

## A New Robot for High Dexterity Microsurgery

Paul S. Schenker, Hari Das, and Timothy R. Ohm

Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Drive /MS 198-219  
Pasadena, CA 91109

Email: [schenker@telerobotics.jpl.nasa.gov](mailto:schenker@telerobotics.jpl.nasa.gov)

**Abstract.** We report the development of a new six degree-of-freedom (d.o.f.) manipulator. This robot and its task-space controls enable relative tip positioning to better than **25** microns over a singularity-free work volume exceeding 20 cubic centimeters. By virtue of an innovative cable drive design, the robot has zero backlash in five joints and can sustain full extent loads of over three pounds. The robot is applicable to both fine motion manipulation of microsurgical tools and also dexterous handling of larger powered devices for minimally invasive surgery. Our current development emphasis is a teleoperated system for dexterity-enhanced microsurgeries; we believe the new robot will also have useful applications in computer assisted surgeries, e.g. image-guided therapies. In this brief paper, we outline the robot mechanical design, controls implementation, and preliminary evaluations. Our accompanying oral presentation includes a five minute videotape that illustrates engineering laboratory results achieved to date.

### 1 Introduction

Robotics researchers are exploring several new medical applications thrusts, as surveyed in proceedings of recent special interest meetings and workshops [1]. These applications include robot-assisted stereotaxic interventions (imaging-guided biopsy), orthopedic preparations by robot (precision joint emplacements), endoscopic & laparoscopic assists (minimally invasive procedures), teleoperative remote surgeries (telesurgery), and recently, robotic 1 y-enhanced microsurgery (high dexterity, scaled operations under microscopic viewing). Our primary interest is the last area. Building on our recent work in high dexterity telerobotics [2], we have begun development of a *Robot Assisted MicroSurgery* (RAMS) workstation for procedures of the eye, ear, brain, face, and hand. Jet Propulsion Laboratory is conducting this work in cooperation with MicroDexterity Systems, Inc., a USA-based medical products and microsurgical tools venture. Collectively, JPL/MDS plan to evaluate the RAMS developments in clinical microsurgery procedures circa 1996, and initiate some basic medical laboratory experimentation in 1995. The JPL-based work is closest in spirit to prior pioneering efforts of Hunter et al., who to date have performed significant engineering development and quantitative characterization of a force-reflecting teleoperator for microsurgery [3]. By comparison to this more mature light-weight parallel-link robot system, RAMS design targets a comparatively lower position scaling (-1 :3), larger force regimes (fractions of an oz. sensitivity), a large included work angle of surgical access (>120 degree cone), and mechanically stiff precision tracking at low speeds and higher payloads (viz. minimized backlash, stiction, deflections, inertia,

develop force-reflecting teleoperative systems for medical applications including telesurgery, as they have reported in recent IEEE conference papers [4]. In particular, while addressing surgeries of conventional scale (e.g., laparoscopy), the SRI telepresence system of Green et al. is a mature R&D effort that has been demonstrated in simulated surgeries.

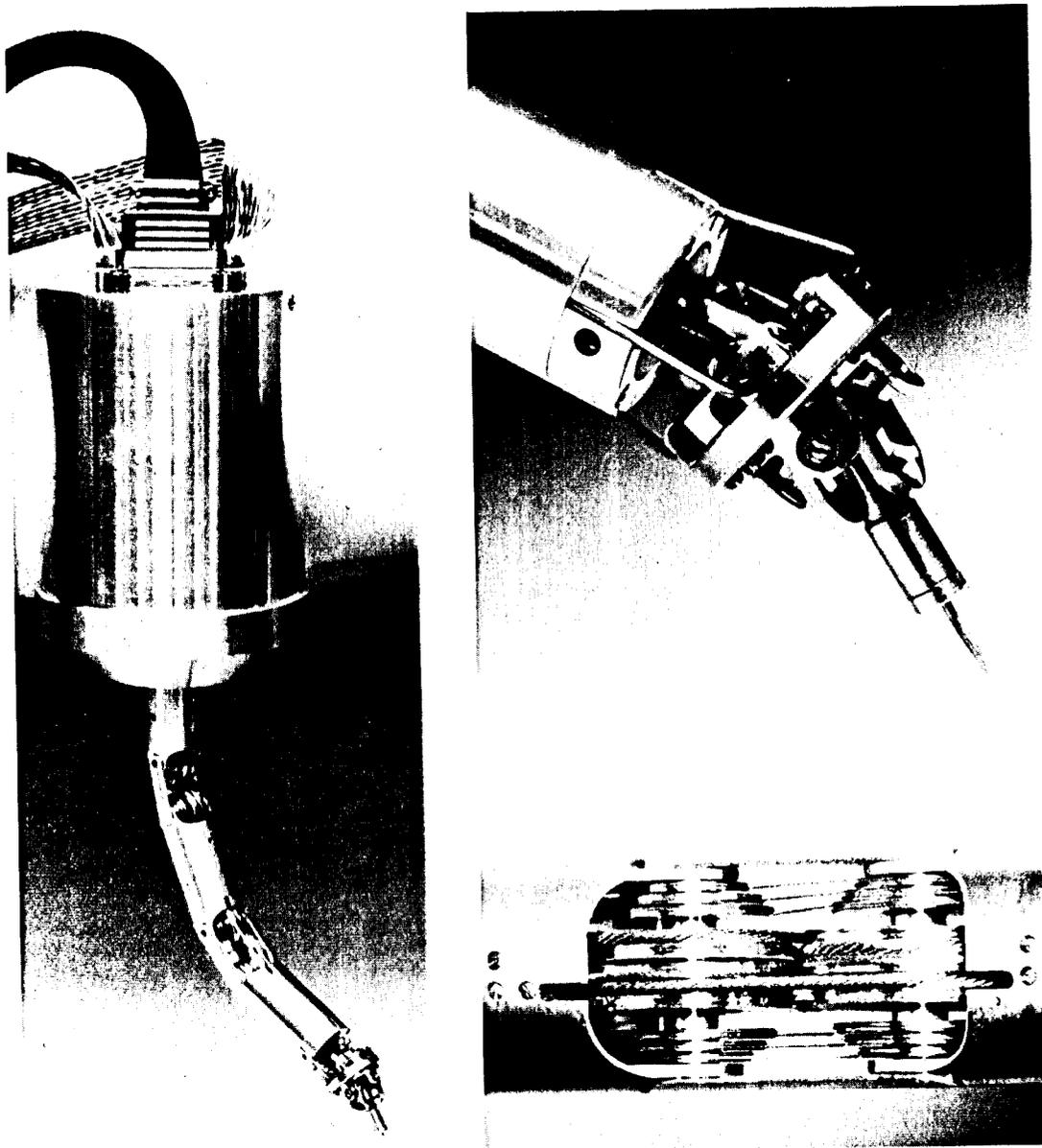
## 2 Robot Design

### 2.1 Motivation

The RAMS workstation is conceived as a dual-arm 6-d.o.f. master-slave telemanipulator with programmable controls, one arm handling primary surgical tooling, and the other auxiliaries (suction, cauterization, imaging, etc.). The primary control mode is to be teleoperation, including task-frame referenced manual force feedback and possibly a cross-modal textural presentation. Later sensor-related developments include *in situ* imaging modes for tissue feature visualization and discrimination. The operator will also be able to interactively designate or telerobotically "share" automated control of robot trajectories, as appropriate. RAMS is intended to refine the physical scale of manual microsurgical procedures, while also enabling more positive outcomes for the average surgeon during typical procedures -- e.g., the RAMS workstation controls include features to enhance the surgeon's manual positioning and tracking in the face of the 5-10 Hz band myoclonic jerk and involuntary tremor that limit many surgeons' fine-motion skills. The first RAMS development, now completed and undergoing engineering evaluation, is a small six-d.o.f. surgical robot ("slave"), the configuration of which is a torso-shoulder-elbow (t/s/c) body with non-intersecting 3-axis wrist. This robot manipulator is approximately 25 cm. full-extent and 2.5 cm. in diameter. Robot actuation is based on a new revolute joint and cable-drive mechanism that achieves near zero backlash, constant cable length excursions, and minimized joint coupling. The robot design and controls currently allow relative positioning, of tools to at least 25 microns over a non-singular work volume of  $\sim 20 \text{ cm}^3$ . Note this resolution is several times better than that observed in the most exceptional and skilled manual medical procedures to date (e.g., vitreo-retinal manipulations of  $\sim 50$ - $100$  micron tissue features).

### 2.2 Design

We describe the robot design in this section, briefly outlining related design requirements, as motivated both by kinematic control objectives and robot suitability to re-usable and safe application in a sterile medical environment. *Figure 1* highlights some recent robot mechanical developments, e.g., the integrated six-d.o.f. robot slave (manipulator and motor-drive base), a 3-d.o.f. wrist (close-up view), and the highly novel double-jointed tendon drive rotary joint mechanization used in shoulder-and-elbow actuation. In the presentation that follows we list a design objective (*in italics*) and its definition; we then provide a brief technical description of the technical approach we took to meet the objective. Where appropriate, and known to date, we give quantitative information. We have as yet done relatively little modeling or quantitative experimental analysis of the robot kinematics & dynamics (explicit calibration, inertial properties, impedance/mechanical response, etc.).



**Fig. 1.** Robot Assisted Microsurgery (RAMS) manipulator: on *left* the six-degree of freedom cable-driven robot arm (length -25 cm, outer diameter -2.5 cm), with motor-drive base and sterile containment (torso rolls 165 degrees within); at *upper right* the Rosheim-derived three degree-of-freedom wrist enabling 180 degrees pitch-and-yaw and 540 degrees continuous roll; and at *lower right* the cable-driven double-jointed mechanism enabling full 360 degree rotary motions in the shoulder and elbow, while decoupling interactions between the primary robot actuation joints.

**Drive Unit Separability.** Autoclaving of the robot is possible by removing the motor/encoder units at the base prior to sterilization. The motor/encoder units can be re-attached in a quick and simple procedure.

This is done by integrating the motors/encoders into two distinct sets of three on a common mount and registering these packages via alignment pins. The resulting two motor packages can be easily removed by undoing two screws and one connector on each set. The mechanism can then be autoclave. The two motor packages can be reinstalled quickly by reversing the removal procedure. In normal operation the motors are contained inside the robot's base, protecting anything they might contaminate. An added advantage obtained with this design is that debugging of servo and kinematics control systems can be done while the motors are not attached to the robot, thereby sparing the robot damage during software development and validation.

**Zero/Low Backlash.** Low backlash (free play) is essential to fine manipulation, especially when position sensors are on the motor shafts.

Five of the robot's six degrees of freedom have zero backlash and the sixth has about 20 microns. Zero backlash is achieved by using dual drive-trains that are pre-loaded relative to one another. These dual drive-trains are coupled together at only the motor shaft and the joint output. The steel cables which actuate each joint also act as springs to pre-load the gear-train. The drive-train's pre-load can be easily adjusted by disengaging the motor, counter-rotating the dual drives until the desired pre-load is reached, and re-engaging the motor. This also allows for easy cable adjustment as the cables stretch with time. The one axis that does not have zero backlash is a result of the wrist design which makes low backlash possible but zero backlash difficult, especially if stiction is a concern as with this robot.

**Low Stiction.** Stiction (stick/slip characteristic) must be minimized to achieve small incremental movements without overshooting or instability.

Stiction was minimized by incorporating precision ball bearings in every rotating location of the robot (pulleys, shafts, joint axes, etc.), so as to eliminate metal-to-metal sliding. Due to severe size and loading constraints, some of these bearings had to be custom designed. Indeed, there is only one location in the wrist where such direct contact exists, because size constraints therein restricted use of bearings. Backlash was allowed here to reduce stiction, per above.

**Decoupled Joints.** Having all joints mechanically decoupled simplifies kinematics computations as well as provides for partial functionality should one joint fail.

Developing a six axis, tendon-driven robot that has all joints mechanically decoupled is very difficult. Decoupling requires driving any given joint without affecting any other joint. The shoulder and elbow joints incorporate a unique double-jointed scheme that allows passage of any number of activation cables completely decoupled from these joints. The three axis wrist is based on a concept (as originated by Mark Rosheim, Ross-Hime Designs, Inc., Minneapolis, MN) that not only decouples the joints, but also has no singularities. Further, the torso simply rotates the entire robot base to eliminate coupling. *If any one of the joints were to fail mechanically, the remaining five would be unaffected.*

**Large Work Envelope.** A large work volume is desirable so that the arm's base will not have to be repositioned frequently during tasks.

To achieve a large work envelope, each joint needs to have a large range of motion. The torso was designed with 165 degrees of motion while both the shoulder and elbow have a full 360 degrees. This high range of motion in the shoulder and elbow is attained by the unique double-

jointed scheme mentioned above. The wrist design (utilizing the Rosheim concept) has 180 degrees of pitch and yaw with 540 degrees of roll. **Such large motion ranges greatly reduce the chance of a joint reaching a limit during operation, thus increasing the work volume.**

***High Stiffness.*** A stiff manipulator is necessary for accurate positioning under gravitational or environmental loads, especially when position sensing is at the motor drives.

When a robot changes its orientation relative to gravity, it will deflect due to its own weight. Likewise, if a force acts on the arm, it will also deflect. Furthermore, if **position sensing is done** at the motor drive, this deflection will not be known. Therefore, such deflections must be minimized by increasing stiffness. The stiffness of RAMS arm is about 15 lb./inch at the tip. This high stiffness is achieved by using high spur gear reductions off the motors, combined with large diameter, short path length stainless steel cables to actuate each joint. The pitch and yaw axes also include an additional 2:1 cable reduction inside the forearm (near the joint) for added stiffness.

***Compact/Lightweight.*** In some applications, a restricted work-space warrants a small serial manipulator to minimize both geometric and visual interference.

The physical size of the arm is about one inch in diameter and about 25 cm long. The robot base, containing the motor drives and electrical interfaces, has a 12 cm diameter and is 17.75 cm long. The entire unit (arm and base) weighs about 5.5 lbs. All electrical cables connect to the bottom of the base so as to not protrude into the robot's work-space.

***Fine Incremental Motions.*** Human dexterity limitations constrain surgical procedures to feature sizes of about 50-to-100 microns. This arm is designed to achieve 10 microns relative positioning.

By combining many of the features mentioned above (low backlash, low stiction, high stiffness, etc.), this arm is designed to make very small incremental movements. **This means that the manipulator can make incremental steps of 10 microns.** Note conversely this does not necessarily mean that the arm is repeatable to within 10 microns absolute position accuracy.

***Tool Wiring Provisions.*** Some tools require electrical or pneumatic power which can be routed through the arm in some cases.

The arm is designed to allow running a limited amount of wiring or hoses from the base to the arm's tip (where the tool is mounted). This passageway is about .35 cm in diameter through the wrist and exits through the center of the tooling plate. The wiring can be passed out the base of the robot so that it does not interfere with its work-space, as would be the case if such wiring was routed externally.

***Configuration Management and Control.*** It is necessary to sense, monitor, and control basic failure conditions (e.g., to implement corrective motion control/braking actions)

A Programmable Logic Device (PLD) controls power and braking relays through an optically isolated interface, and allows fault detection and error recovery. The major features of this electronic system are: 1) power up and down button, manual start-stop buttons to switch motor power from a brake mode to control mode, panic button to stop motors, and brake relay fault detection, 2) watchdog timer fault detection to insure control processors are functioning, 3) amplifier power supply & fuse fault detection, and 4) PLD logic fault detection.

### 3 RAMS System Computing and Control

Operator-robot interaction is at present implemented through a *graphics user interface* (GUI) that resides on a UNIX workstation. This workstation also is host for a VxWorks real-time control environment. The VxWorks-based *kinematic & joint controls* are in turn implemented on a MC 68040 board installed in a VME chassis. A Delta Tau Data Systems PMAC board, also on the VME chassis, controls the six axes of the robot by directly reading the robot sensor outputs and driving the motors through amplifiers.

#### 3.1 Graphics User Interface

The GUI is based on the X Windows and OSF/Motif libraries. We have developed a number of GUI-driven demonstration modes to show and evaluate the robot capabilities:

- a *manual joint control mode* wherein the user moves individual joints manually by selecting buttons in a control window, incrementing and decrementing a desired joint position
- an *autonomous joint control mode* demonstrating the workspace of the robot. In this mode, the robot simultaneously moves each of its joints in a sinusoidal motion between set limits
- a *manual teleoperated mode* in which the robot is controlled either by using a mouse (or by selecting buttons on a display), incrementing or decrementing motion along single axes of a world-referenced coordinate frame, or by using the spaceball input device to simultaneously move all six axes of the robot
- an *autonomous world space control mode* in which the robot moves its endeffector in a sinusoidal motion about one or more Cartesian-defined axes simultaneously.

#### 3.2 Kinematic and Joint Controls

The control software of the robot resides on the VME-based system. *Figure 2* sketches the control flow for the manual and autonomous world coordinate frame-referenced control modes. The general scheme by which the operator currently commands forward control to the robot is as follows: he inputs to the system from the GUI and this input is passed forward using the UNIX socket facility over an Ethernet link. What thus passed into the control system is specified as desired changes in the robot tip position. We relate these world frame tip coordinate changes to commanded robot joint motions through a Jacobian inverse matrix, which is computed using a JPL-developed Spatial Operator Algebra [5]; this inverse is then multiplied with the input tip displacement vector to determine a corresponding joint position change vector. The primary advantage afforded by the Spatial Operator Algebra for this application is its concise recursive formulation of the kinematics equations, allowing rapid software development and testing -- a simple addition of the joint position change vector to the actual position of the joints results in the desired joint positions for the robot. The desired joint positions are then downloaded to the PMAC controller board wherein joint servo control is performed using a PID loop for each joint axis. In the manual and autonomous joint control modes, the PMAC controller correspondingly receives the joint position change vector as its input. The vector is

added to the actual joint positions of the robot and the resulting vector is the desired joint position vector sent to the servo controller.

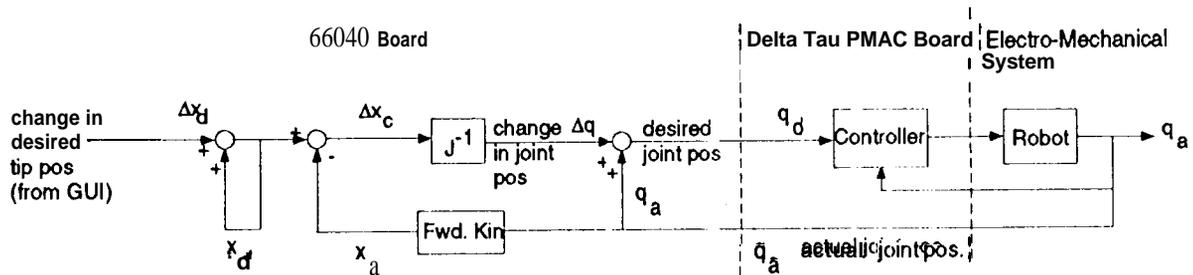


Fig. 2: RAMS control flow diagram

## 4 Results and Future Plans

As of end-year, 1994, we have integrated the slave robot system described above and demonstrated its successful operation in all control modes. On initial integration, without benefit of significant mechanical tuning or refitting of the robot mechanisms, we achieved repeatable relative positioning of the robot tip to 25 microns or less. This measurement, verified in a number of calibrated and videotaped [6] experiments, was performed both mechanically and optically. In the former case, we utilized calibrated mechanical dial indicators on three orthogonal axes of a wrist-tip-mounted needle; for the latter, we utilized a calibrated viewing field microscope with integrated CCD camera, and programmed and visually monitored a number of different free space, small motions within a 800 micron full-extent reticle. Cumulatively, we observed that both small (micron) and large (centimeter) free space motion trajectories are smooth. Impromptu tests in which a leading microsurgeon compared his free hand motions with that of the robot indicate that the desired scaling will be possible and highly beneficial, given an appropriate hand master interface. Development of such a non-replica master is one immediate project focus, as is also continuing, more quantitative evaluation of the robot, including its loaded (contact) motion performance. Another planned activity is development of control compensation techniques to reject feed-forward "disturbances" arising from the surgeon's involuntary tremor and jerk. And of course, we want to begin evaluation of the robot design in medical laboratory settings at appropriate opportunities.

## 5 Acknowledgments

The Robot Assisted Microsurgery (RAMS) task is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Related New Technology Notices have been filed, and a JPL-Industry Technology Cooperation Agreement with MicroDexterity Systems (MDS), Inc., exists. MDS Chief Officer Steven T. Charles, M. D., is an instrumental partner in defining RAMS system operational requirements, elements of the engineering conceptual design, and strategies & practice for subsequent medical evaluation.

## References

1. Report on **NSF Workshop on Computer Assisted Surgery**, February 28-March 2, 1993, Washington, D.C. (Orgs., R. H. Taylor and G.A. Bekey). **Proc. Medicine Meets Virtual Reality 111**, January 19-22, 1995, at San Diego, California, sponsored by the Univ. Cal if. San Diego (Publisher: Aligned Management Consultants, San Diego, CA.). **Proc. First Intl. Symp. Medical Robotics and Computer Assisted Surgery (MRCAS'94)**, September 22-24, Pittsburgh, PA (Eds., A.M. DiGioia, III, '1'. Kanade, and R. Taylor); **NCI-NASA-SCVIR Workshop on Technology Transfer in Image Guided Therapy**, August 5, 1994, San Francisco, CA (Chr., H. Y. Kressel). **Virtual Reality: Scientific and Technological Challenges**, a report of the Committee on Virtual Reality Research & Development (Chr., N. Durlach), National Research Council, NAS Press (1994), Washington D.C.
2. S. Schenker, A. K. Bejczy, W. S. Kim, and S. Lee, "Advanced man-machine interfaces and control architecture for dexterous teleoperations," in *Proc. Oceans '91*, pp. 1500-1525, Honolulu, HI, October, 1991, and references therein. H. Das, J. Zak, W. S. Kim, A. K. Bejczy, and P. S. Schenker, "Operator performance with alternative manual modes of control," *Presence*, Vol. 1, no. 2, pp. 201-218, Spring 1992; see also, H. Das, P. S. Schenker, H. Zak, and A. K. Bejczy, "Teleoperated satellite repair experiments," in *Proc. 1992 IEEE-RSJ Intl. Conf. IROS*, Raleigh, NC, July. 1'. S. Schenker and W. S. Kim, "Remote robotic operations and graphics-based operator interfaces," in *Proc. 5th Intl. Symp. on Robotics and Manufacturing (ISRAM '94)*, Maui, HI, August 14-17, 1994, and references therein. 1'. S. Schenker, W. S. Kim, and A. K. Bejczy, "Remote robotic operations at 3000 miles -- dexterous teleoperation with tunc-delay via calibrated virtual reality task display," in *Proc. Medicine Meets Virtual Reality II*, San Diego, CA, January, 1994. 1'. S. Schenker, S. F. Peters, E. D. Paljug, and W. S. Kim, "Intelligent viewing control for robotic & automation systems," in *Sensor Fusion VII*, in *Proc. SPIE 2355*, Boston, MA, October, 1994.
3. Hunter, T. Doukoglou, S. Lafontaine, P. Charette, L. Jones, M. Sager, G. Mallinson, P. Hunter, "A teleoperated microsurgical robot and associated virtual environment for eye surgery," *Presence*, Vol. 2, no. 4, pp. 265-280, fall, 1993.
4. Salcudean and J. Yan, "Towards a force-reflecting, motion-scaling system for microsurgery," in *Proc. 1994 IEEE Intl. Conf. Robotics and Automation*, May, San Diego, CA; see also, S. Salcudean, N.M. Wong, and ILL. Hollis, "A force-reflecting teleoperation system with magnetically levitated master and wrist," in *Proc. 1992 IEEE Intl. Conf. Robotics and Automation*, Nice, France, May. K. W. Grace, J. E. Colgate., M. R. Glucksberg, and J. H. Chun, "A six degree-of-freedom manipulator for ophthalmic surgery," in *Proc. 1993 IEEE Intl. Conf. Robotics and Automation*, Atlanta, GA, May. J. W. Hill, P. S. Green, J. F. Jensen, Y. Gorfu, and Ajit S. Shah, "Telepresence surgery demonstration system," in *Proc. 1994 IEEE Intl. Conf. Robotics and Automation*, San Diego, CA, May
5. Rodriguez, "Kalman filtering, smoothing and recursive robot arm forward and inverse dynamics," *Journal of Robotics and Automation*, Vol. 3, No. 6, pp. 624-639, 1987; G. Rodriguez, K. Kreutz, and A. Jain, "A spatial operator algebra for manipulator modeling and control," *International Journal of Robotics Research*, Vol. 10, No. 4, pp. 371-381, 1991.
6. "Robot Assisted Microsurgery project accomplishments for FY94 -- demonstration of robot joint motion, Cartesian control, and precise tip control," Production AVC-94-228 (VHS Videotape), September 1, 1994, Audiovisual Services Office, Jet Propulsion Laboratory: E. Barlow, C. Boswell, H. Das, S. Lee, T. Ohm, E. Paljug, G. Rodriguez, and P. Schenker (PI), for NASA Headquarters.