N94- 30441

A Force-Controllable Macro-Micro Manipulator and its Application to Medical Robotics

Neville I. Marzwell
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91190

51-37
2437
P. 14

and

Darrin R. Uecker and Yulun Wang
Computer Motion, Inc.
Goleta, CA 93117

ABSTRACT

This paper describes an 8-degrees-of-freedom macro-micro robot. This robot is capable of performing tasks that require accurate force control, such as polishing, finishing, grinding, deburring, and cleaning. The design of the macro-micro mechanism, the control algorithms, and the hardware/software implementation of the algorithms are described in this paper. Initial experimental results are reported.

In addition, this paper includes a discussion of medical surgery and the role that force control may play. We introduce a new class of robotic systems collectively called Robotic Enhancement Technology (RET[1]) [1]. RET systems introduce the combination of robotic manipulation with human control to perform manipulation tasks beyond the individual capability of either human or machine. The RET class of robotic systems offers new challenges in mechanism design, control-law development, and man/machine interface design. We believe force-controllable mechanisms such as the macro-micro structure we have developed are a necessary part of RET. Work in progress in the area of RET systems and their application to minimally invasive surgery is presented, along with future research directions.

1. INTRODUCTION

There are two main difficulties that have impeded the development of a high-precision, force-controlled robot. First, the execution of control strategies that enable precise force manipulation is difficult in real time because these algorithms have been too computationally complex for available controllers. Second, a robot mechanism that can quickly and precisely execute a force command and, at the same time, cover a large enough work-space for practical manufacturing applications is difficult to design. Actuation joints must be sufficiently stiff, frictionless, and lightweight so that desired torques can be accurately applied.

We have addressed the computational-complexity problem by building a high-performance, real-time, cost-effective multiprocessor system [2]. This system is highly modular in structure and was designed to support the needs of advanced robotic systems. Our robot mechanism uses a macro-micro design, which allows the end-effector to have the properties of a small and light robot, yet preserves the workspace capability of a large robot. The approach was to attach a small low-inertia, 3-degrees-of-freedom manipulator to the end of a larger and heavier 5-degrees-of-freedom manipulator.

---

[1]RET is a registered trademark of Computer Motion Inc.

Clearly this robotic structure could have many applications, and, traditionally, robotic systems have been placed into one of two application categories: manufacturing robotic systems or tele-operated robotic systems. The commonality of tasks within each category dictates that in each category there will be general characteristics associated with a robot's design and its method of use or users interface. Manufacturing robotic systems have been characterized by repetitive tasks programmed by the user, usually through a computer console or teach pendant. These robots typically operate at high speeds and are very accurate. Task examples include pick-and-place, spray painting, and welding, just to name a few. Teleoperated robotic systems are different in that they are designed to imitate the exact actions of the user, usually through a master/slave interface. They are typically used in hazardous tasks such as bomb deployment and hazardous-waste cleanup. They can also be used to attenuate or amplify the actions of the user to perform delicate assembly or move large objects.

A new class of robotic systems is currently being developed that we have termed Robotic Enhancement Technology (RET) [1]. RET will be different from the traditional robotic systems described above in that it will combine robotic manipulation with human control to perform manipulation tasks beyond the individual capability of either human or machine. The fundamental difference is the cooperative interaction of the human and the robot; the interaction is under control of the human. This interaction gives the human greater ability to perform complex manipulation. In turn, it presents new challenges in robot-mechanism, robot-control and man/machine interface design, which together make up the different parts of RET.

We can apply RET to problems where one's mind can see a solution but performance is limited by one's physical capabilities. Computer Motion, Inc. has attacked one such application in minimally invasive surgery, or, more specifically, laparoscopy. Laparoscopic procedures make use of a camera, known as the laparoscope, which is typically held by an assistant while a surgeon performs an operation. Thus, the assistant has control of the surgeon's field of view. This is tantamount to somebody holding a flashlight for someone else trying to do very delicate work. From the surgeon's perspective, this is far from ideal; clearly he would like to be in control of the camera himself. With this in mind, we have developed the Automated Endoscopic System for Optimal Positioning (AESOP), which holds the laparoscope and is guided by the surgeon with a foot- and/or hand-controlled interface. Thus, the surgeon is able to gain control of his eyesight by coordination between himself and the robot. This is our first RET system in a medical application. We feel that RET systems will find their way into many more medical applications, and, furthermore, we believe the macro-micro force controllable manipulator concept will play an important role in future RET systems.

The macro-micro mechanism is described in Section 2, which is followed by a discussion of the control algorithms and their hardware/software implementation in Section 3. Initial experimental results are given in Section 4 and the medical applicability of the macro-micromechanism as used in the RET systems is covered in Section 5.

2. A FORCE-CONTROLLABLE MANIPULATOR

A manipulator capable of delicate interactions with its environment must be designed differently from today's position-controlled robots. It has been shown that a high-bandwidth, low-effective-inertia design is helpful for precise force control [3,4]. The approach we have taken is to attach a low-inertia small manipulator to the end of a larger and heavier manipulator. This macro-micro structure results in a combined structure with the low end-effector inertia of the micro robot and the large workspace of the macro robot. A photograph of the complete robot is shown in Figure 1.

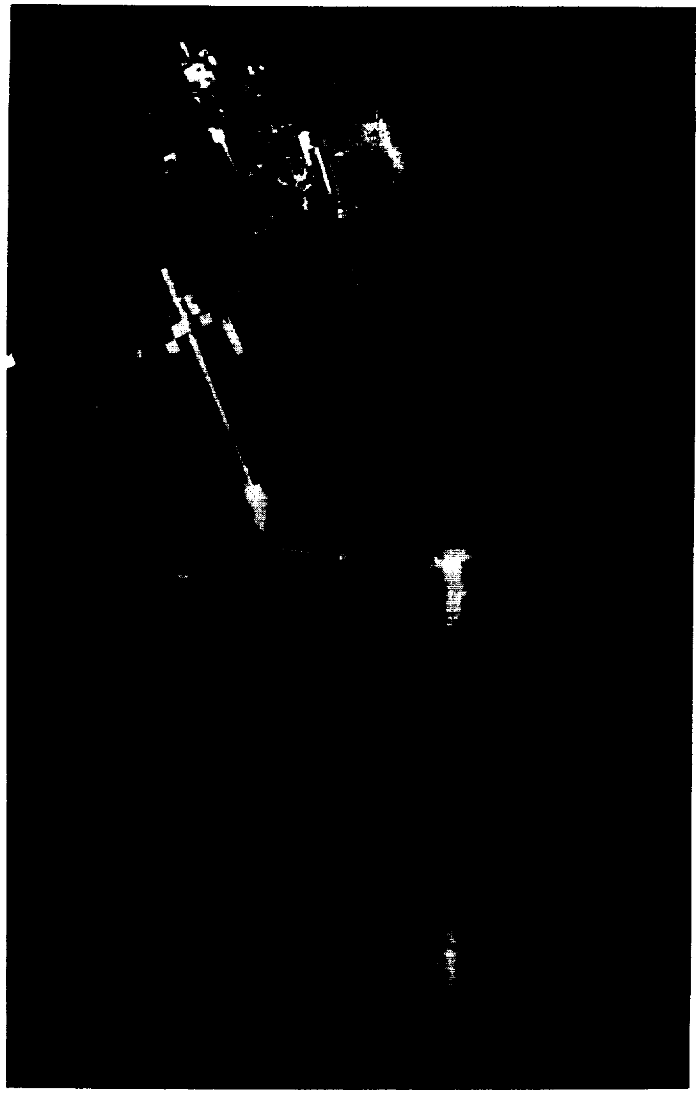


Figure 1. Photograph of the Macro-Micro Manipulator

The design strategy was to simplify the macro design by providing the micro robot with more capability. The main consequence of this decision is a large micro workspace, which allows less accuracy and performance capability in the macro. However, the micro's workspace volume directly influences the overall mass and size of the design considerably. In our design, reducing travel along each dimension by a factor of two roughly reduces the size and mass of the micro robot by roughly a factor of two.

The macro design is that of a 5-degrees-of-freedom articulated manipulator. This manipulator supports the weight and continuous force-exertion capability of the micro-manipulator throughout the workspace with 1-g acceleration. A 1-m reach was chosen as a reasonable workspace. The main features of this design are high mechanical rigidity, simple kinematics, large workspace volume, and cost effectiveness. The kinematic structure is very similar to that of the first five joints of a PUMA 560 robot [5]. A sixth joint is unnecessary because the tip of the micro robot spins continuously during grinding or polishing applications. We considered a variety of actuation methods, and after various optimization procedures, we decided on a harmonic drive/worm gear double-reduction scheme for the first three joints. The last two joints, which carry a much smaller load, use harmonic drives.

The macro-micro design couples a 3-degrees of freedom micro robot to the end of the 5-degrees of-freedom macro robot. A photograph of the micro design is shown in Figure 2. Motion along the x and y directions is actuated with parallel sets of 5-bar-link mechanisms, one attached to each of the two motor shafts. The z motion is actuated by a fixed motor oriented

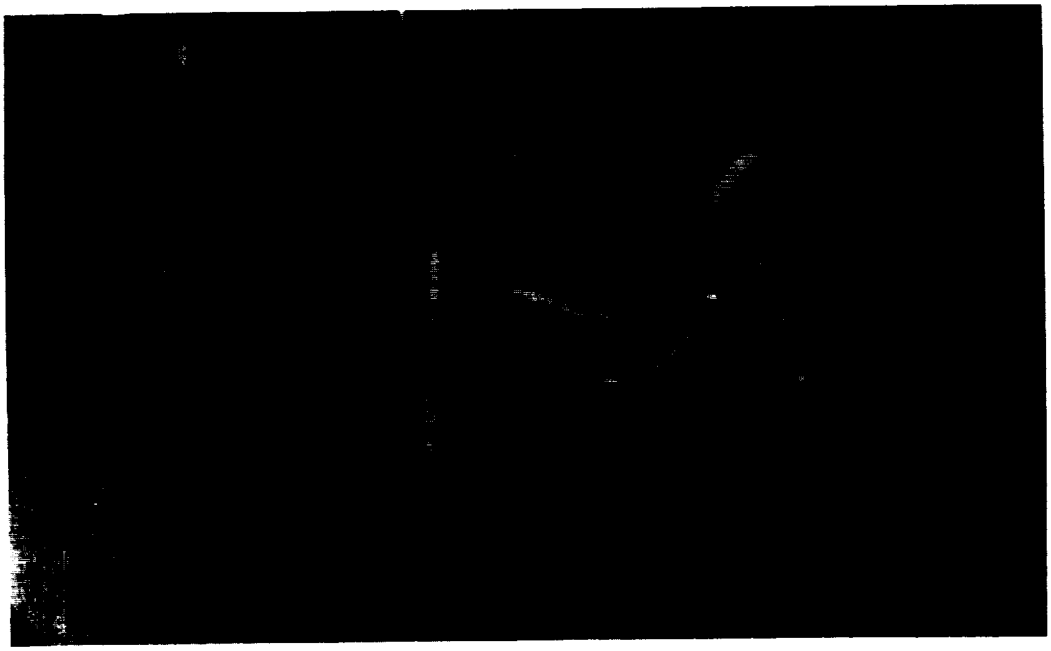


Figure 2. The Micro-Manipulator

perpendicularly to the x and y motors. This motor is attached to the parallel link mechanism through a pair of universal joints. The range of motion is 2 cm along each axis. A fourth pneumatic motor, located further from the tip than the other motors rotates the tip through a series of transmissions at a constant speed for polishing, finishing, and grinding applications.

The main objectives of the micro design were to minimize end-effector inertia, minimize joint friction, maintain tip orientation throughout the workspace, and support a maximum payload (i.e., force exertion) of 3 kg. The resulting tip inertia is roughly 250 gms. The joint friction was minimized by using direct-drive transmission and limited-angle flex bearings at the joints. Tip orientation is maintained by the parallel 5-bar-link structures.

The Secondary goals were to minimize the size and weight of the micro-manipulator. The final size is 35.5 by 19 by 17.8 cm, and the weight is 6.3 kg. Detailed analysis of the kinematics and dynamics of the micro-manipulator can be found in past publications [2,6].

3. REAL-TIME MACRO-MICRO FORCE CONTROL

A. Force-Control Algorithm

To control the macro-micro manipulator so that it will apply the desired force, we chose to use an impedance control method. The impedance-control method enables a robot to interact with its environment in a well controlled and precise manner [7]. The manipulator's end-effector reacts to environmental disturbances in the same manner as a linear mass-spring-damper does system. The mass, spring, and damper values are controlled electronically and can be different along different axes, and they can continuously change during a trajectory.

This method is different from hybrid position/force control [8], since particular forces or positions are never specified. The control variable is the equilibrium point of the mass-spring-damper system unaffected by external forces. The advantage of this methodology is that a single control variable and control algorithm can be used to guide a robot through interactions with the environment. Hybrid position/force control, on the other hand, requires a switch in control methods and control variables whenever the robot changes the configuration in which it interacts with its environment.

Figure 3 shows an example of a trajectory specified by the equilibrium path; in the trajectory, the manipulator comes into contact with a surface, slides across it, and then leaves the surface. Note that the nominal force exerted on the surface is proportional to the spring constant. By using the spring constant and surface location information, it is simple to calculate the equilibrium point's trajectory so as to produce a desired force across the surface. The force at the contact point will be influenced by contributions from the mass and damper as well. Consequently, if precise force control is important, the smaller the mass and damper values are, the better. The macro-micro design facilitates small mass values.

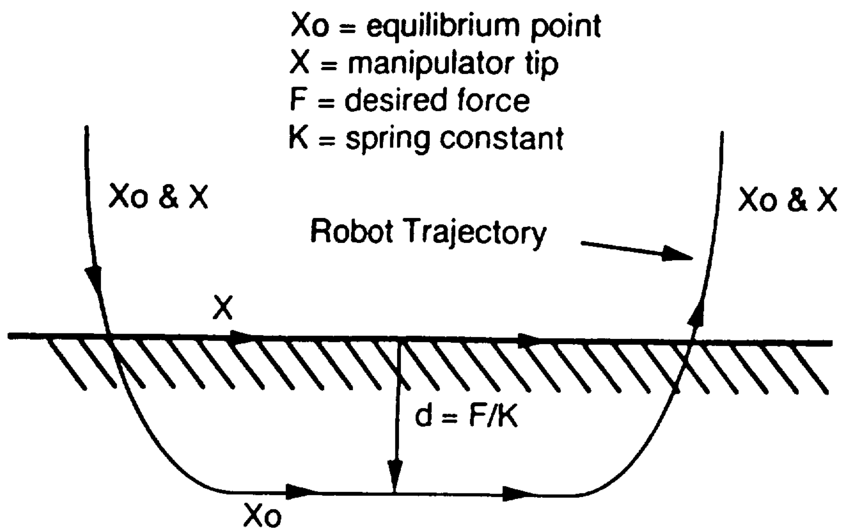


Figure 3. The Manipulator Trajectory Specified by the Equilibrium Point

The impedance equation can be written as follows:

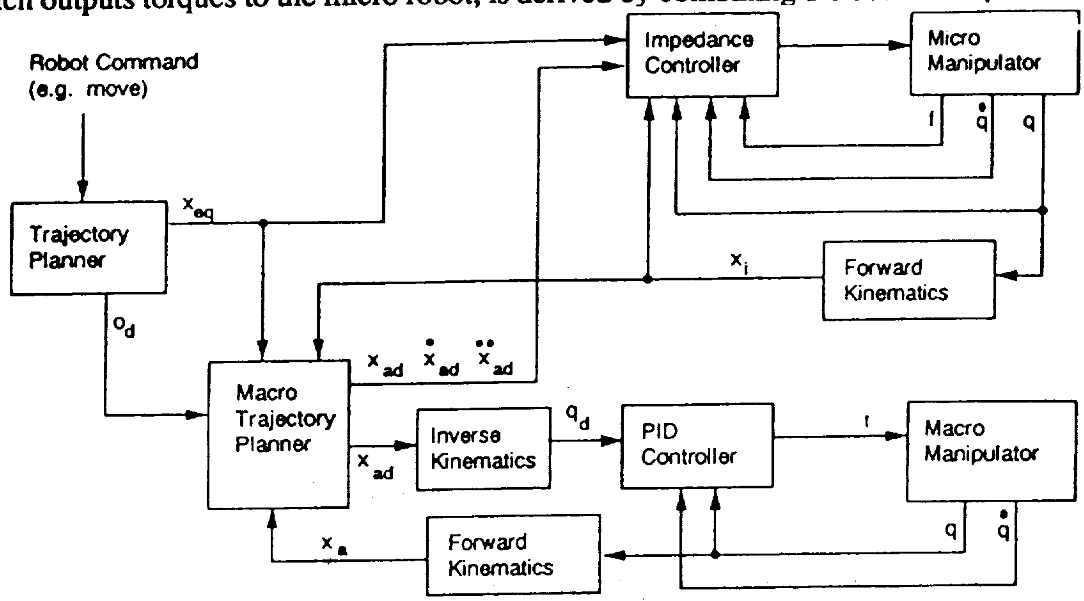
$$F_{ext} = M_s(\ddot{X}_R - \ddot{X}_o) + C_s(\dot{X}_R - \dot{X}_o) + K_s(X_R - X_o)$$

where

F_{ext} = external force applied to robot tip
X_R = tip position of macro-micro robot
X_o = desired equilibrium point of macro-micro robot
M_s = desired mass constant
C_s = desired damper constant
K_s = desired spring constant

Impedance control of a macro-micro design has the further complexity of managing the manipulator's redundancy so as to optimize force interactions, which is achieved by exploiting the micro robot's low tip inertia. In other words, the redundancy should be used to keep the micro robot from reaching its workspace limit, where one or more degrees of freedom would be lost. Our robot has 3 degrees of redundancy along the translational axes. Delicate interactions for translational motion are possible because of the micro robot. Orientation is left to the macro robot and is position controlled.

A block diagram of the control structure is shown in Figure 4. The impedance control law, which outputs torques to the micro robot, is derived by combining the desired impedance



x_i - micro robot's actual tip position

f - micro robot's force sensor readings

x_a - macro robot's actual tip position

o_d - desired orientation of macro-micro robot

x_{ad} $\dot{x}_{ad}$ $\ddot{x}_{ad}$ - desired tip position, velocity, and acceleration of macro robot

q_d - desired joint position

x_{eq} - equilibrium point

q - actual joint position

$\dot{q}$ - actual joint velocity

τ - torque

Figure 4. Impedance Control of Macro-Micro Manipulator

equation (stated above) with the equations of motion of the micro robot. Note that the servo-control law for all 5 joints of the macro robot is set by a simple position controller without feedback from the micro robot. However, feedback from the micro robot is input into a real-time trajectory generator for the macro robot. This trajectory generator uses the micro robot's redundant degrees of freedom to constantly update the macro robot's desired position, which is such that the micro robot is centered in the macro robot's workspace, and hence far from its workspace boundary. Consequently, the entire manipulator can respond to external disturbances with the quick reaction of the micro robot over the entire workspace of the macro robot.

B. The Control Computer

A high-performance multiprocessor system is used to satisfy the significant computational demands of controlling this robot. We designed this control system as a general-purpose high-performance controller with both hardware and software modularity as key features. The ability to easily rearrange and add other hardware and software modules to support different requirements for various tasks is particularly important in experimental projects such as this. Frequently, designs are unable to accommodate even minor modifications without a major impact to the existing system configuration.

The system is a VME-based system that is capable of using a number of compute, global-memory, and I/O modules. The compute modules are based on the TMS320C31 floating-point digital signal processor from Texas Instruments. This processor offers 33 MFLOPS of peak power. The global memory unit contains 2 Mbytes of memory for passing messages between compute units, for passing them to and from the host, and to store global variables shared by multiple compute units. The I/O modules are used to provide feedback for position, velocity, and force signals and as outputs for actuator commands.

Programs are developed in either C or C++ on the host computer and downloaded to the appropriate unit before run time. Several libraries are provided to support program development. Remote procedure calls were provided so that UNIX services, such as printf(), scanf(), open(), and close(), would be available for code development. Math functions, functions for accessing sensory data, and message-passing functions for multi processing are also provided.

4. EXPERIMENTAL RESULTS

The macro-micro robot has been fully assembled at Computer Motion, Inc., and we are in the early stages of experimentally verifying this design. At the time of this writing we have not reached the point of coordinated motion; however, we do have experimental results using the macro and the micro independently. These results follow.

The macro robot has been tested to verify that it will be capable of moving the micro robot throughout the macro's workspace without the need for torque control by the computer. To do this, the macro robot must be able to accurately move about the workspace with the load of the micro at the tip. The large gear reduction we have used should allow individual joints to have (PID) control of the manipulator. In Figure 5 we have plotted all five joints moving through different angular trajectories. The joints all move with very little trajectory-following error. The only joint that does have some tracking error is joint 5. This is mainly because of the load of the micro at this joint. This error is very small at the micro tip. We think that with some better tuning the tracking error will be reduced. The micro manipulator has been tested to insure that it has the characteristics described in Section 2. These initial experiments are with the micro detached from the macro, so we are primarily interested in their contact stability characteristics and disturbance-tolerance characteristics. These are the two areas in which traditional force-control mechanisms have experienced difficulties [4,7].

To test the contact stability, the equilibrium point of the micro was moved to a surface, in a configuration similar to the example in Figure 4. The results of this experiment are shown in Figure 6. Figure 6(a) shows the position along each axis, and Figure 6(b) shows the forces exerted on the tip. Initially, the tip is sitting at its equilibrium point without any contact forces (the forces seen are the results of gravity). At approximately 0.6 seconds, the tip equilibrium is moved +0.5 inches in the z-direction. The figure clearly shows the tip contacting the surface approximately 0.1 inch in that direction. The force in the z-direction quickly increases, with very little overshoot, and stabilizes at a constant force.

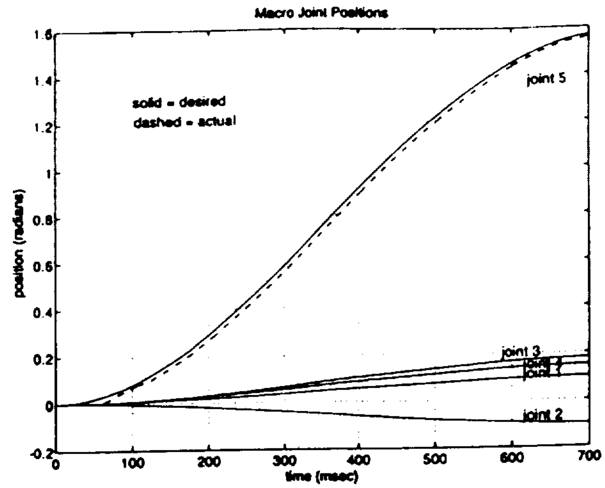


Figure 5. Macro-Manipulator Experimental Results

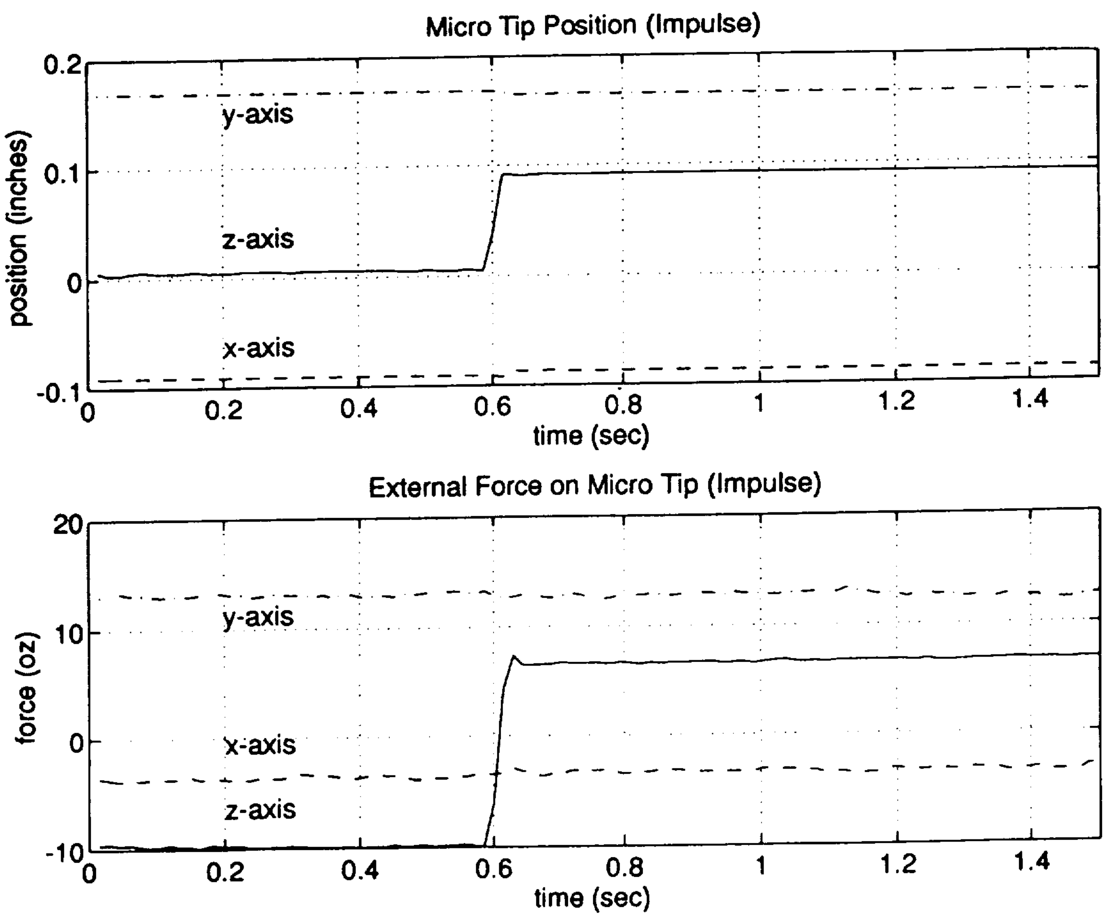


Figure 6. Contact Stability of the Micro: (a) Tip Position Data and (b) Force Data

The ability of the micro to tolerate disturbances while applying a constant force to a surface or object is demonstrated in Figure 7. In this experiment the entire micro is being moved in the y-direction while it is applying force in the z-direction. A disturbance is reached by the micro as it moves along the surface. The disturbance is shown graphically in Figure 7(a). Figure 7(b) and 7(c) show the position and the forces of the tip as it comes into contact with the disturbance. In this figure, one can see that the tip of the micro contacts the disturbance at approximately 0.8 seconds, and that the contact creates an increase in tip force in the z-direction. The tip moves along the disturbance and comes off of it approximately 4.5 seconds.

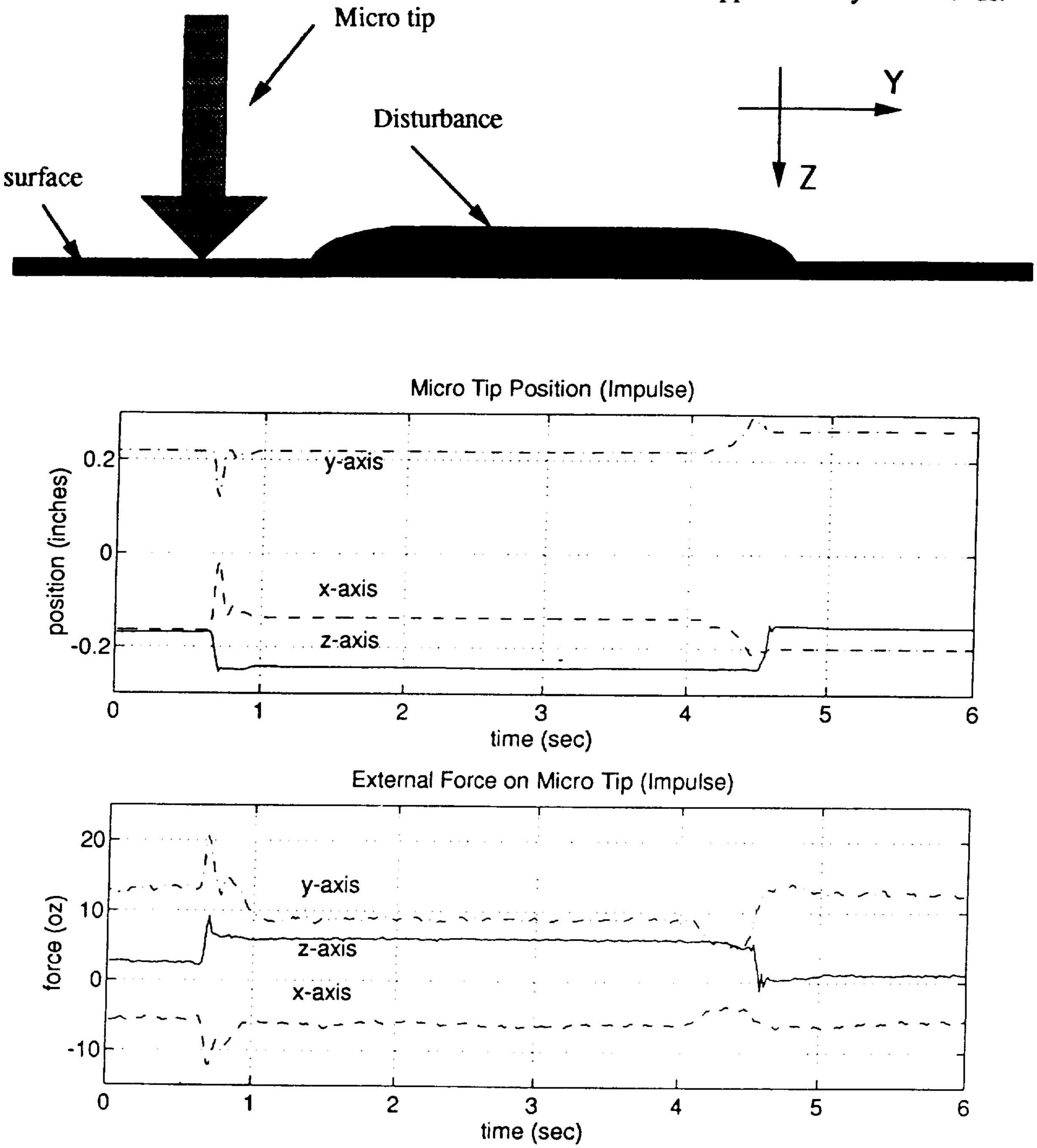


Figure 7. Disturbance Tolerance of the Micro: (a) Graphical Disturbance Model, (b) Position Data, and (c) Force Data

Transient forces are seen in the x and y directions at the beginning and end of the disturbance. The force in the y-direction along the disturbance is the result of friction. In the experiments described above we demonstrated the ability of the micro and the macro to perform their given tasks independently of each other. The next step, which we are currently working on, is the coordinated motion- and force-control of the two mechanisms.

5. MEDICAL APPLICATIONS FOR THE MACRO-MICRO FORCE-CONTROLLABLE MANIPULATOR

The macro-micro manipulator structure discussed above was conceived with manufacturing robotics in mind. However, we believe the structure will fit nicely in the RET framework. In this section we discuss current work at Computer Motion, Inc. in RET and the application of RET to laparoscopic surgery, as well as the potential application of the macro-micro force-controllable manipulator to this surgery.

A. The Automated Endoscopic System for Optimal Positioning (AESOP)

We have introduced the concept of RET into the surgical environment with the advent of AESOP, a robotic laparoscope holder for all forms of laparoscopic surgery [9]. Typical

Figure 8. Photograph of AESOP

procedures include gall bladder removal and hernia repair. There are three basic components which make up AESOP: the manipulator, the control computer, and the interface to the surgeon, which consists of a controller that can be operated by one's hand or foot. Figure 8 shows a photograph of AESOP and its components while Figure 9 shows a sketch of how AESOP would be incorporated into the operating environment.

The manipulator has 6 degrees-of-freedom, four actuated joints, and two passive joints. The structure of the manipulator is shown in Figure 10. The actuated joints are 1, 2, 3, and 6. Joints 1, 2, and 3 are used to control the tip of the manipulator, and hence the Cartesian location of the end of the laparoscope. Joint 6 is used to rotate the laparoscope for the correct orientation during movement. The passive joints, 4 and 5, are designed so that the laparoscope can rotate freely about the pivot-point constraint imposed by the cannula when the cannula is inserted through the patient's abdominal wall.

The fault-tolerant control computer translates the interface inputs from the surgeon into movements by the manipulator. The control computer includes a CPU and all of the digital, analog and encoder I/O needed for the feedback paths. The control computer begins running the control algorithms directly on power up, requiring no special boot up from the user.

The man/machine interface is composed of a controller that works by hand and a controller operated by one's foot.. Both controllers have the same functionality. This functionality consists of being able to move the laparoscope tip up/down, left/right, and zoom-in/zoom-out.

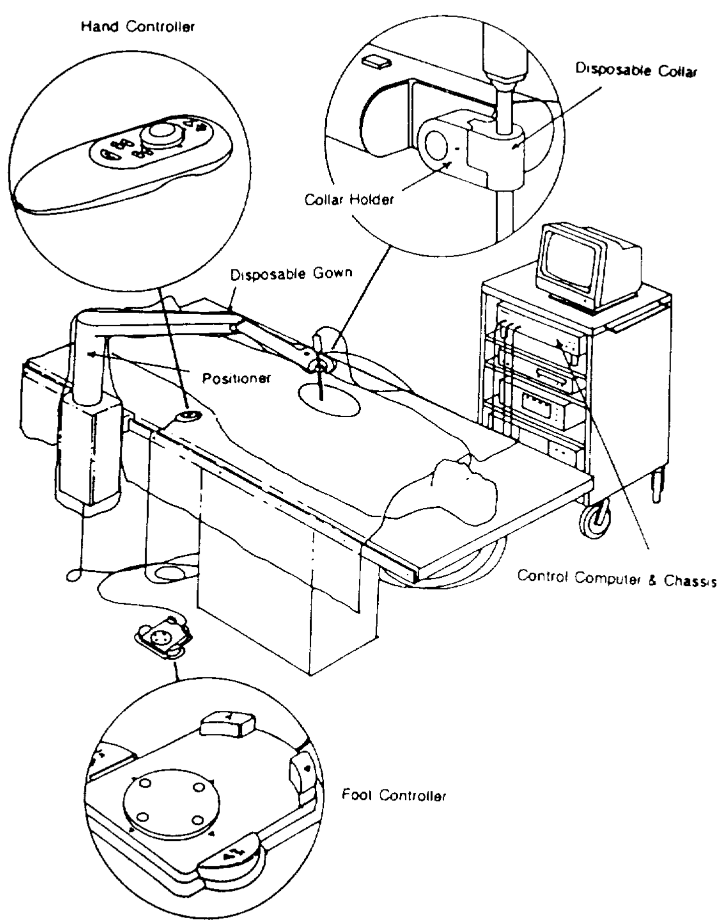


Figure 9. The AESOP System in the Surgical Environment

The surgeon merely watches the video image presented by the laparoscope and commands movements relative to the video images. AESOP is also capable of remembering past positions that were programmed by the surgeon and then returning to them on command from the surgeon. We call this function ReView, and it is a very valuable feature in our system.

AESOP represents the first generation of RET. Currently, the hand and foot controllers allow the surgeon to control the robot so as to enhance his or her overall performance. However, we feel these interfaces are just solutions for the immediate future. We are currently working on a natural-language interface and image-processing technology to create a more seamless interface between the surgeon and the robot.

B. Force Controllable Manipulators in Medical Robotics

As RET systems such as AESOP become accepted in surgical applications, their role in surgery will certainly become more active. The surgeon will become an "operating octopus" using many manipulators to aid in a variety of tasks. Clearly, this will not happen with mechanisms that are purely position controlled. RET systems will have to posses the ability to sense forces and react to them. Thus, force-controllable manipulators will have to play an integral part in RET. We feel the concept of the macro-micro manipulator we have described above can fill this need.

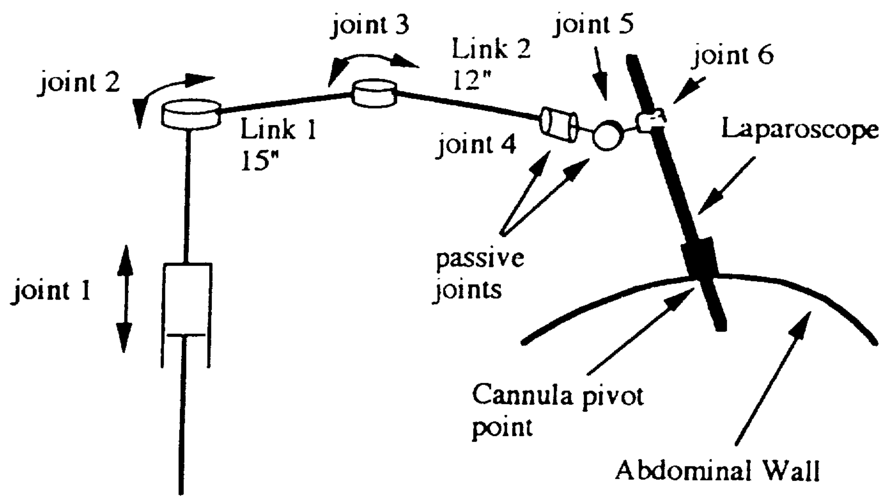


Figure 10. Schematic of AESOP as Used in Abdomen Surgery

An application that we have identified that requires a delicate interaction of forces is tissue approximation, or suturing. One of the key aspects of tissue approximation is tissue handling [10,11]. Tissue must be held steady with the proper tension and position so the surgeon can perform the appropriate suturing technique. Also, the tissue must be handled very delicately so as to avoid tearing or scarring, which can cause poorer overall recovery for the patient. One of the current problems is that tissue approximation usually involves long, leveraged instruments operated by less experienced than the surgeon assistants. Thus, this is another example where the surgeon would prefer to operate the machine if his or her hands were not already full. Static tissue holders can be used, but tissue is easily torn by any movement of the patient.

A force-controllable macro-micro manipulator would be the ideal mechanism to handle this problem. Modification of the impedance-force-control method may be needed for force regulation. With the proper interface, the surgeon would be able to set the correct force on the tissue, and then the macro-micro mechanism would always work to keep that force constant. The macro would be designed very much like AESOP, having a relatively large workspace and being stiff. The micro-manipulator would be small enough to actually enter the patient through one of the ports. The micro would work close to the tissue, keeping the appropriate forces applied at all times while the macro would be responsible for positioning the micro. Micro-mechanisms for laparoscopic surgery have recently been researched [12,13], although we are not aware of any force-controllable mechanisms.

One of the challenging design aspects of this RET system will be the man/machine interface. The surgeon will not know the exact quantitative forces that must be exerted on the tissue. Thus, for him or her to program numerically would be difficult and clearly not very intuitive. Part of the RET hypothesis requires a seamless man/machine interface. Thus, the surgeon should be able to "teach" the robot the required force through example, just as he or she would an assistant. The surgeon should be able to transfer some of his or her knowledge and experience directly to the RET system. The surgeon would then be operating with a robotic assistant that is acting like he or she would.

The design of the interface will drive the mechanism and control-law design. The interface will allow the surgeon to actually use the robot as an extension of his or her arm and feel the forces that are being exerted on the micro. When the surgeon has the proper hold on the tissue he or she will be able to let go of the manipulator and it will continue to regulate the forces to keep them as desired. A natural-language interface will also allow the surgeon to command minor in situ adjustments without interrupting the suturing process. Thus, the mechanism and control-law design must permit this type of interface.

6. CONCLUSION

An 8-degrees of freedom macro-micro manipulator has been described that can delicately interact with its environment. The mechanism includes a large macro that is mechanically stiff and has a large workspace, combined with a micro manipulator that has a low effective inertia with minimal friction and therefore a high mechanical bandwidth. A high-performance multiprocessor system was described that implements the impedance-control law for stable control and interaction with the environment. We have presented preliminary experimental results that validate this design. Further results will be obtained by the end of the year.

We have also discussed this macro-micro manipulator concept and its application to medical surgery. We introduced RET, a new class of robotic systems based on an interactive use of robots and humans. AESOP, the first RET system developed for minimally invasive laparoscopic surgery, was also introduced. Finally, we justified the need for force-controllable mechanisms in RET, as well as their application to tissue approximation. Computer Motion, Inc., plans to pursue developments in RET including medical applications.

7. ACKNOWLEDGMENTS

The authors would like to thank Amante Mangaser, Keith Laby, Steve Jordan, and Jeff Wilson of Computer Motion, Inc. for their efforts in designing and implementing this robot. We would also like to thank Professor Yoshihiko Nakamura of UCSB for his assistance in developing the control algorithm.

The research described in this paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, Office of Advanced Concepts and Technology. Computer Motion, Inc. funding from NASA/Jet Propulsion Laboratory under SBIR contract number NAS7-1149.

REFERENCES

[1] Wang, Yulun "Introducing Robotic Enhancement's New Applications," Technical Note #1, Computer Motion, Inc., Goleta, Calif., 1993.

[2] Marzwell, Neville, and Yulun Wang, "A Macro-Micro Robot for Precise Force Applications," *NASA Technology 2002*, Baltimore, Md., 1992.

[3] Khatib, Oussama, "Augmented Object and Reduced Effective Inertia in Robot Systems," *Proc. of the American Control Conference*, Atlanta, Ga., June 1988.

[4] Sharon, Andre, Neville Hogan, and David E. Hardt, "High Bandwidth Force Regulation and Inertia Reduction Using a Macro/Micro Manipulator System," *Proc. of the IEEE Conf. on Robotics and Automation*, Philadelphia, Penn., April 1988.

[5] Leahy, M.B., et al., "Efficient Dynamics for the PUMA-600," *Proc. of the IEEE Conf. on Robotics and Automation*, San Francisco, Calif., 1986.

[6] Wang, Yulun, Amante Mangaser, Keith Laby, Steve Jordan and Jeff Wilson "Design and Control of a Macro-Micro Robot for Precise Force Applications," *Proc. of the 5th NASA/NSF/DOD Workshop on Aerospace Computational Control*, 1993.

[7] Hogan, Neville, "Stable Execution of Contact Tasks Using Impedance Control," *Proc. of the IEEE Int. Conf on Robotics and Automation*, Raleigh, N. C., 1987.

[8] Raibert, M., and J. Craig, "Hybrid Position/Force Control of Manipulators," *Journal of Dynamic Systems, Measurement, and Control*, vol. 102, pp. 126-133.

[9] Wang, Yulun, "AESOP: Automated Endoscope for Optimal Positioning," Technical Note #2, Computer Motion, Inc., Goleta, Calif., 1993.

[10] Szabo, Zoltan, "Laparoscopic Suturing and Tissue Approximation," in *Minimally Invasive Surgery*, John G. Hunter and Jonathan M. Sackier (eds.), McGraw Hill Inc., 1993, pp. 141-155.

[11] Nathansan, L. K., "The Sutured Laparoscopic Gastrointestinal Anastomosis, in *Minimally Invasive Surgery*, John G. Hunter and Jonathan M. Sackier (eds.), McGraw Hill Inc., 1993, pp. 157-170.

[12] Rinisland, H. H., "Basics of Robotics and Manipulators in Endoscopic Surgery," *Endoscopic Surgery and Allied Technologies*, Vol. 1, No. 3, June 1993, pp. 154-159.

[13] Mueglitz, A, G. Kunad, P. Dautzenberg, B. Neisius, and R. Trapp, "Kinematic Problems of Manipulators for Minimal Invasive Surgery," *Endoscopic Surgery and Allied Technologies*, Vol. 1, No. 3, June 1993, pp. 160-164.