Millirobotics for Telesurgery*

Michael B. Cohn[†] Lara S. Crawford[†‡] Jeffrey M. Wendlandt[§]
S. Shankar Sastry[†]
University of California, Berkeley 94720

Abstract

Minimally invasive surgical techniques, in particular endoscopy and laparoscopy, have many advantages over traditional surgery, most notably rapid patient recovery. Limitations of current instrumentation, however, can make minimally invasive techniques awkward for the surgeon. In this paper, we present prototypes for improved endoscopic and laparoscopic instruments and human interfaces which will allow the surgeon greater dexterity and control.

1 Introduction

Minimally invasive surgical techniques, including endoscopy (gastrointestinal surgery) and laparoscopy (abdominal surgery), are revolutionizing surgery. These techniques, which involve inserting surgical instruments into the body through a natural orifice or a small incision, have several advantages over traditional surgical methods. Most importantly, they minimize trauma to healthy tissue and therefore reduce hospitalization time and the risk of complications such as infection and scar adhesion. However, there are several drawbacks to the instruments currently used in these procedures that exact a price in surgical access, dexterity, and efficiency. It is our goal to design improved instruments and human interfaces for endoscopy and laparoscopy. We further envision a teleoperative surgical workstation which would combine the improved interface and tools for laparoscopy to enhance the surgeon's control of the operation.

2 Endoscopic Manipulators

Discussion of endoscopic techniques can be found in Baillie [2], Siegel [17], and Silverstein and Tytgat [18]. An endoscope is a flexible tube 70–180 cm long, typically 11 mm in diameter. Remote operations in the colon or in the esophagus are performed by inserting various tools through a 2.8 mm channel in the endoscope to the operative site. The instrument can be positioned by sliding it in and out of the channel and by controlled bending of the last 10 cm of the endoscope. This bending has too large a radius for some tasks, and also tends to displace the surrounding tissue, adding to the difficulty of positioning. For example, biopsies in the esophagus are difficult since the esophageal channel is long and rigid and the biopsies must be performed perpendicular to the tool channel.

We have designed a device, the endo-platform, which allows finer endoscopic tool positioning. The platform is composed of two plates separated by a rigid tube and a short spring, through which the tool passes. The diameter of the plates is the same as that of the endoscope. The spring serves as a spherical joint which resists side forces and provides a pivot point. Three tendons running between the plates can be pulled individually to change the orientation of the outer plate relative to the inner plate, which moves the tool tip. The entire assembly is designed to be attached to the end of an existing endoscope. Large motions can be controlled as before by deforming the last 10 cm of the scope, while fine motions are accomplished by reorienting the outer plate of the endo-platform.

We have built a prototype of the endo-platform (see Figure 1) and have demonstrated the device's ability to position endoscopic tools. The diameter of the prototype is 19 mm (but could easily be scaled to 11 mm), and the length of the device is less than 20 mm from plate to plate. The three tendons are attached to pulleys on DC motors with optical position encoders. The endo-platform is capable of 90 degree bends. Currently, only open-loop control has been implemented. The kinematics and dynamics of the device and a simulation of a closed-loop controller are described in detail in [20]. We are using 0.1 mm Kevlar tendons since they have a higher tensile strength (37 Newtons) and are more durable than metal tendons. At the tensile strength of the Kevlar tendons, a 13 Newton force is produced at the tool tip with the tool at a 45 degree angle.

To test the dynamic response of the endo-platform, we applied a power step to one of the motors. In the idle state, we applied a 17-18% duty cycle 0–12 volt pulse-width-modulated signal to each motor to provide tension to the tendons. For the dynamic test, we increased the duty cycle to 50% and recorded the angular position of the motor shaft at 100 Hz. We then brought the duty cycle back to 18% and recorded the response. During these

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[†]Department of Electrical Engineering and Computer Sciences
[‡]Graduate Group in Biophysics
[§]Department of Mechanical Engineering

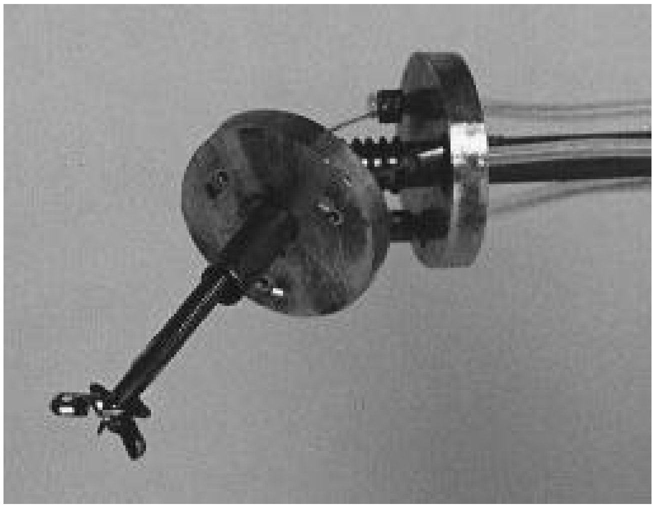

Figure 1: Endo-Platform

tests, a biopsy forceps was placed in the tool channel of the platform. The relatively large force and small inertias gave rise to fast responses; the step response reached its final value in 50 ms.

Here we have presented a design to provide fine motion at the tip of the endoscope; other designs for providing rotation about the tool axis (currently only transmitted passively down the tool, which is not torsionally stiff) and improving the ability to snare polyps can be found in [20]. Future work will focus on implementing closed-loop control, incorporating a user interface, and fine-tuning the design so that it can eventually be used in surgical experiments.

3 Laparoscopic Manipulators

Discussion of laparoscopic techniques can be found in Graber, *et al.* [11], Semm [15], and Saleh [14]. A laparoscope is essentially a video camera with a rigid, elongated lens assembly. Laparoscopic surgery takes place in an approximately 18 cm by 18 cm workspace inside the patient's abdomen. The scope and instruments enter the body via 5-10 mm cannulae inserted through portals in the abdominal wall. In laparoscopy, as in endoscopy, dexterity is compromised; the single access point to the abdomen makes it impossible for instruments to reach arbitrary positions and orientations, and since the instruments are rigid and unarticulated, they cannot bend around obstacles. The lack of dexterity when operating with these instruments makes some tasks, like suturing and tying knots, especially difficult. Because the current instruments only have four positional degrees of freedom, a surgeon can hold the needle in a natural orientation only when suturing along a line radiating from the entry portal. Another example is colon resection for suspected cancer, when the surgeon must dissect individual lymph nodes to assess the degree of malignancy. This procedure cannot be performed with current laparoscopic equipment, but might be possible with more dextrous instruments. Greater dexterity would also allow a surgeon to react faster in an emergency such as bleeding from a large vessel.

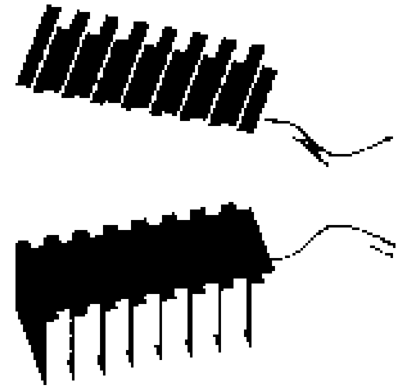

Figure 2: Laparoscopic manipulator fingers, constructed as molded rubber balloons.

In designing an improved laparoscopic tool, we have focused on increased dexterity and on the need for a more versatile tool to replace the single-purpose devices which have evolved for specific surgical tasks. For suturing, dissection, and related tasks, a device must also be able to generate a force of approximately 10 Newtons in any direction. A peak velocity of 20 cm/sec and a frequency response of at least 10–20 Hz would be desirable (see [3]). We have proceeded under the assumption that significant advances will call for new actuator technology, both to implement a given design, and to make it manufacturable. We thus directed our efforts toward integrated fabrication approaches reminiscent of the IC manufacturing process. Such a process would eliminate most of the assembly steps.

Our initial design was for a roughly anthropomorphic hand which fit within a 10 mm diameter, 25 mm long cylinder. Each finger was an elongated balloon, ribbed to allow expansion only on the dorsal surface and in a longitudinal direction (see Figure 2). Inflating the finger with air caused it to curl. This design was inspired by Suzumori's flexible micro-actuator [19]. The fingers were built up in layers of molded silicone rubber. The molds were machined in hard wax using a table-top CNC (computer numerically controlled) mill. With this technique, we could attain 50 μ accuracy and 500 μ feature size.

The main problems with this device were its low force output and poor controllability. In our prototype, the force was on the order of 0.13 Newtons, an order of magnitude lower than desired. The low force output was caused mainly by the low burst pressure of the unreinforced rubber (2×10^5 Pascals). In addition, while the all-rubber design simplified fabrication and miniaturization, the finger structure was highly compliant and had an effectively infinite number of freedoms. Since there was only one control, the system was underconstrained, which would lead to problems whenever the manipulator

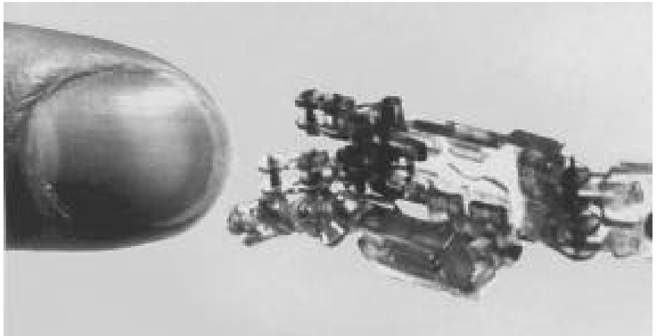

Figure 3: Hand-like end-effector.

encountered significant opposing forces.

One potential application of this device, nonetheless, is in palpation of the lung for detection of tumors. Such an application would require some form of tactile feedback, for example, using a strain-sensor array on the end-effector surface (see [6]). In addition, this rubber manipulator could replace roticulator devices, which are used to route ligatures for retraction of the esophagus (pulling it up and away from the chest wall). Such tasks call for a small, flexible device which need not generate exceptional force.

Nevertheless, we desired a more robust, controllable device, particularly for the suturing task. We used the molding technique again, but with rigid materials such as polyester and epoxy, to fabricate jointed fingers with a structure similar to that of a bicycle chain. These fingers were approximately 10 mm long and 2.5 mm in diameter. We incorporated the fingers into hand-like end-effectors having two fingers and a thumb, as well as a single-axis wrist (see Figure 3). The hands were actuated using Kevlar tendons. A typical example possessed seven degrees of freedom: two in each of three fingers, and one in the wrist.

This design displayed acceptable dexterity, but had several limitations, chiefly insufficient force output (in the range of several hundred milliNewtons). Under larger forces, the casting resin used in the device tended to fracture, though this problem could be reduced by using an injection-molded material instead. The Kevlar tendons had surprising strength, as mentioned above, and therefore should not be a limitation in future designs. Other limitations of this design included the friction and backlash introduced by the joints, the friction due to routing tendons through the hand, and the kinematic problems inherent in tendon-driven serial links [8], as well as potential manufacturing problems.

In our final design, we chose to use hydraulic actuation, because this technology combines high force and stiff output in a small actuator. In addition, compact hydraulic actuators opened the possibility of a direct-drive design, i.e. with the actuators placed directly in the end-effector links. This design would simplify both kinematics and mass-production. We used the CNC molding process described above to cast several prototype hydraulic cylinders in epoxy resin. A two-axis end-effector with a claw-like gripper and a one-axis wrist were similarly constructed. (It should be borne in mind that a laparoscopic instrument already has one degree of orientational freedom via rotation about its long axis; a full three degrees therefore require only a two-axis wrist.) The end-effector had a length of 43 mm (from the wrist joint to the tip of the gripper) and a diameter of 10 mm (see Figure 4). The device operated on hydraulic oil at 500 pounds per square inch (psi) and demonstrated gripping and tangential forces of 1.9 Newtons and 0.5 Newtons respectively. Subsequent cylinders and two-jaw grippers fabricated in metal were operated at pressures up to 1900 psi and generated gripping forces in excess of 14 Newtons.

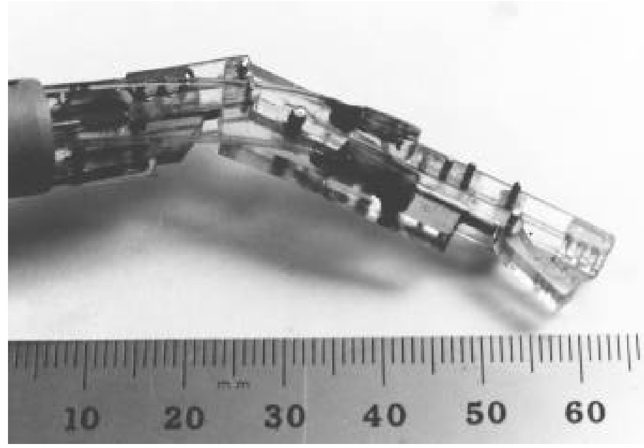

Figure 4: Hydraulic end-effector with two degrees of freedom.

Though there were several initial difficulties with this approach – such as creating reliable connectors – hydraulics seem favorable for millimeter-scale surgical manipulators since large forces can be generated. The weakest component in the above manipulators was the hydraulic tubing, rated at 4000 psi. In a 10 mm diameter cylinder, this yields a characteristic force of approximately 2000 Newtons. Practical designs should come within one order of magnitude of this figure, allowing space in the device for components other than the hydraulic cylinder itself, as well as the possible mechanical disadvantage of the kinematics. This leaves a generous margin with respect to the desired 10 Newtons, and suggests the possibility of smaller or more complex devices. The most serious potential limitation of this approach lies in the slender supply hoses required by the size constraints, which have high flow resistance and might limit dynamic response. However, we measured typical joint velocities of about half the maximal human finger joint velocity using a 100 centipoise hydraulic fluid; hydraulic fluids with viscosity as low as 1 centipoise are available.

Future work will focus on implementation of a two-axis wrist, as well as position, force, and eventually tactile feedback. We are using Hall-effect devices to sense the linear positions of the hydraulic cylinders; these sensors yield a resolution of 75 μ, which translates to 0.8 mm at the tip of the gripper. Force feedback could assist in suture and knot tensioning as well as guard against accidental laceration of tissue by manipulators outside of the scope's field of view. Tactile sensing might be useful for manipulating suture material or other objects held in the gripper, locating small anatomical features such as subsurface blood vessels, or detecting features which are obscured from the video camera. We hope to implement tactile feedback using strain sensor arrays on the end-effector coupled to stimulator arrays worn on the surgeon's fingertips. A "teletaction" system has recently been demonstrated [6] and appropriate tactile sensors spanning the 1 mm to 3 cm size range are being developed in our laboratory. These devices have a resolution of 64 to 128 elements and employ capacitive sensing [9], [12]. The stimulator is a 25 element (5×5) array of air pistons spanning a 1 cm square area. This system allows tactile features to be located with 100 μ accuracy.

4 Human Interface

There are many issues to consider in designing a human interface for a teleoperative task; discussions can be found in Brooks [3], Brooks and Bejczy [4], Burdea and Zhuang [5], Fischer, Daniel, and Siva [10], McAffee and Fiorini [13], and Sheridan [16]. For the endo-platform device, a simple, nondextrous master such as a joystick is sufficient for natural control. The laparoscopic manipulator, however, requires a more complex, dextrous human interface. The commercially available dextrous masters are not ideal because they are quite expensive, do not incorporate wrist sensors (which we feel are important for orienting the robotic tool inside the body cavity), and have many more degrees of freedom than we need for controlling the prototype robotic hand.

We designed and built a glove-like prototype human interface for the laparoscopic telesurgical system. This device will provide a more natural interface than current laparoscopic instruments possess; for example, one reason current instruments are clumsy is that they pivot about a fulcrum in the patient's abdominal wall, so that as the surgeon moves the handle, the instrument tip moves in the opposite direction. The glove senses thumb and index finger flexion, wrist flexion, and wrist rotation. The flexion sensors were made using strips from a Nintendo Power Glove which change resistance when bent. The wrist rotation sensor is made from two concentric plastic tubes (see Figure 5). The inner tube has a photomicrosensor mounted in it, and the outer tube has a grayscale attached to its inner surface. When the two cylinders are rotated with respect to one another, the photosensor moves along the grayscale.

A grayscale generated by a logarithmic function with a small polynomial component produced a nearly linear relationship between input and output. We tested the linearity by sampling the sensor output every 0.5 in along

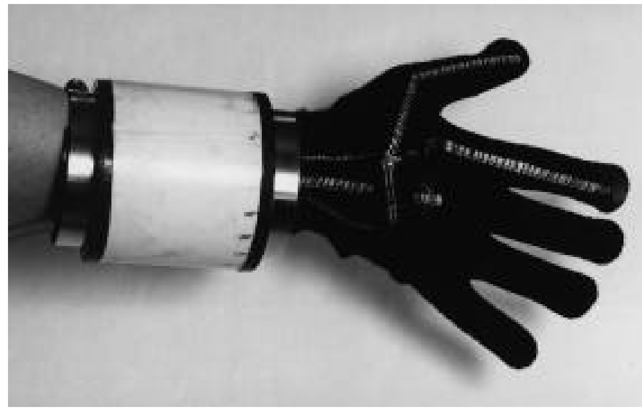

Figure 5: Prototype glove device.

the circumference of the outer tube (about every 16.2 degrees). Four data sets were taken in this manner, in different conditions designed to test play in the device. The best linear fit had a slope of 1.94 volts per radian over a range of about 3.4 radians. On average, the error at each data point was 1.5% of the linear fit value. If the rotation sensor is calibrated each time it is used, its output can be mapped directly to the rotation of the robotic hand about its axis.

In order to map the bend sensor readings to appropriate output signals for the miniature robotic hand, the glove needs to be calibrated. The sensor readings can be functionally mapped to the robotic joint positions by mapping the sensor readings taken from standard hand poses to similar standard poses of the robotic hand. Each operator will have a slightly different map. Since suturing is one of the more difficult procedures to do laparoscopically ([11], pp. 23-25; [15], p. 98), we used the thumb-two finger grasp a surgeon uses with a hand-held surgical needle (the thumb on one side and the index and middle fingers on the other; [1], pp. 58-60) as one of our hand poses. We developed a simple calibration procedure to take sensor readings from four right-handed subjects' hands in nine standard poses. Each subject also underwent tests designed to assess the consistency and relevance of the calibration measurements. In the first of these tests, subjects were asked to move their wrists smoothly up and down, with the peaks and valleys of the movement synchronized with a timer. They were instructed not to bend their wrist upward past the flat position, since the wrist flex sensor tended to buckle when the wrist was bent upward, producing anomalous readings. In the second test, the subjects were asked to move smoothly between a comfortable open position (index and thumb separated) and the pincing position described above, again with the endpoints of the movement coinciding with the timer. The sensor readings for each test were recorded every tenth of a second for ten to eleven seconds, and then the tests were repeated.

Although there were differences between subjects, the pattern of relationships among calibration values was fairly consistent across subjects (see Table 1). The timed

subject	relaxed wrist (36)	flat wrist (6)	flexed wrist (6)	relaxed index (36)	open index (6)	pinced index (18)	relaxed thumb (36)	open thumb (6)	pinced thumb (18)
DB	5.254	5.126	6.622	5.829	5.657	7.323	5.954	6.114	6.669
	0.109	0.064	0.322	0.211	0.022	0.211	0.105	0.045	0.246
AC	6.091*	5.145	7.063	5.882*	5.642	7.028	5.997*	6.199	6.333
	0.129*	0.016	0.129	0.282*	0.027	0.177	0.129*	0.209	0.122
LC	5.461	5.061	6.882	5.844	5.676	7.457	5.952	5.943	6.694
	0.190	0.031	0.209	0.206	0.046	0.105	0.064	0.144	0.076
DM	6.065	5.213	7.370	5.728	5.674	7.275	5.955	6.272	6.318
	0.141	0.067	0.034	0.063	0.055	0.144	0.067	0.043	0.160

Table 1: Mean and standard deviation of calibration values for all subjects, in volts. Numbers in parentheses indicate total number of samples (two calibration runs combined). Top figure is mean, bottom is standard deviation for each subject. Hand positions used were: relaxed hand, wrist held flat, wrist maximally flexed (downward), maximally open hand (index and thumb spread as far as possible), and pincing (the thumb-two finger grasp). *Only 35 values were recorded for the relaxed position for subject AC.

movement data from subject DM (a fairly typical data set) is shown in Figure 6. A more detailed discussion of this experiment can be found in [7]. For the stylized movements tested, the calibration values appear to be fairly consistent with the values recorded during movement for both the index finger and the wrist. The thumb traces were much more variable and did not correspond well with the thumb calibration values. Therefore, we decided to use the more consistent index reading to control the robot gripper position. When using the glove to control the robotic hand, as in the platform described in section 5, we generated position control signals for the robot's joints by mapping the sensor readings to desired robot joint positions. The calibration values allowed us to define an appropriate correspondence. For the gripper, the operator's open index calibration value (and anything below it) was mapped to a fully open gripper and her index pincing value (and anything above it) was mapped to a fully closed gripper. Intermediate sensor values were mapped to intermediate gripper positions. A similar map was used for the wrist.

Many improvements can be made on this initial prototype. To more accurately sense finger and, especially, thumb position, the glove should have separate flex sensors for each joint. A sensor should be incorporated to measure upward wrist flexion as well as downward, and the buckling problem needs to be addressed. The calibration procedure should also be further developed. Eventually, the glove should also incorporate force feedback and possibly tactile feedback.

5 Telesurgical Workstation

Toward the goal of a teleoperative surgical workstation (see Figures 7 and 8), we have begun installing the prototype robotic manipulator and glove onto a robotic

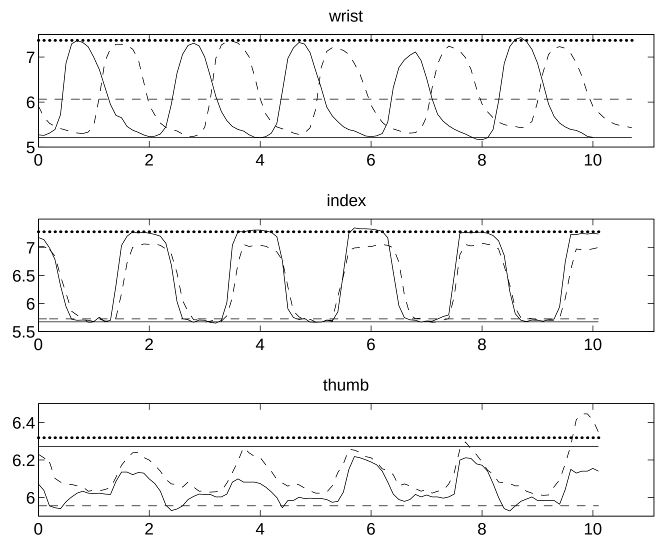

Figure 6: Movement data for subject DM (first trial is solid trace, second trial is dashed trace). Calibration data averages are shown as horizontal lines. For wrist: flat=solid, relaxed=dashed, flexed=dotted. For index and thumb: open=solid, relaxed=dashed, pincing=dotted. Horizontal axis is seconds and vertical axis is volts for each plot.

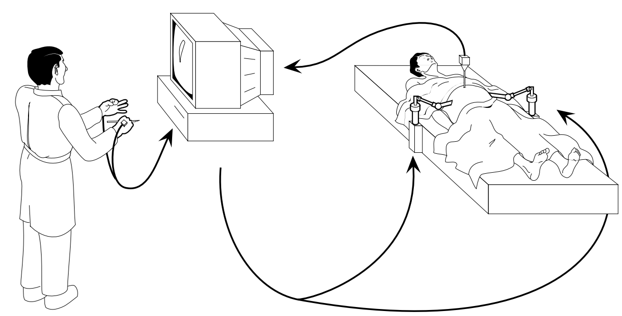

Figure 7: Telesurgical workstation.

platform (see Figure 9). The platform can provide the manipulator with x, y, and z (vertical) positioning and rotation (θ) about the z axis and can sense force in the z and θ axes. Preliminary open-loop tests (run at 10 Hz) of the gripper and wrist controls have been promising. The platform will help to evaluate prototypes' effectiveness on laparoscopic tasks such as suturing, and will help identify problems in designing a teleoperative workstation for use in the operating room.

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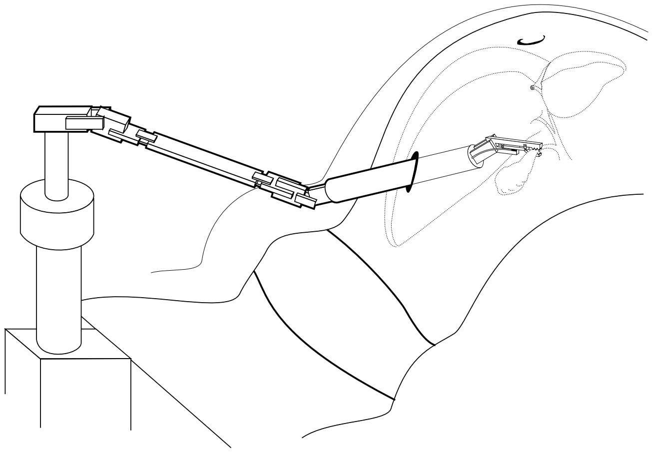

Figure 8: Close-up of telesurgical workstation.

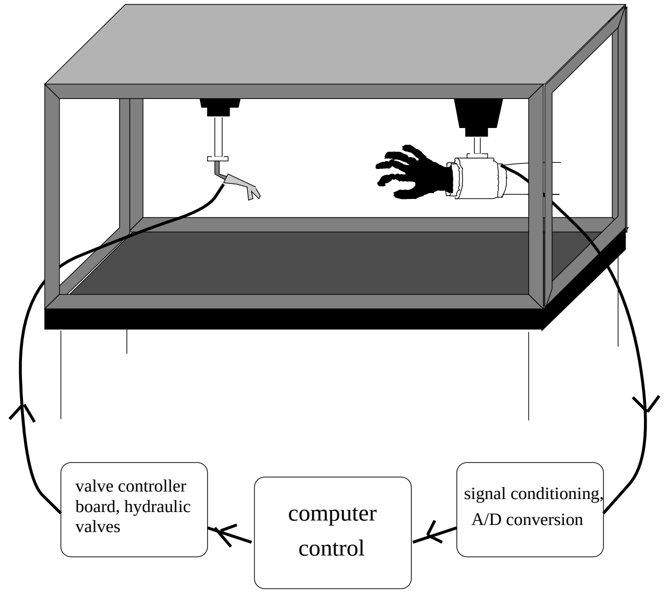

Figure 9: Planned setup of robotic platform with prototype manipulator and glove. The x, y, z, and θ signals may be generated by a sensor attached to the glove or by simply using a module of the platform as a master for global positioning, as shown in the figure. The wrist and gripper control signals are generated from the wrist and index readings of the glove, as described in section 4.

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