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Towards a Force-Reflecting Motion-Scaling System for Microsurgery

S. E. Salcudean and J. Yan
Department of Electrical Engineering
University of British Columbia
Vancouver, BC, V6T 1Z4, Canada

Abstract

This paper presents design aspects of a force-reflecting, motion-scaling teleoperation system for use in microsurgery experiments. A coarse-macro-micro approach is proposed. Two magnetically levitated wrists — a macro-master and a micro-slave — would share a common base positioned at the surgical site by a coarse-motion transport robot. The discussion includes features of the proposed system, a detailed slave wrist description, and aspects of coordination and control for the multi-stage teleoperation.

1 Introduction

Microsurgery is a demanding practice requiring special training and equipment. The tasks performed require dexterity levels bordering on the normal range of unaided human abilities, involving motions as small as a few microns and forces as delicate as a few grams. Microsurgery, when required, commonly constitutes up to three hours of an operation and is usually performed after several hours of routine surgical procedures. Therefore, fatigue is a significant problem.

From observations of a number of surgical procedures and from discussions with several surgeons, it became clear that the tool forces experienced during microsurgery tasks are so small that manipulation is guided mainly by vision (through a microscope) and not by kinesthetic feedback. The kinesthetic sensations that would significantly enhance a surgeon's performance both in speed and safety can be provided by teleoperation.

Although traditionally, teleoperation has been seen as a way of extending the human reach into hostile or distant environments [1], this notion has started to encompass the extension of human reach through barriers of scale. This allows, for example, a person to work on individual living cells [2] or to "feel" atom surfaces [3] or excavator payloads [4]. Thus, by sensing forces exerted on a surgical tool and magnifying them to the surgeon's hand, while at the same time, scaling down the movements from the surgeon's hand to the surgical tool, teleoperation could endow the surgeon with an increased level of dexterity.

The increasing number of applications of robotics in the medical field (see [5, 6]), demonstrate that the medical community is receptive to new devices, both of the "assistive type" aimed towards low-cost, "solo" surgery [5], and of the "enabling type" (such as the custom milling of bone for cementless implants [6]) that would permit the execution of difficult or impossible tasks.

It has been shown in previous work that the performance achievable in bilateral teleoperation systems is very much limited by difficulties encountered when building sensitive, multi-degree-of-freedom masters or slaves [1, 7]. According to [1], these are defined as backdriveable, light, fast, frictionless, backlash-free, smooth-motion devices capable of providing sufficiently high forces and frequency response for good kinesthetic feedback. Conventional robotic technology, whether it involves serial or parallel mechanisms, is inadequate for these purposes. Therefore, this paper proposes that hand motion be scaled down to the surgical instrument by employing devices with Lorentz magnetic levitation (maglev). These devices provide six degree-of-freedom (6 DOF), limited-range, frictionless motion with high resolution and high force and position bandwidth [8].

A coarse-fine slave, fine master teleoperation system using maglev wrists was presented in [9], while experimental results showing excellent performance were presented in [10]. The system modifications necessary to adapt such a system for microsurgery experiments are described in this paper, including the detailed design of a miniature maglev wrist suitable as a surgical slave.

The remainder of this paper is organized as follows: Features of the overall system are described in Section 2 followed by a detailed description of the slave in Section 3. In Section 4, issues pertaining to the control of the teleoperation system are presented. Finally, conclusions and future work are presented in Section 5.

2 A Coarse-Macro-Micro Approach to Motion-Scaling

Through consultation with surgeons, observations of several microsurgical procedures, and a search of the related literature [11], it was determined that a system that would be used in microsurgery should satisfy the following qualitative requirements:

1. *Downward displacement scaling from master to slave.* This would increase the resolution of the surgical tool and attenuate physiological tremor.

2. *Upward force scaling from slave to master.* When relying only on visual feedback, delicate tissues and vessels can easily be damaged even by experienced microsurgeons.

3. *Programmable motion/force scalings and limits.* The scaling ratio and motion/force limits, as well as tool compliance should be adjustable to a particular surgeon and surgical procedure.

4. *Backdriveability over a large motion range.* This would allow quick removal of the system when the microsurgery is concluded or in the event of complications.

5. *Convenient manual override of motion scaling.* For safety reasons, the surgeon should be close to the operating site and have a means to override the teleoperation.

6. *Conventional command tool.* The overall system should be commanded by a tool similar to commonly used medical instruments in order to promote its acceptance among surgeons.

To satisfy these requirements, a structure consisting of a fine-motion scaling system transported by a coarse-positioning stage is proposed and illustrated in Figure 1. The macro-motion master and micro-motion slave would share a common stator mounted at the distal end of the transport stage. By implementing coarse-fine control concepts, the system would support the large workspace of the transport robot while retaining the performance characteristics of the fine-motion devices [12, 8].

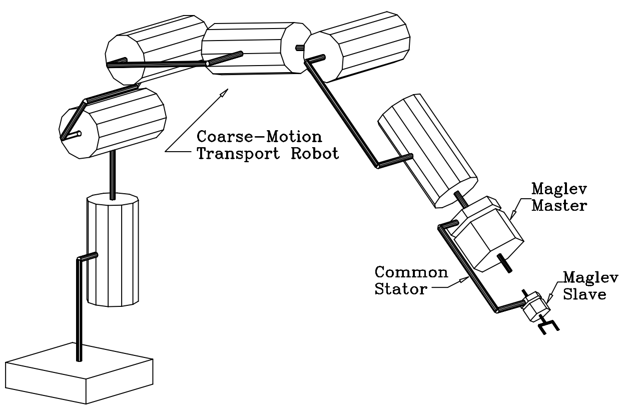

Figure 1: Proposed System Configuration

The coarse-motion stage can be serial (*e.g.*, an elbow manipulator with a spherical wrist), or parallel (*e.g.*, a Stewart platform) and it should compensate for the weight of the scaling system it is transporting. For convenience and safety, the transport robot should be easily backdriveable (a passive mechanism could also be employed) and have a counterbalanced design. Although high accuracy is not necessary, it should have a high position resolution for smooth motion.

Lorentz maglev devices were selected for the macro-micro master-slave system. Each such device has a single light, rigid, fast *flotor*, actuated by six coils operating in the strong magnetic fields produced by a *stator*. Flotor levitation with respect to the stator, programmable stiffness, as well as commanded forces and torques are achieved through optical position/orientation sensing, optional force/torque sensing and digital feedback control of the coil currents [8]. The only physical connection between the flotor and its stator is a flexible connector for sensor signals and coil currents. Thus, the master and slave dynamics interact with the hand and environment in the same way as a surgical tool would, leading to more transparent teleoperation.

Two previously designed maglev wrists have been used successfully in teleoperation experiments, in unilateral mode [3], and force-reflecting mode [9], including a system having identical master and slave maglev wrists [9, 10]. It was found that the motion range and performance provided by the maglev masters used (see Table 1 of Section 3.2) are adequate, leading to fast free motion tracking and excellent kinesthetic feedback [10]. Therefore, no major design changes for the teleoperation master are required for scaled manipulation experiments.

The quantitative requirements for the slave were determined through observations of several microsurgery operations and from the limited literature on the subject. From a videotape of a right facial nerve palsy operation, involving suturing of nerves roughly 1 mm in diameter, the motion range of a pair of microforceps was determined. The tool translational motion was primarily along the tool axis, less than ± 2.5 mm, while rotational motion was mostly about an axis perpendicular to the tool, less than $\pm 2.5°$. Data in [11] shows the tissue/tool force encountered in actual eye surgery averaged 30 g and did not exceed 43 g. A slave with low mechanical impedance is desired and measurements of microsurgical instruments indicate that its mass should be less than 50 g.

Additional data will be collected from microsurgery to confirm the slave force and positioning requirements, while subjective experiments concerning comfort level will be performed to determine the master requirements.

3 Micro-wrist Design

3.1 General Scaling Characteristics

As a first step in designing a microwrist with the slave characteristics outlined above, the simple scaling of previous maglev wrists should be examined. A scaling factor n is assumed.

The basic Lorentz actuator used before [8, 9, 13], illustrated in Figure 2, consists of a flat coil situated between a pair of magnet assemblies producing a strong magnetic field. A Lorentz magnetic force $\mathbf{F}$ is generated when current I is passed through the coil:

$$\mathbf{F} = I \int_L (d\mathbf{l} \times \mathbf{B}) \tag{1}$$

where $\mathbf{B}$ is the gap magnetic field, $d\mathbf{l}$ is a differential wire element pointing in the current direction, and the integration is performed over the coil wire length L.

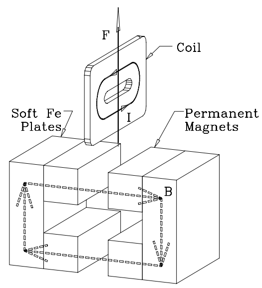

Figure 2: Basic Maglev Actuator

Magnetic Field. The force achievable in each actuator is directly proportional to the magnitude of $\mathbf{B}$. A general analysis of the effect of n on this field can be performed by comparing the vector potentials, $\mathbf{A_1}$ and $\mathbf{A_2}$, for a body V_1 at a point P_1, and the scaled body V_2 at the scaled location P_2 (see Figure 3 and [14, p. 362-3]). For V_1,

$$\mathbf{A_1}(\mathbf{p}) = \frac{\mu_0}{4\pi}\int_{V_1}\frac{\mathbf{M}\times\mathbf{r}}{r^3}dV_1 \qquad (2)$$

where $\mathbf{M}$ is the magnetization, $r = \|\mathbf{r}\|$, and μ_0 is the permeability of free space. For V_2 ($\mathbf{M}$ unchanged),

$$\begin{aligned}\mathbf{A_2}(n\mathbf{p}) &= \frac{\mu_0}{4\pi}\int_{V_2}\frac{\mathbf{M}\times n\mathbf{r}}{(nr)^3}dV_2 \\ &= \frac{\mu_0}{4\pi}\int_{V_1}\frac{\mathbf{M}\times\mathbf{r}}{n^2r^3}n^3dV_1 = n\mathbf{A_1}(\mathbf{p}) \quad (3)\end{aligned}$$

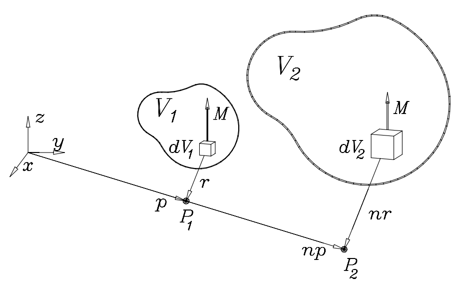

Figure 3: B-field scaling from a magnetized body

Using (3) and the relationship $\mathbf{B} = \nabla \times \mathbf{A}$, it can be shown that $\mathbf{B_2}(n\mathbf{p}) = \mathbf{B_1}(\mathbf{p})$. Thus, for any shape and configuration of magnetized bodies, $\mathbf{B}$ *is invariant to dimension scaling.*

Power. The continuous power that can be delivered to the actuator is equivalent to the maximum rate of thermal dissipation, $P = \bar{h}A\Delta T$. The area A for thermal dissipation is proportional to n^2, while the allowed temperature gradient ΔT does not change. The average heat transfer coefficient $\bar{h}$ for free convection from horizontal plates is roughly constant [15], while formulae for vertical and inclined plates indicate an expected increase in $\bar{h}$ for $n < 1$, which has favourable implications for the microwrist design. *Thus P scales approximately as n^2.*

Force. Using the coil resistance equation, $R = \rho L/A_x$ (for a wire with resistivity ρ, total length L, and cross-sectional area A_x), we get $R \propto n^{-1}$. The relation $I^2 = P/R$ and the previous result for power shows the maximum current scales according to $I \propto n^{3/2}$. Finally, from (1), we find $F \propto n^{5/2}$.

Acceleration. The acceleration capability is the actuator force-to-mass ratio. The mass m is proportional to n^3 and so the ratio scales according to $F/m \propto n^{-1/2}$. This relationship demonstrates that the actuator acceleration capability is expected to improve for $n < 1$.

These scaling aspects apply to maglev actuation in general and is not unique to our design.

3.2 Mechanical Design

Influential factors in the mechanical design of the slave wrist include weight, size, motion range, actuation strength, maintenance, safety, and comfort.

A drawing and photograph of the resulting slave wrist design are shown in Figures 4 and 5, respectively. All parts can be easily manufactured within reasonable tolerances and are easy to assemble and disassemble.

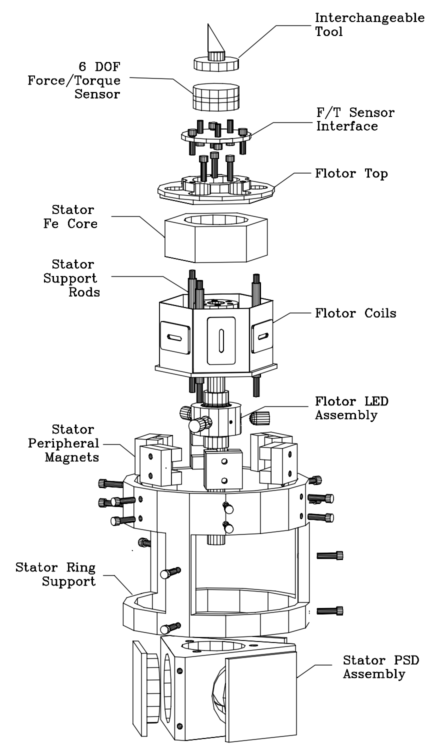

Figure 4: Slave maglev wrist assembly

The lightweight flotor and the configuration of several actuators are shown in Figure 6. Most of the

Figure 5: Micro-wrist stator and flotor

flotor parts are made from aluminum and the coils are mounted using thermally conductive epoxy for better heat dissipation. After addition of the tool and force/torque sensor, the flotor is expected to weigh 40 g. Having the actuators on the periphery maximizes the torque for a given size. The magnets being used have the highest energy product commercially available (NdFeB 45 MG·Oe). Soft iron used for the back plates and stator core, are inexpensive means of increasing the field (the resulting field in the gap centers of the slave wrist was measured to be 0.4 T).

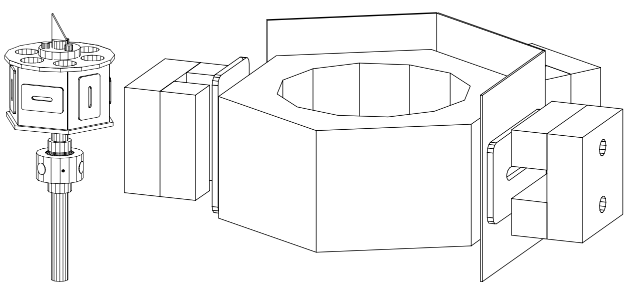

Figure 6: Flotor and Actuator Configuration

The flotor's position when each of its coils is centered on its respective magnet is called the *center position.* The axial direction is taken to be the z-axis. The flotor has a translational motion range from its center position of ± 2.25 mm along z and up to ± 1.7 mm in the x-y plane. The rotational motion range is $\pm 10°$ about z, and $\pm 4°$ about an axis in the x-y plane. The expected maximum continuous force is 0.12 N axially and 0.06 N laterally (ignoring the flotor mass) while the maximum continuous torque is 20 N·mm about z and 10 N·mm about an axis in the x-y plane. The force resolution expected is 2 mN. The slave designed is expected to meet the tool requirements outlined in Section 2.

Some measured and estimated characteristics of the system's maglev wrists are presented in Table 1.

Table 1: Maglev Wrist Characteristics

Characteristic	Master†	Slave
Flotor mass	700 g	40 g
Cylindrical Dimensions:		
Diameter	13 cm	7 cm
Height	11 cm	6 cm
Single Actuator:		
Max cts current	3 A	0.5 A
Force/Amp	2 N/A	0.8 N/A
Max cts axial force	18 N	1.2 N
Nominal Motion range:		
Translational	± 4.5 mm	± 1.7 mm
Rotational	$\pm 7°$	$\pm 10°$
Position Bandwidth	20-30 Hz	20-30 Hz
Force Bandwidth‡	500 Hz	500 Hz
Position Resolution	5 μm	0.5 μm
Force Resolution	0.1 N	0.002 N

† UBC maglev wrist presented in [9, 10]
‡ Force bandwidth is limited by computational delays

4 Motion Coordination and Control

4.1 Decoupled Coarse-Fine Control

A decoupled coarse-fine, hybrid rate/position control strategy is proposed for the robot tool positioning. In this scheme (see Figure 7), the slave local motion x_s is controlled in position mode to track the master local motion x_m (scaled down by n_p), while the transport robot's gripper location X_R is controlled in rate mode to track the master only when it is near its local workspace edge. The small centering motion, barely noticeable to the operator, is necessary to allow the slave manipulator to be positioned against a stiff obstacle with the master flotor in its center [16]. The control could then be implemented as follows:

$$\begin{aligned} x_{sd} &= x_m/n_p \\ \dot{X}_{Rd} &= \begin{cases} K(|x_m| - r)sgn(x_m); & |x_m| > r \\ K_c x_s & \text{otherwise} \end{cases} \\ X_m &= X_R + x_m \text{ and } X_s = X_R + x_s \end{aligned} \quad (4)$$

where r gives the deadband range, and X_m and X_s are the absolute master and slave positions, respectively.

With the common stator, the surgeon gains a very natural control of the slave using the master because their orientations are identical and the master is close to the operating site. The slave can be operated in scaling or non-scaling mode (*e.g.,* when relatively large motions are required). When using rate control, the quality of smooth motion is dependent upon the robot's positioning resolution but this is not perceived to be a problem; high positioning accuracy is achieved through visual endpoint sensing.

4.2 Wrist Level Fine-Motion

The motion of the two maglev wrists with respect to the common base is coordinated by a scaling force-reflecting controller. After linearization and gravity

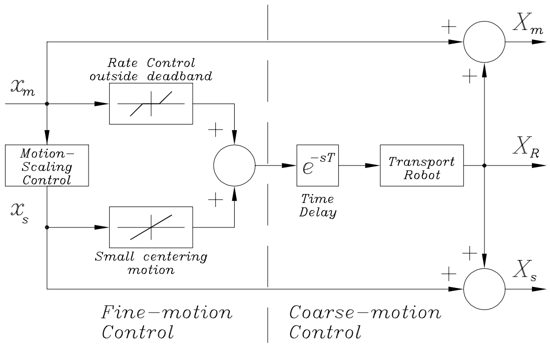

Figure 7: Decoupled Coarse-Fine Control

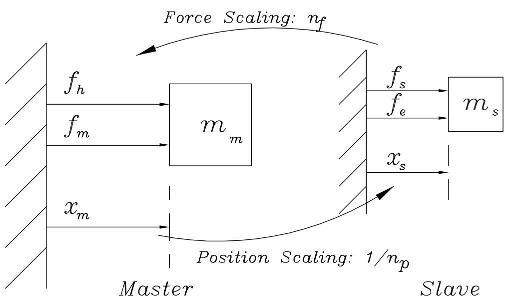

Figure 8: Single Degree-of-Freedom Teleoperation

feedforward, the maglev wrist flotors can reasonably be modelled as single rigid bodies with the motion along orthogonal axes being decoupled. A single DOF model of teleoperation (see Figure 8) can be used with the bodies obeying the following equations of motion (Laplace transforms are used throughout and all signals have implicit frequency dependence):

$$\begin{aligned} m_m s^2 x_m &= f_h + f_m = f_h^e - H x_m + f_m \\ m_s s^2 x_s &= f_e + f_s = f_e^e - E x_s + f_s \end{aligned} \qquad (5)$$

where m_m, f_m, m_s, f_s, f_h, and f_e are, respectively, the master mass and actuator force, slave mass and actuator force, and operator hand and environment forces. For the stability analysis, f_h and f_e are each considered to possess active exogenous components f_h^e and f_e^e, respectively, and passive feedback components $-Hx_m$ and $-Ex_s$ dependent on the hand and environment impedances, respectively.

Ideal teleoperation implies complete system transparency (*i.e.*, the operator feels as if he/she is directly manipulating the environment). For identical master/slave systems and unity scaling ratios, this concept can be realized by setting $f_m = f_e$ and $f_s = f_h$, where hand and environment force measurements are assumed to be available and exact.

For the force-reflecting motion-scaling system of Figure 8, transparency is slightly more complicated. Consider that the force-scaling ratio n_f and the motion-scaling ratio n_p are independently chosen (*i.e.*, $f_m = n_f f_e$ and $x_m = n_p x_s$). Then, for the mass ratio $n_m = m_m/m_s$, these desired scalings are achieved with the control law:

$$\begin{aligned} f_m &= n_f f_e \\ f_s &= \frac{f_h + (n_f - n_m n_p) f_e}{n_m n_p} \end{aligned} \qquad (6)$$

This results in the following equations relating exogenous forces to positions:

$$\begin{aligned} f_h^e + n_f f_e^e &= \left(m_m s^2 + H + \frac{n_f}{n_p} E \right) x_m \\ \frac{f_h^e}{n_f} + f_e^e &= \left(\frac{n_p n_m}{n_f} m_s s^2 + \frac{n_p}{n_f} H + E \right) x_s \end{aligned} \qquad (7)$$

When $n_f = n_m n_p$, the force scaling from master to slave is $1/n_f$ as we would expect. However, when $n_f \neq n_m n_p$, (6) results in a local feedback term at the slave making its "apparent" mass a scaling of the actual mass by $n_p n_m / n_f$, as seen in (7). At the master end, the environment impedance will feel like E scaled by the ratio n_f/n_p, while the slave feels H by the inverse ratio. These equations demonstrate that transparency can be achieved for n_p and n_f chosen independently by applying (6). It was shown that a local feedback could occur in the slave to change its apparent mass but a similar feedback could just as easily be used to make the master's apparent mass different. For transparency in which the apparent master and slave device properties do not differ from their actual ones, we require $n_f = n_m n_p$.

Of course, ideal teleoperation is impossible due to time delays, modelling errors, measurement noise, *etc.*. Each wrist would suffer from positional drift even without any exogenous forces (this problem can be remedied with a local controller, *e.g.,* PID, to each wrist). Using a controller with only force measurements (as in (6)) would also result in a loss of kinematic correspondence between master and slave; this problem can be solved by using a coordinating torque term f_c based on the positional error:

$$\begin{aligned} f_c &= (k_p + s k_v + \frac{k_i}{s})(x_m - n_p x_s) \\ f_m &= n_f f_e - f_c \\ f_s &= \frac{f_h + (n_f - n_m n_p) f_e}{n_m n_p} + \frac{f_c}{n_f} \end{aligned} \qquad (8)$$

Even when force measurements are not available, f_c can be used to control the wrists although very high gains (k_p and k_v) are required. One final note about the controller (6) is that positive local feedback generally leads to less stability so this restricts the independance in choosing the scaling ratios.

The controller should provide a high degree of transparency and yet be robust to uncertainties. An H_∞ control approach to trading off these conflicting requirements has been pursued. Successful experiments of fine-motion teleoperation have already been performed with PID and H_∞-based controllers.

5 Conclusions

Work towards a bilateral teleoperation system for microsurgery experiments being developed at UBC has been discussed. For the initial experiments, a CRS A460 robot will be employed as the transport robot. The macro-maglev wrist which has performed successfully in previous experiments [10] will be employed as the master while the micro-maglev wrist presented in this paper will be employed as the slave.

It was shown that for the maglev actuators described, the force-to-mass ratio improves with smaller sizes and a design with desireable features has been presented. Issues of transparency for the control of bilateral motion-scaling teleoperation have been presented. The slave wrist was recently completed and has been successfully controlled in teleoperation under PID as well as H_∞-based controllers.

The issue of safety is certainly an important one for this system but is beyond the scope of this paper. The envisaged applications of the system described in this paper are in microsurgery for enhancing a surgeon's ability in tool positioning and kinesthetic force sensing. Reconstructive surgery, often requiring microvascular work, is the first targetted application, but the system might prove useful for eye surgery and neurosurgery as well.

6 Acknowledgements

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References

[1] J. Vertut and P. Coiffet, *Robot Technology, Vol. 3A: Teleoperations and Robotics: Evolution and Development.* Prentice-Hall Series on Robot Technology, Prentice-Hall, 1986.

[2] I.W. Hunter, S. Lafontaine, P.M.F. Nielsen, P.J. Hunter, and J.M. Hollerbach, "A microrobot for manipulation and dynamical testing of single living cells," in *Proc. IEEE Micro Electro Mechanical Systems*, (Salt Lake City), pp. 102–106, February 1989.

[3] R.L. Hollis, S.E. Salcudean, and D.W. Abraham, "Towards a tele-nanorobotic manipulation system with atomic scale force feedback and motion resolution," in *Proc. 3rd IEEE Micro Electro Mechanical Systems*, (Napa Valley, CA), February 1990. 6 pages.

[4] M. Ostoja-Starzewski and M. Skibniewski, "A Master-Slave Manipulator for Excavation and Construction Tasks," *Robotics*, vol. 4, no. 4, pp. 333–337, 1989.

[5] J.A. McEwen, "Solo Surgery with Automated Positioning Platforms," in *Proceedings of the New Frontiers in Minimally Invasive and Interventional Surgery*, (New Orleans, LA), October 13 1992.

[6] H.A. Paul, B. Mittlestadt, W.L. Bargar, B. Musits, R.H. Taylor, P. Kazanzides, J. Zuhars, B. Williamson, and W. Hanson, "A Surgical Robot for Total Hip Replacement Surgery," in *Proceedings of the IEEE International Conference on Robotics and Automation*, (Nice, France), pp. 606–611, May 10-15 1992.

[7] P. Fischer, R. Daniel, and K.V.Siva, "Specification and Design of Input Devices for Teleoperation," in *Proc. IEEE Conference on Robotics and Automation*, pp. 540–545, May 1990.

[8] R.L. Hollis, S.E. Salcudean, and P.A. Allan, "A Six Degree-of-Freedom Magnetically Levitated Variable Compliance Fine Motion Wrist: Design, Modelling and Control," *IEEE Transactions on Robotics and Automation*, vol. 7, pp. 320–332, June 1991.

[9] S.E. Salcudean, N.M. Wong, and R.L. Hollis, "A Force-Reflecting Teleoperation System with Magnetically Levitated Master and Wrist," in *Proceedings of the IEEE International Conference on Robotics and Automation*, (Nice, France), pp. 1420–1426, May 10-15, 1992.

[10] S.E. Salcudean and N.M. Wong, "Coarse-fine motion coordination and control of a teleoperation system with magnetically levitated master and wrist," in *Third International Symposium on Experimental Robotics*, (Kyoto, Japan), Oct 28-30, 1993.

[11] S. Charles and R.E. Williams, "Measurement of Hand Dynamics in a Microsurgery Environment: Preliminary Data in the Design of a Bimanual Telemicro-operation Test Bed," in *Proceedings of the NASA Conference on Space Telerobotics*, (Pasadena, CA), Jan.31 - Feb.2 1989.

[12] R. H. Taylor, R. L. Hollis, and M. A. Lavin, "Precise manipulation with endpoint sensing," *IBM J. Res. Develop.*, vol. 2, pp. 363–376, July 1985.

[13] S.-R. Oh, R.L. Hollis, and S.E. Salcudean, "Precision Assembly with A Magnetically Levitated Wrist," in *Proceedings of the IEEE International Conference on Robotics and Automation*, (Atlanta, USA), pp. 127–134, May 2-6, 1993.

[14] P. Lorrain, F. Lorrain, and D.P. Corson, *Electromagnetic Fields and Waves, 3rd ed.* W.H. Freeman and Co., New York, 3rd ed., 1988.

[15] J.P. Holman, *Heat Transfer, Sixth Edition.* New York: McGraw-Hill, 1986.

[16] N.M. Wong, "Implementation of a force-reflecting telerobotic system with magnetically levitated master and wrist," Master's thesis, University of British Columbia, December 1992.