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Abstract

This paper reports the development of a robotic system designed to extend a human's ability to perform small-scale (sub-millimeter) manipulation tasks requiring human judgment, sensory integration, and hand-eye coordination. Our novel approach, which we call steady-hand micromanipulation, is for tools to be held simultaneously both by the operator's hand and a specially designed actively controlled robot arm. The robot's controller senses forces exerted by the operator on the tool and by the tool on the environment, and uses this information in various control modes to provide smooth, tremor-free, precise positional control and force scaling. Our goal is to develop a manipulation system with the precision and sensitivity of a machine, but with the manipulative transparency and immediacy of hand-held tools for tasks characterized by compliant or semi-rigid contacts with the environment.

KEY WORDS—medical robotics, microsurgery, human performance augmentation, cooperative control, steady-hand manipulation

1. Introduction

1.1. Medical Robotics and Computer-Integrated Surgery

Computer-integrated surgical (CIS) systems exploiting "robotic" technologies—image processing, modeling, mechatronics, intelligent control, and human-machine interfaces—will have a comparable effect on the practice of medicine in the 21st century to that of computer-integrated manufacturing (CIM) systems on 20th-century industrial production. Further, the factors that will make this prediction come true are in many ways analogous to the factors that drove the CIM revolution.

First, CIS systems will provide new capabilities to surgeons in the treatment of disease and deformity. By permitting less invasive and more accurate surgical interventions, they will reduce patient morbidity, improve clinical outcomes, and reduce the cost to society associated with disease and health care. Second, the improved consistency of CIS systems will significantly improve quality of care by reducing surgical errors and making it possible for many surgeons to

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provide treatments that can now be performed safely (if at all) by only a very few exceptionally skilled individuals. Finally, the widespread deployment of CIS systems will permit the automated collection and analysis of information about what was actually done in the surgical suite. These data can be compared to patient outcomes, and eventually permit the same sort of "process learning" that has enabled CIM systems to revolutionize semiconductor and computer manufacturing. Further, the greater consistency and improved data collection possible with CIS systems will significantly speed the development of new and more efficient therapies.

As CIS systems evolve, two related paradigms will emerge. The first, computer-assisted surgical planning/computer-assisted surgical execution (CASP/CASE), is directly analogous to industrial CAD/CAM. In computer-assisted surgical planning (surgical CAD), medical images and other information will be combined to make a computer model of an individual patient. This model will be used for diagnosis and for planning an optimized surgical intervention, much as parts models are used in the design of manufacturing processes. As part of the planning process, alternative procedures may be simulated, and the surgeon can select the plan that seems most appropriate for the patient. In computer-assisted surgical execution (surgical CAM), all of this information will be brought into the operating room. Real-time images or other sensory information will be used to register the virtual reality of the preoperative model and plan to the actual reality of the surgical patient. Once this registration has been performed, a number of technical means, ranging from robotic devices to advanced image displays, may be used to assist the surgeon in carrying out the planned intervention with great accuracy and consistency. We can extend the analogy further to computer-assisted surgical assessment (surgical TQM), in which images and models are combined with logged information from the procedure and other post-operative measurements to verify that the intervention was performed successfully, to determine whether the condition for which it was performed has been corrected, and to promote process learning to improve future procedures.

The second paradigm, surgical assistance, emphasizes interactive cooperation between information-driven machines and human surgeons. As a grand challenge, one might foresee the eventual development of something like a "robotic resident" with specialized capabilities that could operate alongside its human counterparts and respond to the same sort of general supervisory commands that surgeons are accustomed to using today. Our expectation, however, is that these systems will evolve from rather simpler systems in which surgeons directly control machines that augment human capabilities. As computers' abilities to model anatomy and surgical tasks improve, the systems will be able to perform more complicated tasks and surgical steps in response to supervisory commands, in a manner analogous to cooperative telemanipulation systems that have been proposed for space, construction, and other environments. Ultimately, they will merge with CASP/CASE systems. Indeed, the hardware may often be indistinguishable. The main difference is one of emphasis between preoperative and intraoperative modeling and planning. Which paradigm is considered more appropriate will really depend on the needs of a particular procedure.

1.2. Augmentation of Human Micromanipulation Capabilities

This paper describes the first steps in the ongoing development of a robotic assistant for microsurgery and other precise manipulation tasks. It reports a new robotic system developed to extend a human's ability to perform small-scale (sub-millimeter) manipulation tasks requiring human judgment, sensory integration, and hand-eye coordination. Our approach, which we call *steady-hand micromanipulation*, is for tools to be held simultaneously both by the operator's hand and a specially designed robot arm (Fig. 1). The robot's controller senses forces exerted by the operator on the tool and by the tool on the environment, and uses this information in various control modes to provide smooth, tremor-free, precise positional control and force scaling. The result will be a manipulation system with the precision and sensitivity of a machine, but with the manipulative transparency and immediacy of hand-held tools for tasks characterized by compliant or semirigid contacts with the environment.

Humans possess superb manual dexterity, visual perception, and other sensory-motor capabilities. We manipulate best at a "human scale" that is dictated by our physical size and manipulation capabilities, and roughly corresponds to the tasks routinely performed by our cave-man ancestors. Tasks that require very precise, controlled motions are difficult or impossible for most people. Further, humans work best in tasks that require relative positioning or alignment based on

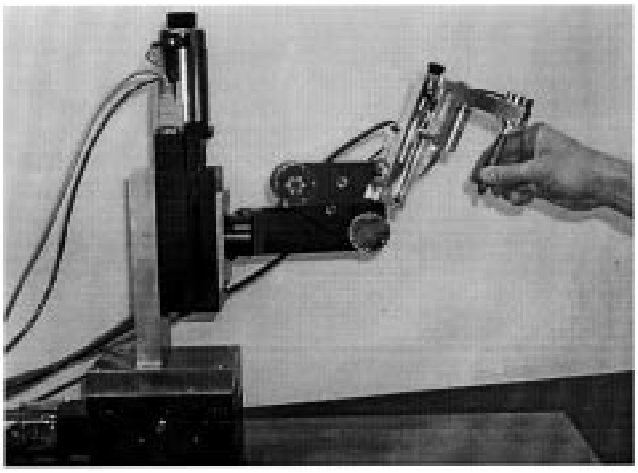

Fig. 1. The Johns Hopkins University Steady-Hand robot for cooperative human-machine microsurgical manipulation.

visual or tactile feedback. We do not come equipped with an innate ability to position or fabricate objects accurately relative to arbitrary measuring standards, or to perform tasks based on nonhuman sensory feedback. For these tasks, we rely on machines. A good machine tool, for example, can routinely measure and fabricate parts to a precision of 2.5 μm ($\approx$ 0.001 in). Fine-scale tasks such as microsurgery require both precise manipulation and human judgment. Other tasks may require combining precise manipulation with sources of information (assembly specifications, nonvisible-light images, etc.) that are not naturally available to a human. We thus have a choice: either automate the human judgment aspects of the task (difficult at best and often impossible) so that a machine can automatically perform the task, or else find a way to use a machine to augment human manipulation capabilities while still exploiting the human's natural strengths.

Most prior robotic micromanipulation systems have emphasized traditional master-slave and telerobotic manipulation. Our approach might offer several advantages compared to these systems in the context of micromanipulation. These include:

1. simplicity,
2. potentially cheaper implementations,
3. a more direct coupling to the human's natural kinesthetic senses
4. straightforward integration into an existing application environment, and
5. greater "immediacy" for the human operator.

The principal drawbacks are the loss of the ability to "scale" positional motions and the loss of the ability to manipulate objects remotely. These are certainly important abilities, but we believe there are many tasks in which they are not crucial and for which a simpler alternative is more attractive. These advantages are especially attractive in applications like microsurgery, where surgeon acceptance is crucial and where approaches that do not require a complete reengineering of the surgical workstation are much easier to introduce into practice.

2. Robotically Assisted Micromanipulation

Mechanical systems have been developed which extend the capability of human operators using telerobotic principles (Sheridan 1995), including virtual training (Hunter et al. 1995), manipulation of objects in hazardous environments (Mindell et al. 1993), remote surgery (Satava 1992; Green et al. 1992), and microsurgery (Hunter et al. 1995; Charles 1994; Misuishi et al. 1997; Jensen et al. 1997; Salcudean, Ku, and Bell 1997; Schenker, Das, and Timothy 1995). In general, telerobotic devices rely on an operator commanding the motion of a robot using a secondary input device. The operator may reside in close proximity to the robot, observing its motions through a microscope as in microsurgery, or may be many miles away as in space exploration. In both cases, the operator is an integral part of the system and has direct control over how the manipulator moves. An ideal teleoperated system would be transparent to the operator and give the impression of direct control. The input device manipulated by the operator may be either passive, such as a trackball, joystick or stylus, or made up of active devices such as motors. An active input device allows forces imposed on the robot to be measured, scaled, and mimicked at the input device to be subsequently felt by the operator.

Several systems have been developed for teleoperated microsurgery using a passive input device for operator control. Guerrouad and Vidal (1989) described a system designed for ocular vitrectomy in which a mechanical manipulator was constructed of curved tracks to maintain a fixed center of rotation. A similar micromanipulator (Pournaras et al. 1991) was used for acquiring physiological measurements in the eye using an electrode. While rigid mechanical constraints were suitable for the particular applications in which they were used, the design is not flexible enough for general-purpose microsurgery, and the tracks take up a great deal of space around the head. An ophthalmic surgery manipulator built by Jensen et al. (1997) was designed for retinal vascular microsurgery and was capable of positioning instruments at the surface of the retina with submicron precision. While a useful experimental device, this system did not have sufficient range of motion to be useful for general-purpose microsurgery. Also, the lack of force sensing prevented the investigation of force/haptic interfaces in the performance of microsurgical tasks.

Many microsurgical devices (Hunter et al. 1995; Charles 1994; Misuishi et al. 1997; Salcudean, Ku, and Bell 1997; Schenker, Das, and Timothy 1995) are based on force-reflecting master-slave configurations. This paradigm allows an operator to grasp the master manipulator and apply forces. Forces measured on the master are scaled and reproduced at the slave and, if unobstructed, will cause the slave to move accordingly. Likewise, forces encountered by the slave are scaled and reflected back to the master. This configuration allows position commands from the master to result in a reduced motion of the slave, and for forces encountered by the slave to be amplified at the master. While a force-reflecting master-slave microsurgical system provides the surgeon with increased precision and enhanced proprioception, there are some drawbacks to such a design. The primary disadvantage is the complexity and cost associated with the requirement of providing two mechanical systems, one for the master and one for the slave. Another problem with telesurgery in general is that the surgeon is not allowed to directly manipulate the instrument used for the microsurgical procedure. While physical separation is necessary for systems designed to perform remote surgery, it is not required during microsurgical procedures. In fact, surgeons are more likely to accept assistive devices if they are still allowed to directly manipulate the instruments.

2.1. Shared Autonomy and Cooperative Control

There is a large body of literature concerning provably stable control techniques for robots. Standard paradigms include 1) preprogrammed trajectory control of position (Dinsmoor and Hagermann 1993; Sakakibara 1996) and force (Whitcomb, Rizzi, and Koditschek 1993; Whitcomb et al. 1997); 2) fully autonomous robots (e.g., Suzuki and Arimoto 1988; Krotkov and Simmons 1992; Yoerger, Bradley, and Walden 1992); and 3) master-slave teleoperators (e.g., Xu and Kanade 1993; Morikawa and Takanashi 1996; Guo, Tarn, and Bejczy 1995). In our case, we are interested in developing provably stable controls for cases where both the robot and the human manipulate a single tool in contact with a compliant environment. The work most relevant to this includes that of Kazarooni (Kazerooni 1989a, 1989b; Kazerooni and Jenhwa 1993), who developed exoskeletons to amplify the strength of a human operator. Kazarooni and colleagues (Kazerooni 1989a, 1989b; Kazerooni and Jenhwa 1993) reported a linear-systems analysis of the stability and robustness of cooperative human-robot manipulator-control systems in which the manipulator scales up the human operator's force input by a factor of ~ 10. The authors report that a stability analysis of this closed-loop system (comprising a dynamical model of both the robot arm and the human arm) is complicated by the fact that precise mathematical plant models do not exist for the hydraulically actuated robot and the operator's human arm. In consequence, in Kazerooni 1989a, 1989b; Kazerooni and Jenhwa 1993, the authors perform a robustness analysis to develop stable robot force-control laws that accommodate wide variation in both human- and robot-arm dynamics. In contrast, we propose to address the control problem of cooperative human-robot manipulator systems in which the manipulator scales down the human operator's force input by a factor of ~ 0.1. To achieve this scaling down of human input, we anticipate comparable (or greater) difficulties to arise from unknown human-arm dynamics. We can construct the system using electrical motors (rather than hydraulic motors) for which accurate dynamical models are available.

A number of authors (e.g., Guo, Tarn, and Bejczy 1995; Cho, Kotoku, and Tanie 1995) have investigated "shared autonomy" for the cooperative control of teleoperators, typically with space or other "remote" applications where time delays can affect task performance. There has also been some work (e.g., Yamamoto, Eda, and Yun 1996) on control of robots working cooperatively with humans to carry loads and do other gross motor tasks relevant for construction and similar applications.

Within the area of surgery, we have long used "hands-on" guiding of robots for positioning within the operating room (e.g., in the Robodoc [Bargar et al. 1995; Taylor et al. 1994; Mittelstadt et al. 1994] hip-replacement surgery system and in the JHU/IBM LARS system [Funda et al. 1994; Eldridge et al. 1996; Funda et al. 1993; Funda et al. 1994; Funda et al. 1994; Goradia, Taylor, and Auer 1997; Taylor et al. 1995; Taylor et al. 1996] for endoscopic surgery). Davies and colleagues (Harris et al. 1997; Ho, Hibberd, and Davies 1995; Troccaz, Peshkin, and Davies 1997) have combined hands-on guiding with position limits and have demonstrated 3-DoF machining of shapes in the end of a human tibia.

At Johns Hopkins University (JHU), we have been using the LARS robot (Funda et al. 1994) to perform a variety of steady-hand tasks combining hand guiding, active control, and safety constraints in neuroendoscopy and other areas. In one experiment, the LARS robot-assisted evacuation of simulated hematomas was found to take longer (6.0 min vs. 4.6 min) than freehand evacuation but was found to remove much less unintended material (1.5% vs. 15%) (Goradia, Taylor, and Auer 1997). We have also made some preliminary experiments using the LARS for micromanipulation (Kumar et al. 1997), although the compliance of the LARS upper linkage severely limits the benefit gained.

3. A Robotic System for Steady-Hand Micromanipulation

3.1. Design Goals

Cooperative micromanipulation requires capabilities not commonly found in conventional robots or teleoperator systems. Typically, these tasks are performed by a human operator looking through a microscope while grasping a "handle" on the instrument or tool being used to perform the task. In the tasks that we are considering, we believe that motion "scaling" (in the sense that a 1-cm human-hand motion might cause a 100 μm instrument motion) is much less important than smooth motion naturally aligned with the human's own kinesthetic senses. Pulling on the tool's handle should produce intuitively natural translation and orientation motions. Performance goals are summarized in Table 1. Specific requirements are discussed below.

3.1.1. Positioning Performance

We are interested in manipulation tasks requiring very precise positional control, with controlled end-effector motion resolution on the order of 3–10 μm when rotational motion is decoupled at the tool tip and 5–25 μm tip resolution when motion is decoupled about a fulcrum point 2 cm from the tool tip (i.e., when a point 2 cm from the tool tip remains fixed in space).

3.1.2. Safety

Our strong preference is for relatively low-power actuators with high-reduction, nonbackdrivable joints. Such systems

Table 1. Steady–Hand Robot Design Goals

Base (xyz) Assembly	**(Off-the-Shelf)**
Work volume	100 mm × 100 mm × 100 mm
Top speed	40 mm/sec
Positioning resolution	$\approx 2.5\ \mu$m (0.5 μm encoder resolution)
RCM Orientation Assembly	**(Custom)**
Link length	100 mm
Range of motion	Continuous 360°
Top speed	180°/sec
Angular resolution	≈0.05° (0.01°encoder resolution)
End-of-Arm/Guiding Assembly	**(Custom)**
Range of motion	150 mm; 360° continuous
Positioning resolution	5 μm; 0.1° (1.5 μm, 0.01° encoder resolution)
Top speed	40 mm/sec; 180°/sec
Handle-force resolution	0.03 N

are relatively easy to monitor, stop, and stay put once stopped. In clinical applications, redundant sensing of manipulator position is generally required. Although the current (preclinical) implementation does not have such sensing, we are exploring several novel options for providing redundant feedback. Future (clinical) implementations will include such sensing.

3.1.3. Manipulation Forces

We are primarily interested in manipulation tasks with a reasonable degree of contact compliance between the tool and the environment being manipulated. In the case of microsurgery, this compliance is provided by the tissue being manipulated. Our goal is moderate bandwidth (3–5 Hz) control and scaling of interaction forces, with tool-tip forces ranging from $\approx$ 0.001 N to $\approx$ 0.01 N, depending on the specific application, and human-interaction forces ranging from $\approx$ 0.01 N to $\approx$ 3 N. We also wish to provide higher bandwidth sensing and haptic feedback of force discontinuities, and to explore the usefulness of such feedback in micromanipulation tasks. We have begun preliminary experiments with vibrotactile displays (Kontarinis and Howe 1995). Effective incorporation of such displays into a practical system will require both significant human factors work and addressing mechanical design and control issues introduced by potential coupling of virbotactile output into sensed forces.

3.2. System Design and Implementation

Our design approach emphasizes modularity in mechanical design, control system electronics, and software. The manipulator itself (shown in Figs. 1 and 2) kinematically decouples surgical instrument orientation and translational motions. It consists of four modular subassemblies: 1) an off-the-shelf *XYZ translation assembly* composed of three standard motorized micrometer stages; 2) an *orientation assembly*, consisting of a custom-designed remote-center-of-motion (RCM) linkage providing two rotations about a "fulcrum" or remote motion center point located in free space approximately 100 mm from the robot; 3) a combined *end-of-arm motion and guiding assembly*, providing one additional rotation about and displacement along a tool axis passing through the remote motion center. This subassembly also comprises a guiding handle with a 6-DoF force sensor and a tool holder for mounting micromanipulator tool; 4) *Specialized instruments* held in the tool holder (e.g., microgrippers) with the ability to sense interaction forces between the tools and the environment being manipulated.

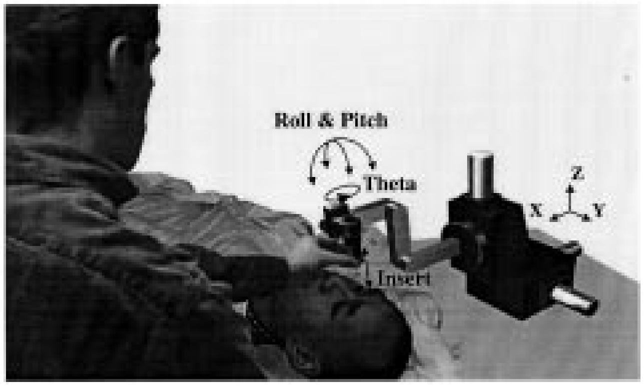

Fig. 2. The steady-hand concept as applied to retinal microsurgery.

3.2.1. Base-Translation Module

For expediency, we have employed a three-axis base-translation module comprised of off-the-shelf motorized micrometer stages from New England Affiliated Technologies of Lawrence, MA. The xyz-translation assembly is formed by mounting a single-axis z-stage (NEAT: LM-400) orthogonal to a dual-axis $x - y$ table (NEAT: XYR-6060). An axis consists of a crossed-roller-way mounted table motivated by an encoded DC servo-motor-driven lead screw. Each axis has 100 mm of travel, can travel at speeds >40 mm/sec, and has a positioning resolution of <2.5 μm (0.5 μm encoder resolution).

3.2.2. *RCM: Remote Center-of-Motion Module*

The RCM robot module (Fig. 3) is a compact robot for surgical applications that implements a fulcrum point located distal to the mechanism (Stoianovici et al. 1998). The robot presents a compact design: it may be folded into a 171 × 69 × 52 mm box, and it weighs 1.6 kg. The robot can precisely orient an end effector (i.e., a surgical instrument) in space while maintaining the location of one of its points. This kinematic architecture makes it proper for laparoscopic applications as well as needle orientation in percutaneous procedures. The RCM accommodates various end effectors. We have applied the RCM in conjunction with the PAKY needle driver for performing image-guided renal access (Stoianovici et al. 1997; Stoianovici et al. 1998). The robot has been successfully used at the Johns Hopkins Medical Institutions for nine surgical procedures (Cadeddu et al. 1998; Bishoff et al. 1998). The RCM design is also very well adapted to microsurgical augmentation, since it permits us to optimize actuators to combine relatively rapid reorientations about a fixed point with very precise and relatively slow translational motions.

3.2.3. *Rotation/Insertion End-Effector Module*

The instrument insertion stage (Fig. 4) provides linear displacement along the tool axis passing through the remote-motion center. The axis utilizes a two-stage telescoping crossed-roller slide mechanism driven via a cable by an encoded DC servo motor. The telescoping crossed-roller slides provide >150 mm of travel from a 70-mm closed-slide length while maintaining high stiffness. The force-transmission path consists of a low-stretch nylon-coated 304 stainless steel cable driven by a grooved drive pulley attached to the DC servo motor. The drive pulley always carries six wraps of cable to maintain good frictional contact and allow high repeatability. The insertion stage can travel at speeds of $\approx$ 30 mm/sec and has a positioning resolution of $\approx$ 5–10 μm (with 1.5 μm encoder resolution).

The rotation end-effector provides rotation about the tool axis and the mounting surface for the force sensor with guiding handle. The rotation stage is driven by a timing belt attached to an encoded DC servo motor. This axis is currently being fabricated and is nearing completion. It will provide a 360° continuous range of motion and is expected to travel at speeds of $\approx$120–180°/sec with a positioning resolution of $\approx 0.05 - 0.10^\circ$ (with 0.01° encoder resolution).

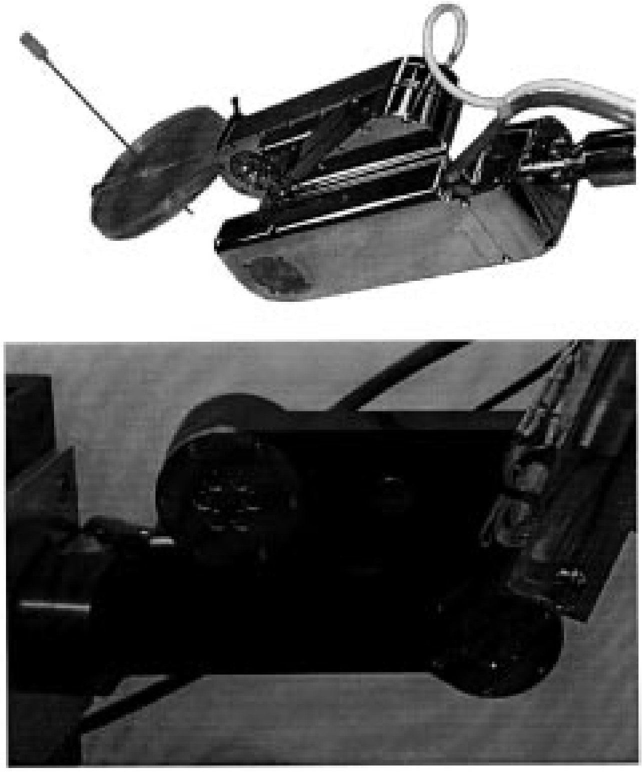

Fig. 3. The remote center-of-motion (RCM) module shown here (above) with the PAKY end effector designed for radiologically guided percutaneous needle applications, and (below) as it is built into the steady-hand robot.

3.2.4. *Handle Force-Sensing Module*

This module uses a small commercially available force sensor (model NANO-17 SI 12/0.12, ATI Industrial Automation, NC) to capture user forces. The 13–8 VAR stainless steel transducer (yield strength of 205 ksi) has a resolution of 0.025 N, 0.0625 N-mm along the z-axis and 0.0125 N, 0.0625 N-mm in the $x - y$ axes. Force ranges of $\pm$22.5 N in the z-axis and $\pm$12.5 N in the $x - y$ axes can be measured. The torque range is $\pm$125 N-mm. The force sensor has overload protection of 800 N in the z-axis, 350 N in the $x - y$ axes, and a 2.5 N-m moment about any axis. The force sensor is 17 mm in diameter and 14.5 mm in height with mounting and tool adapter plates attached, and it weighs 9.4 g. The force sensor is read using a 12-bit ISA bus F/T controller card with up to 7,800-Hz sampling rates. The force sensor is mounted on the instrument-rotation stage with its z-axis parallel to the instrument-insertion stage of the robot.

3.2.5. *Force-Sensing Microsurgical End-Effector Tool Module*

A variety of surgical instruments such as pics, forceps, needle holders, and scissors are required during microsurgical procedures. To utilize the benefits offered by the

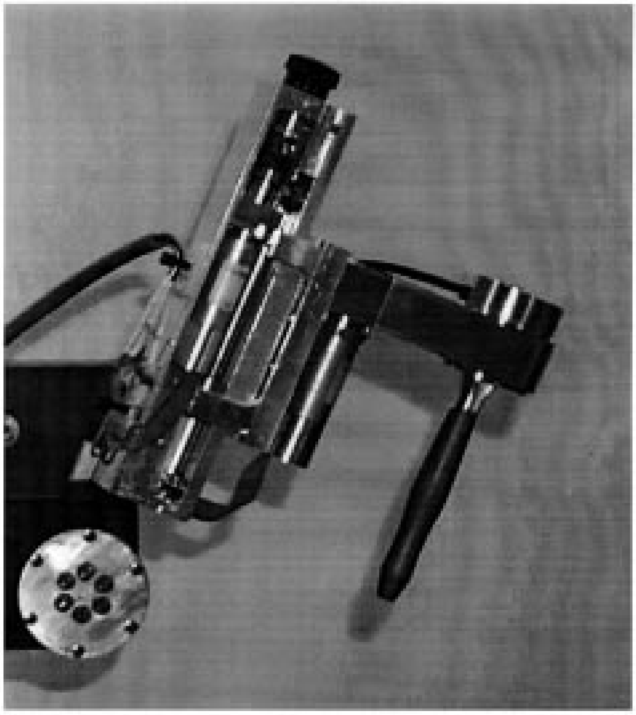

Fig. 4. Insertion and rotation end effectors with force sensor and guiding handle attached to rotation end-effector.

cooperative control algorithms of steady-hand augmentation, these microsurgical tools must be equipped with sensitive, multidimensional force sensors. Our initial approach uses silicon strain gauges configured into bridges located within the surgical tool handle. The tool tip acts as a lever that imparts tourques on the bridge during surgical manipulations.

3.2.6. Control System

The current, rather simple, control system is illustrated in Figures 5 and 6. The robot hardware control runs on a Pentium-II 450-MHz PC with the Windows NT operating system. An eight-axis DSP series controller card (PCX/DSP, Motion Engineering, Inc., CA) is used to control the robot. The card provides servo control using a 40-MHz Analog Devices ADSP-2105 processor. It also has support for user digital and analog input, output lines. The PC also houses the ISA force-sensor controller.

A library of C++ classes has been developed for control purposes. This modular robot control (MRC) library provides Cartesian-level control. It allows with multipriority clients and multiclient servers for distributed robot control transparent to the user application. It includes classes for kinematics, joint-level control, command and command-table management, sensor and peripheral support, and network support. Some exception and error handling is also built in. An array of sensors including serial and parallel ports, ATI force sensors, joysticks, digital buttons, and foot pedals are supported.

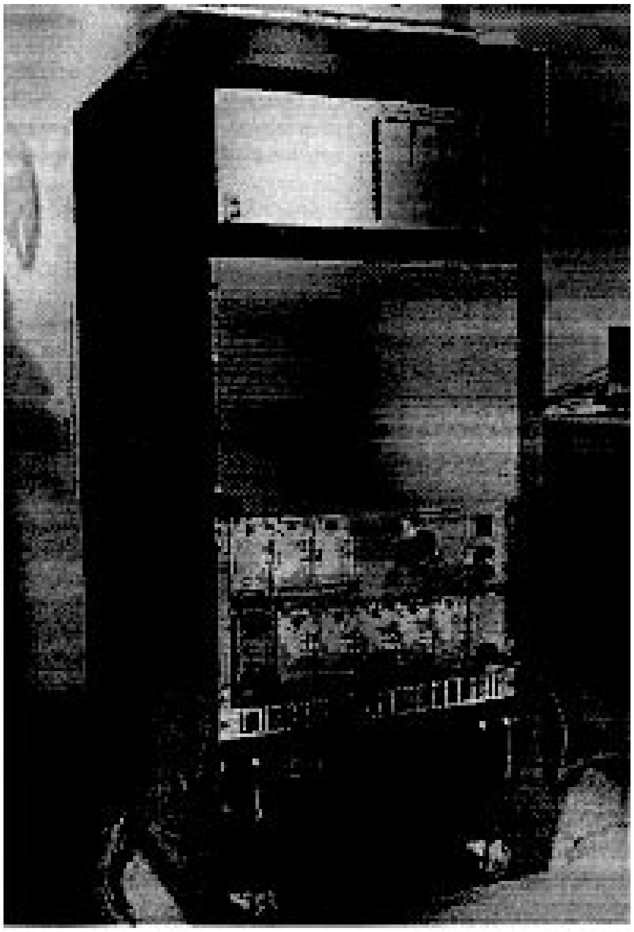

Fig. 5. Controller electronics: The controller consists of a 450-MHz Pentium-II PC (top) with an 8-axis DSP controller card and ISA-bus force sensor interface, together with power supply and a modular rack of servo-amplifiers (bottom). In addition, it contains patch panel wiring and safety interlock circuits.

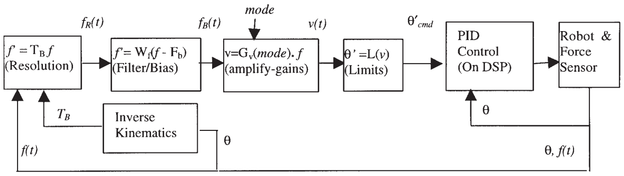

Fig. 6. Control block diagram: The notation is as follows. $f(t)$: sampled forces (f_x, f_y, f_z); $f_R(t)$: forces resolved in the robot base frame, $f_B(t)$: filtered and biased forces; F_b: bias force forces (f_{bx}, f_{by}, f_{bz}), in the robot base frame; T_B: transformation from force sensor frame to robot base frame; *mode*: Base X, Y joints and insertion joint (mode 1), or RCM rotation joints and insertion joint (mode 2); G_v (mode): joint velocity proportional gains, based on user selected *mode*; $v(t)$: joint velocities for selected joints; θ: joint position feedback from encoders; θ'_{cmd}: commanded joint velocities.

Support is also available for MEI motion-controller cards and the proprietary LARS servo controller. Although some of the MRC functionality is limited to WIN32 operating systems, most of the classes are operating-system independent.

A simple force controller has been implemented based on the MRC library. Forces exerted by the user on the tool handle are sensed by the force sensor and resolved into the robot's coordinate frame. These resolved forces are then used as input for a simple force-proportional velocity controller. Both user forces and robot velocity are limited for safety. The base joints and the upper joints can be controlled independently by using a foot pedal. Control rates of over 1,000 Hz can be achieved using this controller. The force control can be used with the force sensor attached to the robot or positioned remotely (connected to another PC, networked to the robot controller). This simple control system is intended to allow us to test/refine the hardware. More sophisticated control will be used for eventual clinical applications.

3.3. Current Status

Our first-generation prototype is complete, and we have begun experimental evaluation of the system. Initial indications are that the basic design assumptions of a stiff robot with force control are valid for surgical manipulations at a microscale. In one experimental study comparing unassisted human versus steady-hand performance in inserting a 10–0 surgical needle into holes of diameter ranging from 150–250 μm, the steady-hand system improved success rates from 43% unassisted to 79% for 150 μm holes and from 49% unassisted to 78% for 250 μm holes (Kumar et al. 1999). In other work (Kumar, Jensen, and Taylor 1999), we have begun exploring the use of simple visual feedback strategies to assist humans in tracking linear features. Potential clinical uses of this capability might include assisted punctures into blood vessels and systematic searches of vessels for defects or obstructions.

3.4. The Future: Evolution from a Surgical Augmentation Aid to a Surgical Assistant

Our immediate goal is a rigorous evaluation of the completed system as a microsurgery augmentation aid, using test environments developed by our colleagues at JHU's Wilmer Eye Institute and CMU (Humayun et al. 1997; Riviere and Thakor 1996; Riviere and Khosla 1999a, 1999b). We will compare the system in-vitro and in cadaveric models, both against unassisted humans and against alternative methods for reducing physiological tremor (e.g., Riviere and Thakor 1996; Riviere and Khosla 1997). Subsequently, we hope to begin evaluation of a clinical system. Initial targeted applications will include epiretinal surgery and retinal vein cannulation under direct surgeon control.

A second stage will combine the steady-hand system with various real-time imaging modalities (video from optical microscopes and endoscopes (e.g., Jensen and de Juan 1999, optical coherence tomography, etc.) to produce an enhanced mosaic image of the patient's eye. This information will be made available to the surgeon, for example, by image injection into the surgical microscope or by a suitable video display.

This "information-enhanced" surgery system will gradually evolve into a more capable surgical assistant. Initial tasks will be rather simple. We anticipate the development of graceful ways to hand off control between the surgeon and the robot for the performance of specific surgical macros. For example, the surgeon may guide an injection instrument to the vicinity of a blocked vein but rely on a specialized function incorporating visual servoing and force sensing to perform cannulation and injection of clot-dissolving drugs. Other examples include such "third-hand" tasks as pointing a micro-endoscope at designated anatomical features or following the surgeon's instrument movements, force-controlled retraction, or the like. As this repertoire of functions increases, the system will become an increasingly effective partner in surgical treatment.

Concurrently, we will be extending the range of clinical application to other eye applications and to other surgical disciplines, including neurosurgery, ENT surgery, and microvascular surgery. A crucial aspect of all this work will be the inclusion of end users (surgeons) in the research team at all phases. One model of collaboration that we have found to be especially productive combines part-time (typically, about 1-2 hours per week) involvement of a lead surgeon with a much higher time commitment by a surgical resident or fellow. We have demonstrated the current system to a number of lead surgeons at Johns Hopkins. The response has been quite enthusiastic, and we are currently forming clinician collaboration teams in the aforementioned disciplines.

4. Summary

Our approach extends earlier work on cooperative manipulation to microsurgery, and focuses on performance augmentation utilizing both force and position control. Our goal is to develop a manipulation system with the precision and sensitivity of a machine, but with the manipulative transparency and immediacy of hand-held tools for tasks characterized by compliant or semi-rigid contacts with the environment. The design is highly modular, and represents one step in the evolution of a family of robotic surgical devices. Although our first focus is retinal microsurgery, we believe that our approach is more general. Other applications will include neurosurgery, ENT, spine surgery, and microvascular surgery.

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