. A commercial 4 DOF force reflecting joystick (Immersion Impulse Engine 3000) with 3 actuated axes is equipped with an additional 2 DOF (one actuated) and a stylus handle. There are position measurements in all 6 joints and the 4 actuated joints give force feedback in translational directions and the roll axis, where the torque is important while driving a needle through tissue. (See Fig. 4).

A complete kinematic analysis of the system can be found in Cavusoglu.[24]

3. CONTROL

3.1. Open Loop Control Issues

The main bottleneck in the dynamics of the slave manipulator is the lag in the hydraulic actuators, which is due to the transmission delay in the tubing, and the first order lag resulting from the RC effect of the tube-bladder configuration.

*Courtesy of Endorobotics Inc.

Table 2. Millirobot test results

Parameter	Measured Value	Target Value
Gripping force	15 N	5 N min
Grasper opening width	6 mm	2–3 mm min
Wrist roll torque	8.8 N-cm	2.2 N-cm min
Wrist roll range of motion	90 degrees	180–270 degrees min
Wrist flexion (yaw) torque	30 N-cm	10-15 N-cm
Bandwidth	~6 Hz	5 Hz

Table 3. Performance goals for the second version of the millirobot

Parameter	Target Value
Wrist joint to grasper length	50 mm max
Gripping force	40 N min
Grasper opening width	8 mm min
Grasper speed: full close in	0.5 sec max
Wrist roll torque	100 N-mm min
Wrist roll range of motion	270 degrees min
Wrist roll speed	540 degrees/sec min
Wrist flexion (yaw) torque	300 N-mm min
Wrist flexion range of motion	90 degrees min
Wrist flexion speed	360 degrees/sec min
Lifetime	6 months min

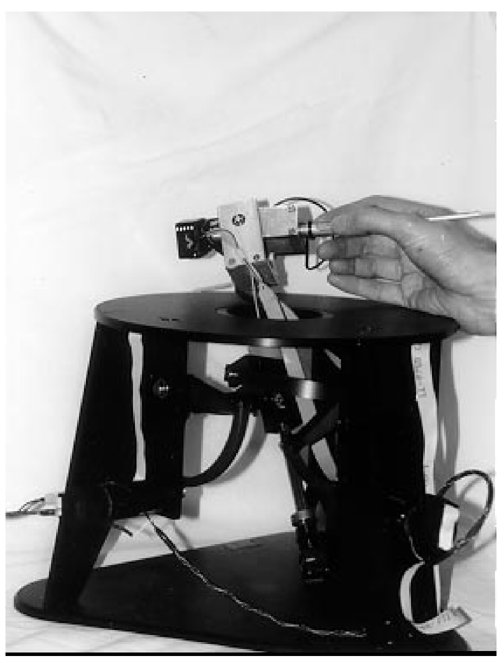

Figure 4. Master manipulator of the laparoscopic workstation

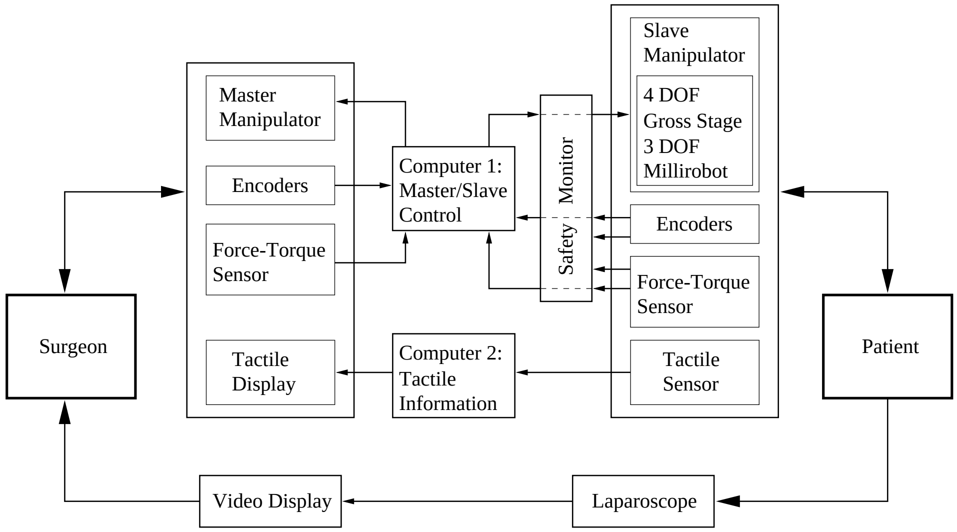

Figure 5. Proposed control system block diagram

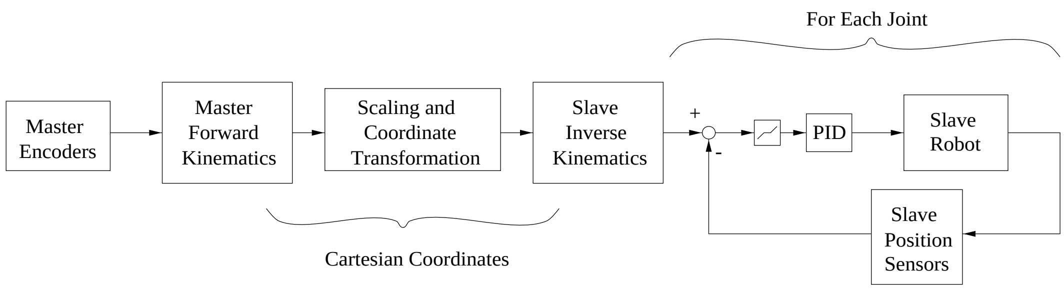

Figure 6. Current implementation of master-slave control

The parallel structure of the gross stage prevents designing a dynamics-based control algorithm (like a computed torque algorithm). Backlash in the linear actuators of the gross stage is another point to keep in mind for the controller design.

3.2. Control Algorithm

The overall structure of the proposed control design for the telesurgical workstation is shown in Fig. 5. In the current implementation, which is shown in Fig. 6, joint level angle control is used. The force and tactile loops and safety monitor are not present. A small dead-band is used at the error signal for linear joints to avoid oscillations due to backlash. Anti-windup integral terms (with saturation) are used in the PID controllers. The sensor outputs are compensated for the nonlinear input-output characteristics.

4. EXPERIMENTAL RESULTS AND EVALUATION OF THE SYSTEM

The robot successfully performed *in vitro* suturing and knot tying tasks in master-slave mode. Experimental tracking responses are given in Fig. 7. As can be seen from these results, the system achieves the desired tracking performance requirements.

Bandwidth and time delay for the hydraulic actuators are the limiting factors for the performance of the millirobot. The effects of the time delay can be observed on the plot for roll joint motion (θ_1), in Fig. 7. During the *ex vivo* experiments, suturing with a straight needle was easier compared to the curved needle due to the limited roll movement available. Although the parallel structure of the gross stage prevents the use of dynamics-based controllers,

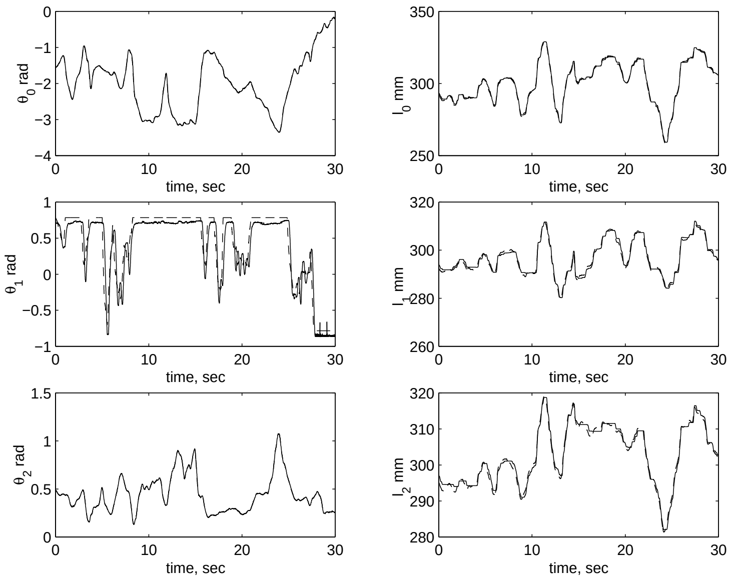

Figure 7. Master-slave tracking response: Dashed lines show the desired trajectory commanded by the master and the solid line show the actual trajectory of the slave.

the powerful actuators used compensate for this, as can observed from the tracking responses for the linear joints (l_0, l_1, and l_2).

The safety features not implemented in this prototype controller will be included in the later designs. The independent high level controller, which should run on a separate computer and have an independent set of sensors, is necessary for safety monitoring. The mission of this safety controller is to monitor the overall system and override commands that violate the safety constraints and to shut down the system in case of failure. A low level control algorithm can also be included to avoid high interaction forces between the manipulator and the environment. Increased safety must also be included in the hardware design to compensate for the potential problems in the actuator and sensor systems.

5. CONCLUSION AND FUTURE WORK

For the Telesurgical Workstation, the proposed control algorithm will be implemented, with the force feedback and safety monitor, followed by experimental studies to further analyze the effectiveness of the robot and the control. A second robot is necessary for bimanual operation. A second version of the system is currently being developed, with modifications to improve performance based on the evaluation of the current system. Animal trials will be performed at the experimental surgery laboratory at the University of California San Francisco.

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