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Development of a Telemanipulator for Dexterity Enhanced Microsurgery

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Abstract

The precision and stability of motion achievable with the human hand limits current microsurgical practice. Were. it possible to overcome these natural limits, better procedures of the eye, ear, hand, brain, and spine would result. Such issues of *dexterity enhancement lie* not only with scaling down surgical skills of the most gifted, but also addressing widely variable skills of the entire surgical community. To this end, we are developing a new system for *robot assisted microsurgery* (RAMS]. The concept at large for this development, guided by reviews of a NASA-convened Medical Advisory Board, is a position-scaling 6-d. o.f. micro-telemanipulator that incorporates bi-lateral master-slave force-reflection and tremor compensating controls. At this point in time, the Jet Propulsion Laboratory team has completed design, fabrication, and initial benchtop engineering tests of a RAMS slave with several significant features. This robot and its task-space controls enable relative tip positioning to better than 25 microns over a continuous workspace greater than 400 cubic centimeters. Robot actuation is based on a new revolute joint and cable-drive mechanism that achieves near zero backlash, constant cable length excursions, minimized joint coupling, and can sustain full extent loads of over three pounds. We report on this robot design, the preliminary experimentation, and ongoing development of a related micro-master. (*keywords: robotic manipulators, telesurgery, computer enhanced surgical dexterity, precision surgeries*)

1 Introduction

The organization of our paper is as follows. in Section 2 we outline some of the medical issues that guide our work and its particular systems design approach. Specifically, we define a concept of"dexterity enhancement," and its embodiment in master-slave telemanipulator design. We have noted some of these points and others in recent briefings to the medical community [1]; this is our first written synopsis. In Section 3 we describe our Robot Assisted Microsurgery (RAMS) slave prototype, its underlying design features, and results of some preliminary engineering tests [2]. In Section 4 we conclude, sketching our developmental progress on a complementary surgeon's micro-master hand controller.

2 Dexterity Enhancement & Design Issues

There are significant human factors issues impeding the advancement of microsurgery. Collectively, the challenges fall in two areas: first, inability of surgeons to resolve their manual dexterity into ever finer, more subtle procedures, and second, variability within the surgical population, and even the individual surgeon, in performing day-to-day procedures, e.g., as reflected in operating characteristics such as excess force, tremor, overshoot/undershoot, etc. Therefore, any broad-scope medical robotics & computer assisted advance for microsurgery should seek to both extend and normalize manual dexterity, i.e., provide *dexterity enhancement.*

Among the microsurgical areas that would benefit are:

- eye (vitreoretinal / cornea / glaucoma / refractive)
- ear (stapedectomy / acoustic tumor)
- hand (reimplantation of digits / hands)
- free graft (vascular anastomosis)
- neurosurgery (robotic assisted & image-based)
- cranio-facial (reconstruction / nerve tissues)
- cardio-vascular (pediatric / small features & vessels)

Relative to use of available microsurgical tools in the above procedures, we have drawn some qualitative guidelines for dexterity enhancement design. These observations are based on Charles' and medical colleagues subjective OR experience, as well as their informal assessment of some quantitatively instrumented clinical procedures [3].

Relative performance of hand motions

- positioning while actuating: worst
- pure rotation: moderate
- telescoping motions: better
- pitch/yaw motions: best
- general: writing -like motions and wrist functions favored

First order system desire improvements

- lighter tools reduce fatigue and tremor
- shorter tools reduce torque load anti systematic track error (e.g., disturbances from tubing, cables, and fibers)
- non-vibrating tools, e.g.-held tools, contoured tools (less grasping force required) improve haptic dexterity

Second order system design improvements

- power actuation reduces task load on surgeon's hand (power gripping, power cutting power clipping/ stapling)
- intrinsically powered functions (drilling / laser / ultrasonics / cautery)

Third order system design improvements

- hand held tools (power rotation, power telescoping)
- *full* 6 *dof master-slave teleoperation*: *1)* surgeon moves a master hand controller in a natural kinesthetic (and haptic) reference with slave robot tool; 2) control computer calculates and commands scaled & enhanced slave motion (referenced to human manual controls performance model, and available closed loop controls)

2.1 **Telemanipulator** Design Considerations

We next survey some issues for design of a surgical micro-telemanipulator. Our comments are focused toward what will make a device: 1) broadly useful in microsurgery, minimally invasive surgery, and their extensions to image-guided therapies, 2) readily acceptable by the medical community, and 3) a reasonable candidate for FDA certification. While the underlying assumption in our comments is physical collocation of the. surgeon and dexterity tool, many ideas here should carry over to remote, telesurgical operations.

The metrics by which dexterity enhancement can be judged include position stability, position accuracy, resolution, velocity limits, acceleration limits, force limits, tremor and singularity free range of motion. The parametrization of these performance factors naturally varies with procedure, but there. are some general extrapolations. Typical microsurgeries obtain 100 micron relative positioning, and some benchmark cases (vitreoretinal, vascular anastomosis) have achieved 50 microns, A 2-to-5x mechanical scaling reduction would yield major breakthroughs in ophthalmology, otology, and most other areas noted above, Even 1:1 replica scaling with the computer-dexterity assists we note would significantly increase positive outcome rates. Tbc surgical work field varies with procedure, and the requirements of vitreoretinal practice provide some good benchmarks: 10-to-20 cubic centimeters spherical volume, requiring up to 120 degree portal access anti telescopic precision motions, preferably with minimal indexing and cross-coupling in the command axes. Thus, there is a general design issue of implementing large ranges of 6-d.o.f. motion with high relative positioning accuracy in tool-referenced frames (whet her teleoperative or autonomous). Given this robotic precision, the surgeon must be able to exploit it, anti myoclonic tremor and jerk arc two impeding factors. These manual control disturbances, lying in a nominal 5-to-lo Hz bandwidth, are present in varying degree in different individuals and, at a given time, vary in any given individual. Tremor is functionally dependent on many operative and personal influences, including hand position, hand orientation, muscle fatigue, payload, surgeon strength & conditioning, anxiety/personality/stress/observers, inexperience & age, caffeine intake, congenital factors, difficult cases, and case order & skill accommodation (first case being the worst). As an intuitive technical strategy, low-pass filtering of teleoperative manual inputs will facilitate the tremor problem in some procedures, but often introduces penalties in closed loop response (loss of tracking stiffness/sluggishness, decreased haptic transfer in direct force reflection modes). In general, surgically acceptable strategies of "tremor compensation" should not require in-line programming, increase task times, or cause perceivable latency. Such compensation should be adaptive to different tremor profi Its, and should also be independent from velocity limits.

The useful role of force presentation in microsurgical telemanipulator design is a somewhat complex issue. From a systemic viewpoint, force feedback (and gravity compensation) can be used to decouple the weight and inertia of both slave tooling and master positioner from the surgeon's hand control. Conversely, introduction of force reflecting mechanization may increase master mechanism friction, stiction, inertia, and other back-drivability factors that impede smooth, precise position control,

The proprioceptive benefits of surgical force presentation include contact and change detection, textural sensing (bone, fibrous, soft tissues), modulation of penetration & cutting pressures, and the generally observed reduction of task times [4]. Direct coupled force-feedback, even when highly scaled (which introduces corresponding issues of closed ioop stability and tracking), may not be the best strategy for delicate procedures of the eye, ear and other -- useful alternatives include ac-coupled, and cross-modal presentations -- e.g., vibro-proprioceptive feedback. Indeed, based on operating room (OR) experience, surgical training observations, and some instrumented operative data, we suggest that the greater value of force presentations may lie in establishing synthesized boundaries on position, velocity, force/acceleration limits. By way of examples, such position boundaries might include: 1) surgeon-delineated and knowledge-based anatomic landmarks and waypoints, 2) references derived from implanted fiducials and registered pre-operative imagery (from MRI, CT, 3D digital subtraction angiography), and 3) intraoperative imaging (MR and 31) ultrasound) features. Thus, there are potentially interesting overlaps in dexterity enhancement design and image-guided therapies. Regarding the motivation for velocity constrained controls, some reasons include maintaining correct feed-rate for power cutting tools, minimizing tissue displacement, avoiding excessive thermal effects, offsetting clogging/ winding/ shredding, anti accommodating time dependent non-linear tissue yield strength (stretching versus breaking factors).

In closing this section, we comment on a few robotic system design considerations. The first is advanced tool functions -- the commercial viability of end market distribution channels for robotic technology in the OR is at least as strongly defined by the end-tooling returns as the robot platform itself. Viewed in the context of both micro-and-minimally invasive applications, dexterity enhancement platform end-effecter functions will likely include cutting (power scissors & shears), gripping (power forceps & clamps), irrigation/suction (servo controlled), coagulation (servo RF & multi-spectral diode laser), device application (power clips, staples, implants, stints, and fixtures), and drilling (brushless DC motors & pneumatic drives). Complementary visualization systems for dexterity enhanced surgery include the operating microscope, binocular operating loupes, unassisted eye, optical and CCD endoscopes. Relative to slave manipulator use in all functions, it will be important to have zero motion on master release. The rationales include both safety and value-added design: e.g., medical emergency of surgeon or patient, tool changeouts, shutdown because of system runaway, and force or position-controlled robotic assistance (deployments, retractions, end-point camera manipulation, etc.) in minimally invasive surgical applications. A final consideration, tied to both design and human factors, is whether surgeons will readily accept robotic dexterity enhancing developments. There is some preliminary evidence in favor: widespread surgeon use of Inderal prior to surgery, frequent discussions about surgeon's "hands," (anecdotal and pejorative observations), and the now widespread adoption of operating microscopes, tool miniaturization, stereotaxic surgery and wrist support systems.

3 Slave Robot Development

The .11'1., team, working in a commercialized cooperation with Charles et al., has designed, developed, and begun engineering tests of a new 6-d.o.f. manipulator for robot assisted microsurgery (RAMS). Charles has provided detailed system requirements and conceptual guidance, reflecting many of the medical engineering issues noted above.

As part of an overall micro/minimally-invasive surgical dexterit y piat form concept, a final commercialized robot slave design would function in the following context

- modular hardware & software
- one or two such manipulators
- same master for all specialties
- same positioner for most payloads
- same controller for all specialities
- interchangeable end-effector tooi ing

The OR setting for the slave, as illustrated in Fig. 1, assumes mounting options which include passive suspension (overhanging larger arm), a registered mask conformal with the surgical area (e. g., head/face mounted), and/or optical tracking and active stabilization of the robot with patient induced movement of the surgical frame.

As defined at this time, sterilization, setup, and system preoperative checkout assumptions for the slave robot include:

- ETO sterilization as a preferred method
- autoclavable or soakable in emergencies
- a resposable cover for motors / encoders
- stowed in case in 0,0,0 position
- a protective case for encoder, motor, & actuator with calibration and testing before anesthesia is initiated
- protective case removed just before operative use

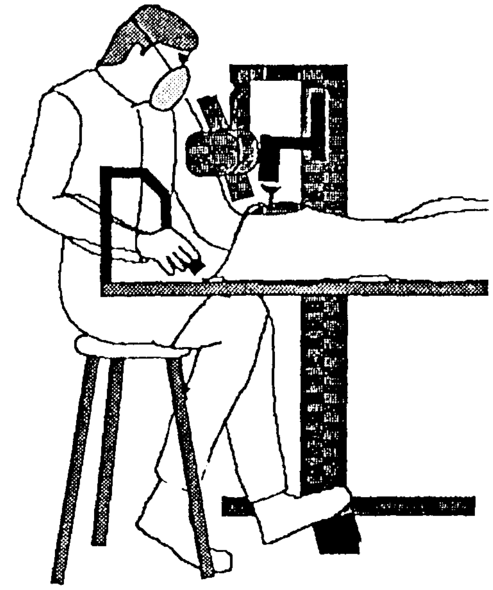

Figure 1: Master-Slave Dexterity Enhancement Concept

3.1 Slave Design Features

Our first technology development in support of the above objectives is a small six-d .o. f. surgical robot ('<slave") having torso-shoulder-elbow (t/s/e) body configuration with non-intersecting 3-axis wrist. Fig. 2 highlights some of the robot mechanical features: the six-d .o. f. arm and attached motor-drive base (torso roll implemented internal to base), the 3-d.o.f. wrist derived from a Rosheim [5] kinematic (Ross-Himc designs, Inc., Minneapolis, MN)., and a new JPL double-jointed tendon drivc. rot ary joint mechanization used in shoulder-and-elbow actuation. Collectively, the joint actuation scheme anti the robot's novel pre-loaded cable-drive mechanization, later discussed, achieve near zero backlash, constant cable length excursions, and minimized joint coupling. Our work is closest in spirit to prior pioneering efforts of Hunter et al. [6], who have to date performed significant engineering development and quantitative characterization of" a f'brce.-rcf'lecting teleoperator for microsurgery. By comparison to this more mature lightweight parallel-link robot system, the RAMS design targets a lesser position scaling (~3:1). a large included angle of surgical access (90-120 degree cone), a large continuous workspace of 30[)-500 cm**3, a non-indexed, non-singular instantaneous work volume of -20 cm**3, anti mechanically

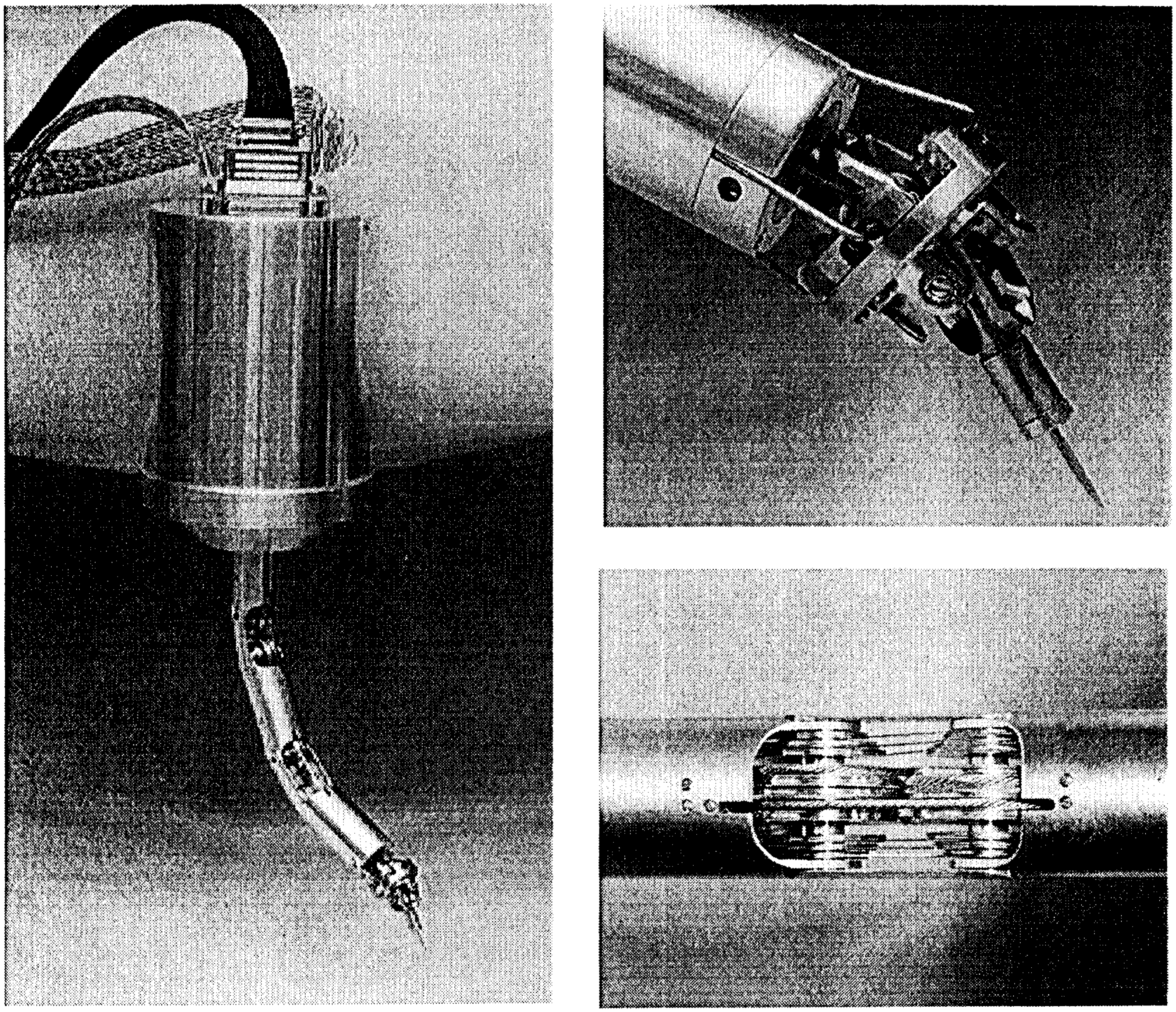

Fig. 2: ***Robot A ssisted*** *Microsurgery* ***(RAMS) manipulator:***

[***on left***: the six-degree of' freedom cable-dl-iven robot arm (length -25 cm, outer clian]cle] -2.5 cm), with motor-drive base and sterile containment (torso rolls 165 degrees within); ***at upper right***: the Rosheim-derived [5] three degree-of-freedom wrist enabling 180 degrees pitch-and-yaw and 540 degrees continuous roll; ***and lower right***: the *cable-d]iven* double-jointed mechanism enabling full 360 degree rotary motions in the shoulder and elbow, while decoupling interactions between the primary joints] stiff precision tracking al low speeds with a higher loads (up to 3 lb. full-extent with minimized backlash, stiction, deflections, etc.). We note also the related efforts of Salcudean et al., Grace et al. and Green et al. to develop force-reflecting teleoperati ve systems for medical applications including telesurgery, as they have reported in recent conference papers [7]. In particular, while addressing surgeries of conventional scale (e. g., laparoscopy), the SRI telepresence system of Green et al. is another mature R&D effort that has been demonstrated in simulated surgeries.

We next summarize the robot design features, and outline considerations of our implementation approach. Where appropriate, and known, we give quantitative information. We have as yet done relatively little modeling or quantitative experimental analysis of the robot kinematics & dynamics, e.g. explicit calibration, inertial properties, impedance & electro-mech anical transfer- response, etc. As experimentally observed and documented to date [2], the robot design allows relative positioning of tools within 25 microns precision over a hemi-spherically continuous work envelope of -400 cm**3 (within which we nominally select an -20 cm**3 non-indexed, non-singular surgical work volume). This initial positioning resolution is several times better than that observed in the most exceptional and skilled manual medical procedures to date -- e.g., benchmark vitreo-retinal and vascular microsurgical manipulations of -50-100 micron tissue features.

Drive Unit Separability: Autoclaving of the robot is easily performed by removing the nlotor/encoder units at the base prior to sterilization; these units can later be re-attached in a quick and simple procedure. This has been accomplished 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 are removed by undoing two screws and one connector on each set. The remaining arm mechanization can then be autoclave. The two motor packages are reinstalled quickly by simply reversing the removal procedure. In normal operation the motors and gear drives are. contained inside the robot's base, thereby protecting the sterile operating field. An added advantage of separable motor-drive design is that debugging of robot servo and kinematics controls can be done while th$_e$ motors are not attached to the robot, facilitating software development (and sparing the robot mechanization from damage during initial control design trials).

Zero/Low Backlash: Low backlash (minimum free play) is essential to fine motion control, especially when robot servo position sensors arc incorporated directly on the motor shafts. Five of the robot's six degrees 01' freedom have zero backlash and the sixth has about 20 microns. This has been achieved by using dual dl-ivc-tl-sins that arc pre-loaded relative to onc another. These dual drive-lr:iins arc coupled together al only the motor shaft and the joint output. The steel cables which actuate each joint also act as springs 10 pi-e-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 if the cables stretch with time. The one robot axis that does not have zero backlash results from our use of a wrist design that makes low backlash possible, but zero backlash difficult, particularly when stiction is a concern -- we comment further below.

Low Stiction: master anti slave robot stiction (stick/slip characteristic) must be minimized if the operator is to achieve small incremental movements without overshooting or instability. We have minimized stiction in the RAMS slave robot design 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 required custom design. indeed, as noted above, there is only one location in the robot, a wrist axis, where such direct contact exists -- simply because size constraints therein restricted use of bearings. In this case, we designed in a small amount of backlash as a preferred trade-oft against the less desirable stiction effect. System level impact on the robot task space relative. positioning specification (- I O microns) is minimal.

Decoupled Joints: mechanically decoupling the joints of a robot simplifies kinematics and enables partial functionality should one joint fail. The latter feature is important in medical applications (along with reasonable back-drivability, which the RAMS device also offers). In general, developing a six axis, tendon-driven robot that has all joints mechanically decoupled has proven difficult and cumbersome, given such a decoupling requires driving any given joint without affecting any other's motion. The RAMS slave shoulder and elbow joints incorporate a new double-jointed scheme (JPL patent applied for, T. Ohm et al.) that allows through-passage of any number of distal joint activation cables completely decoupled from the supporting joint's actuation. We have also developed a torso roll joint internal to the base motor drive system that simply rotates the entire robot base to eliminate coupling. Finally, the three axis wrist design we have developed is, as noted above, based on a kinematic concept originated by M. Rosheim [5] (cfr. Ross-Hime Designs, Inc., Minneapolis, MN) that not only decouples the offset joints. but also has no singularities. Collectively, the robot is mechanically robust to single point failures.

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 this capability with minimum singularity, each joint needs to have a large range of motion, and of' course, well-co[)l~lit]iltcci kinematic design. We designed the torso roll joint with I 65 degrees of motion while both the shoulder and elbow have a full 360 degrees, enabling the above noted hemi-spherically continuous work envelope of -4(N cm**3. The large range of motion in the shoulder and elbow is attained via the unique double-jointed scheme also mentioned above. The wrist design (utilizing the Rosheim concept) has 180 degrees of pitch and yaw with 540 degrees of roll. overall, such large joint motion ranges greatly reduce the chance of a joint reaching a limit during operation, facilitating both operability and safety factors.

High Stiffness: stiffness is important to accurate robot positioning under load, especially if position sensing is non-collocated. When a robot changes orientation relative to gravity, it will deflect due to its own weight and attached tooling. Pose-dependent gravity effects can be compensated in part, with burden of modeling, forward control, and possible additional in-line sensor data. If environmental contact forces act on the robot, it will deflect. If position sensing is done at the motor drive, such deflections will not in principle be known. This issue has not been well addressed in microsurgical robot design, and needs to be if bone and fibrous tissue procedures, and/or image guided therapies are of interest. E.g., consider orological and cranial procedures and/or carrying powered tools for either teleoperative or supervisory automated minimally invasive procedures. (Compliance, when desired, can be introduced actively or through cooperative tooling). The mechanical stiffness of RAMS arm is about 15 lb./inch at the tip. This high stiffness has been 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: The restricted work-space of most microsurgical and minimally invasive applications strongly encourages a serial manipulator design of small outer diameter so as to minimize both geometric and visual interference. As shown in Fig. 2, the RAMS arm prototype as currently scaled is about one inch in diameter and 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 lb. All electrical cables connect to the bottom of the base so as to not protrude into the robot's workspace.

Fine Incremental Motions: As previously noted, human dexterity constrains surgical procedures to feature sizes of , about 50-to- I 00 microns. The RAMS arm, by virtue, its gearing, low backlash, low stiction, high stiffness, etc. is designed to achieve 10 microns relative positioning, This means that the manipulator ideally can make repeatable incremental steps of 10 microns. Conversely this does not necessarily mean that the arm is repeatable to within 10 microns absolute position accuracy (as yet uncharacterized).

Tool Wiring Provisions: As noted in an earlier discussion, there are a variety of micro-and-minimally invasive procedures wherein medical tools requiring electrical and pneumatic power, optical transference, suction, etc. will be utilized. We have designed the RAMS arm so as to enable passing internally, from the base fixture to the arm's tip (where the tool is mounted), a limited amount of such power, optical, air, and fluid feeds. This inner passageway is about .35 cm in diameter (minimum dimension at the wrist) and exits through the center of' the tooling plate. Note this design approach is far preferable to an external routing that interferes with robot workspace and introduces potential complications to sterilization.

System Health & Safety: 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 lie in four principal areas: 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.

3.2 Robot Control and Computing Architecture

We have implemented operator interaction with the above slave robot for functional checkout and preliminary testing through a simple graphics user interface (GUI). This GUI resides on a UNIX engineering workstation that is also the host for a VxWorks control environment subsequently discussed. The VxWorks breed real-time task & joint controls in turn execute on a MC68040 processor board installed in a VME chassis. A Delta Tau Data Systems PMAC controller, also running on the VME chassis, servos the six axes of the robot by directly reading the robot sensor outputs and driving the motors through amplifiers.

We built the GUI from X Windows and OSF/Motif libraries and have integrated a number of GUI-driven demonstration modes to show and evaluate the robot capabilities:

- manual joint control: the user moves individual joints manually by selecting buttons in a control window, incrementing and decrementing a desired joint position
- autonomous joint control: the robot moves each of its joints in programmed simultaneous motion between set limits (sinusoidal test pattern)
- teleoperated: the robot is controlled either by using a mouse to increment or decrement motion along single axes of a viol-l(l-l-ef'el-ence(i coordinate frame, or by using a spaceball input device to simultaneously move all six axes of the robot
- autonomous task control: the robot moves its end effector in programmed, coordinated simultaneous motion along-or-about one or more Cartesian-defined axes.

Per above description, the slave test software resides on a VhfE-based system. **Fig. 3** sketches the manipulator control flow used in the manual and autonomous world coordinate frame-referenced test modes.

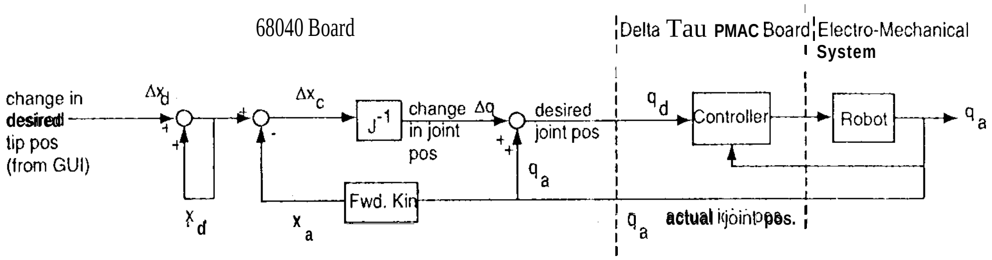

*Fig. 3: **Slave Manipulator** Control Flow (bench checkout and experimental testing)*

The general scheme by which the operator currently commands forward control to the robot is as follows: he/she inputs to the system from the GUI and this input is passed forward using the UNIX socket facility over an Ethernet link. Data 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 the commanded robot joint motions through a Jacobian inverse matrix, which is computed using the Spatial Operator Algebra developed by Rodriguez et al. [8]; 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.

3.3 Results of Preliminary Testing

On initial integration of the slave assemblies and drive mechanisms, without benefit of significant mechanical tuning or refilling, we observed repeatable relative positioning of the robot tip to 25 microns or less. This measurement, documented in videotaped experiments [2], 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. The robot smoothly executed both small (micron) and large (centimeter) free space motion trajectories.

We have conducted *ad hoc* comparisons in which leading microsurgeons perform free hand motions along-side that of the robot under microscopic observation. It appears at least a 3:1 scaling of best manual skills can be derived, given an appropriate hand master interface.

4 Ongoing Work

Developing a micro-master to teleoperatively control the above slave manipulator is the major focus of our present work. We have recently completed a "master" design and constructed a first working prototype as shown in Fig. 4

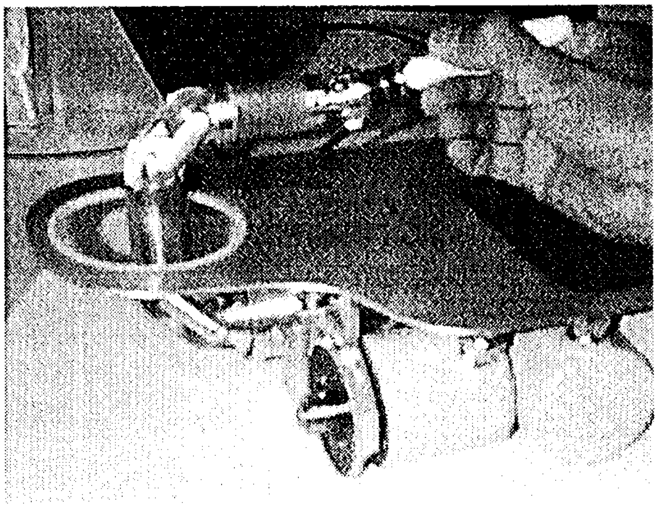

Figure 4: RAMS Master Controller (without case)

The RAMS master is a six-axis input device (left and right hand symmetric) that is kinematically similar to the existing slave, viz. a serial-link mechanism consisting of a torso, shoulder, elbow, and three-axis wrist. We comment briefly