

Preliminary Experiments in Cooperative Human/Robot Force Control for Robot Assisted Microsurgical Manipulation

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Abstract

This paper reports preliminary experiments with a new robot system designed to cooperatively extend a human's ability to perform fine manipulation tasks requiring human judgement, sensory integration and hand-eye coordination. A recently completed steady-hand robot is reported. A stable force control law is reviewed. Preliminary experiments validate theoretical predictions of stable one-dimensional control of tool-tip forces in contact with both linearly and nonlinearly compliant objects. Preliminary feasibility experiments demonstrate stable one-dimensional robotic augmentation and "force scaling" of a human operator's tactile input.

1 Introduction

This paper describes the first steps in the development of a robotic assistant for microsurgery and other precise manipulation tasks. Our approach, which we call "steady hand" micro-manipulation is for tools to be held simultaneously both by the operator's hand and a specially designed 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 simplicity and immediacy of hand-held tools for tasks characterized by compliant or semi-rigid contacts with the environment.

Most prior robotic micro-manipulation systems have emphasized traditional master-slave and telerobotic manipulation [30] including virtual training [15], manipulation of objects in hazardous environments [28], remote surgery [11, 27], and microsurgery [2, 15, 16, 22, 26, 29]. In contrast, we are interested in developing a system where both the robot and the human manipulate a single tool in contact with a compliant environment. Our approach might offer several advantages compared to these systems in the context of micromanipulation. These include: simplicity; potentially

cheaper implementations; more direct coupling with the natural human kinesthetic senses; straightforward integration into existing application environment; and 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.

This paper is organized as follows: Section 2 reviews previously reported results in force control for steady-hand manipulation, and reviews a simple stable force control algorithm for position-controlled manipulators. Section 3 reports a novel robot arm for steady-hand manipulation and the experimental setup for these experiments. Section 4 reports a preliminary experimental performance evaluation for the steady hand robot with the proposed force control algorithm when in contact with linearly and non-linearly compliant environments.



Figure 1: The steady-hand micromanipulation concept as applied to retinal microsurgery

2 Force Control for Steady-Hand Manipulation

There is a large body of literature concerning provably stable control techniques for robots. Standard paradigms include 1) pre-programmed trajectory control of position [4, 25] and force [40, 41]; 2) fully autonomous robots (e.g. [20,

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34]); and 3) master-slave teleoperators (e.g., [12, 24, 42]). In our case, we are interested stable control methodologies 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 Kazerooni [17-19] who developed exoskeletons to amplify the strength of a human operator. Kazerooni et al. [17-19] report 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 . A concise 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 exist for neither the hydraulically actuated robot nor the operator’s human arm. In consequence, in [17-19] the authors report a robustness analysis for stable robot force-control laws that accommodate wide variation in both human and robot arm dynamics.

The problem addressed herein differs from the above in two principal respects: First, we consider the 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 0.01 . Second, we address microsurgical manipulation tasks requiring precision low-speed low-acceleration motion. Based on these performance requirements and paramount safety considerations, we have developed the compact position-controlled manipulator described in Section 3, and have (cautiously) adopted the simplified plant model described in this Section.

A number of authors (e.g., [3, 12]) have investigated “shared autonomy” and 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., [43]) 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 employed “hands on” guiding of robots for positioning within the operating room (e.g., in the “Robodoc” [1, 23, 37] hip replacement surgery system and in the JHU/IBM LARS system [5-10, 35, 36] for endoscopic surgery). Davies et al. [13, 14, 38], have combined hands-on guiding with position limits and have demonstrated 3 DOF machining of shapes in the end of a human tibia.

2.1 Arm Dynamics

The steady-hand robot, described in Section 3, was custom designed to meet the performance, accuracy, and safety requirements of micro-surgery. The robot itself is compact and highly stiff. The joints are actuated by highly geared electric actuators with gear ratios of 0.002 m/rev (translation joints) and 50:1 to 200:1 (rotation joints) – attenuating nonlinear arm dynamics terms (as transmitted to the actuator) by a factor of $1/n^2$. Normal operating speeds during microsurgery are extremely slow – ranging from a few millimeters per second during gross motion down to tenths

of a millimeter per second for delicate tissue manipulations. For safety, the joints are designed to limit peak tool speeds to about 40mm/second. The joints are not back-driveable. The joints are individually controlled by a high-gain PID control loop providing a closed loop joint position bandwidth of about 20 Hz. In normal operation, the system is not subject to significant “disturbance” forces, and we have observed little excitation of unmodeled dynamics. Given these performance characteristics, it is reasonable to adopt a model for the entire joint-controlled robot system as a *position controlled device* whose “control input” is the desired position. As a first approximation, the difference between the desired and actual robot joint position is neglected. In the early stages of this project, we were uncertain if this simple model would be reasonable for our robot and application. As the subsequent experimental data will demonstrate, this has proven to be a reasonable modeling approach for the present robot, joint construction, joint controller, and application.

Note that this approach – modeling the robot as an “idealized” positioning device – differs from the customary approach found in the robotics force-control research literature. Most reports on force control model the plant as a torque-controlled second-order nonlinear dynamical system with the usual inertial, coriolis, gravitational, and interaction forces – e.g. [40]. Relatively few reports – e.g. [39] – directly address the case of force control with position-controlled manipulators. Clearly both approaches are approximations whose applicability must be evaluated in the context of a particular arm, control, and application.

2.2 Force Control with Position-Controlled Manipulators

As a preliminary step toward multi-DOF steady-hand control we have implemented and tested a stable one-DOF force control law for the following force control problem.

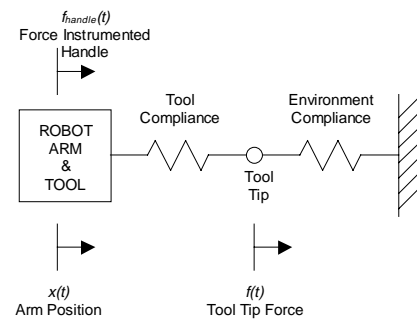


Figure 2: A Simple 1-D Force Control Problem

Consider the case of a 1-DOF position controlled mechanism, depicted in Figure 2, with joint position $x(t)$ and joint velocity $\dot{x}(t)$. The force exerted by the tool tip on a compliant environment is $f(t)$ Newtons. The force exerted by

a user on the rigid robot is $f_{handle}(t)$ Newtons. The robot's end effector and tool has a collective linear compliance of k_{robot} N/m, and the compliant environment in contact with the tool tip has linear compliance k_{env} N/m. The tool and environment combination has an aggregate compliance of

$$(1) \quad k_t = \frac{1}{k_{robot}^{-1} + k_{env}^{-1}}.$$

The tool-tip force at equilibrium is

$$(2) \quad f(t) = k_t x(t).$$

The plant is *position controlled* with control inputs of either $\dot{x}_d(t)$ or $x_d(t)$ – subject to the constraint that the time derivative of $x_d(t)$ is $\dot{x}_d(t)$. A low-level servo-controller with, in our case, about 20 Hz closed-loop position bandwidth ensures that the actual positions and velocities closely track the desired state. As a first approximation, we neglect the tracking error, i.e.

$$(3) \quad x(t) = x_d(t)$$

$$(4) \quad \dot{x}(t) = \dot{x}_d(t).$$

Given a constant desired tool-tip force, f_d , the control task is to ensure that the force tracking error, $\Delta f(t) = f(t) - f_d$, converges asymptotically to zero

$$(5) \quad \lim_{t \rightarrow \infty} \Delta f(t) = 0$$

where

$$(6) \quad \Delta f(t) = f(t) - f_d$$

and

$$(7) \quad \Delta \dot{f}(t) = \dot{f}(t).$$

We assume that tool-tip force, $f(t)$, and the plant state, $x(t)$ and $\dot{x}(t)$, are instrumented. It is easy to show that the control law

$$(8) \quad x_d(t) = -k_f \int_0^t \Delta f(t) dt$$

results in exponentially stable first-order closed-loop force dynamics of

$$(9) \quad \Delta \dot{f}(t) = -k_f k_t \Delta f(t).$$

Note that this control law does *not* require differentiation of a force sensor signal, and does *not* require knowledge of the robot or environmental compliance parameters.

For the case of time-varying desired force, the control (8) will not provide asymptotically exact tracking. To achieve this, the control law must be augmented with an additional feedforward term

$$(10) \quad x_d(t) = -k_f \int_0^t \Delta f(t) dt + k_t^{-1} f_d(t).$$

2.3 Steady-Hand Force Scaling

Steady hand force scaling data shown in Section 4.3 was accomplished by using the simple force control law (8) where the desired force, $f_d(t)$, is computed in real-time by scaling down $f_{tool}(t)$, the force exerted by the user on the force-instrumented tool handle

$$(11) \quad f_d(t) = \alpha \cdot f_{tool}(t)$$

where α is the scale factor of tip-force to handle force. We have experimented with scale factors ranging from 1.0 to 0.02. For a scale factor of 0.02, for example, a 1.0 Newton tool handle force imparted by the user results in a miniscule 0.020 Newton tool tip force.

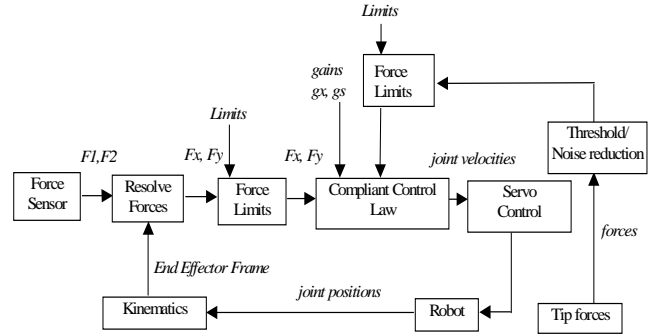


Figure 3: Block Diagram of Force Control Law for Proportional Force Scaling

3 Experimental Setup

This Section first describes the steady-hand robot and experimental setup employed in these experiments, and then reports experimental results evaluating the force control performance and steady-hand force control performance of this system.

3.1 Mechanical Hardware

The experimental platform consists of the robot, a specially designed ergonomic tool holder and tool tip force instrumentation (force sensor, amplifiers, analog to digital conversion). The robot is shown in Figure 4. A high power surgical microscope is used as a visual aid for manual manipulation where required. The new "steady hand" robot is a member of the JHU modular family of robots [21, 31, 32]. It is a 7-degree-of-freedom manipulator with XYZ translation at the base for coarse positioning, two rotational degrees of freedom at the shoulder [33], and instrument insertion and rotation stages. This robot has a mechanically constrained center of motion and overall operational positioning precision of 10s of microns, with position encoder resolution of 0.5 micron.

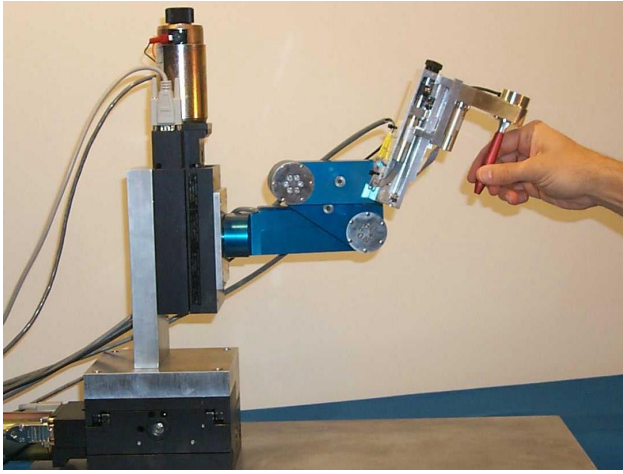


Figure 4: The JHU “Steady-Hand” Robot as configured for these experiments.

Base (XYZ) assembly	(Off-the-shelf)
Work volume	100 mm × 100 mm × 100 mm
Top Speed	40 mm/sec
Positioning resolution	≈2.5 μm (0.5 μm enc. res.)
RCM assembly	(Custom)
Link length	100 mm
Range of motion	Continuous 360°
Top speed	180°/sec
Angular resolution	≈0.05 ° (0.01° encoder res.)
End-effector	(Custom)
Range of motion	150mm; 360° continuous
Positioning resolution	5μm; 0.1° (1.5μm, 0.01° enc. res.)
Top speed	40 mm/sec; 180°/sec
Handle force res.	0.03 N (6-DOF)
Tool force resolution	0.001 N (1-DOF) (presently) 0.001 N (3-DOF) (soon)

Figure 5: Steady-Hand Robot Design Specifications

The robot end-effector is an ergonomically designed tool handle. A force sensor is attached to the end-effector, mounted axially with the tool handle. The sensor is a small commercially available force/torque sensor (ATI Industrial Automation, NC). A vitreoretinal pic was instrumented with strain gages and calibrated to measure forces occurring at the interface between the surgical tool tip and the environment. The signal from the strain gauge was conditioned using a standard strain gauge amplifier (Measurements Group System 2200) and digitized with a 12 bit analog to digital converter channel on the host PC. The resulting force-instrumented retinal pic, shown in Figure 6, provides milli-newton force sensing resolution at tip of the retinal pic.

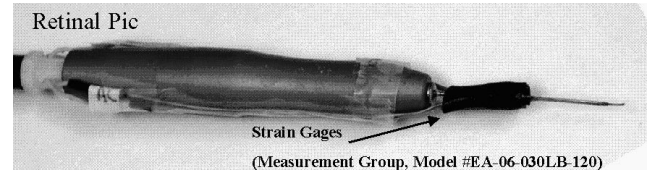


Figure 6: Force-Instrumented Retinal Pic.

3.2 Controller Hardware

The robot control system runs on a Pentium-II 450MHz PC under the Windows NT operating system. An 8-axis DSP series controller card (PCX/DSP, Motion Engineering Inc, CA) is used to control the robot. The card provides 1200 Hz update-rate joint-level servo control using a dedicated Analog Devices DSP processor. The PC also houses the ATI force sensor controller card. The robot is programmed in C++ using the JHU modular robot control (MRC) library – a library of C++ classes providing Cartesian level control. It includes classes for kinematics, joint level control, sensor support, peripheral support, and network support. Some exception and error handling is also built in. A variety of I/O devices including serial and parallel ports, ATI force sensors, joysticks, digital buttons and foot pedals are supported.

3.3 Control Algorithm Implementation

We have implemented the simple force proportional set-point force controller, (8), on the steady-hand robot using the JHU MRC library. The low-level PID joint controller provides high-gain joint-level servo control with an update rate of 1200 Hz, thus providing an approximation of the “joint position” control of (3) and (4). As a first step, we have implemented the I-D force controller (8) (with an update rate of 50 Hz) along a user-selectable 1-D cartesian direction.

4 Force Control Performance

This section reports preliminary experiments with the force control law (8). Setpoint force steps and hand-guided force scaling trajectory responses are reported.

4.1 Force Control Performance with Linear Environmental Compliance

For a first experiment to evaluate the force-control performance of this system, we conducted step-response force-control tests employing a thin (0.003 in diameter) steel wire as the “environmental contact object” in contact with the tool tip. The wire was cantilevered vertically in a vice with the tool tip in transverse contact to the free end of the cantilevered wire. For small transverse deflections, a cantilevered beam exhibits linear elasticity. The robot control program was configured to implement the control law (8) in a direction perpendicular to the axis of the wire.

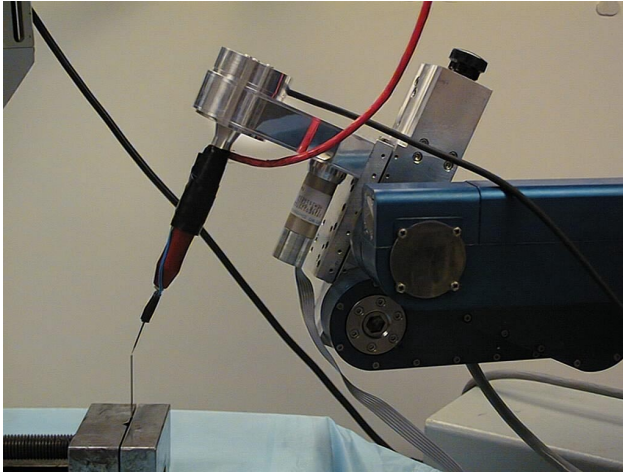


Figure 7: Experimental Setup for Linear Contact Compliance Experiments. Photograph shows steady-hand robot arm, force-instrumented retinal pic, and elastic slender steel “whisker” providing linear environmental contact.

For each experimental run, the robot was first traversed (in position control) until contact was detected between the tool tip and the wire. Once in contact, the force control law (8) was enabled. We have experimented with a variety of force feedback gains, and desired force profiles. Figure 7 shows the results of step response tests in which the desired force profile was a 0.10 Newton step at $t=0$. Results are plotted for several different values of force feedback gain k_f .

The top graph of Figure 8 shows the reference force and measured tool-tip force versus time. The middle graph shows the displacement versus time. These two graphs verify the model’s prediction, (9), – the system exhibits stable linear first-order exponential response. The bottom graph shows force versus displacement. The graph verifies that the overall compliance (comprising both the robot and environment compliance) is linear for small displacements.

4.2 Force Control Performance with Nonlinear Environment Compliance

How does this system perform with a nonlinearly compliant environment? It is well known that living tissue exhibits nonlinear compliance, hysteresis, and damping – the problem of analytical modeling of the mechanics of living tissue is an active area of research. As a second step we repeated the force-control step-response experiments of the previous Section, but with the tool-tip in contact with porcine retinal tissue samples. For these experiments, a porcine eye sample was cut open and its retinal tissue exposed. The robot is then moved close to the retinal tissue, as shown in Figure 9.

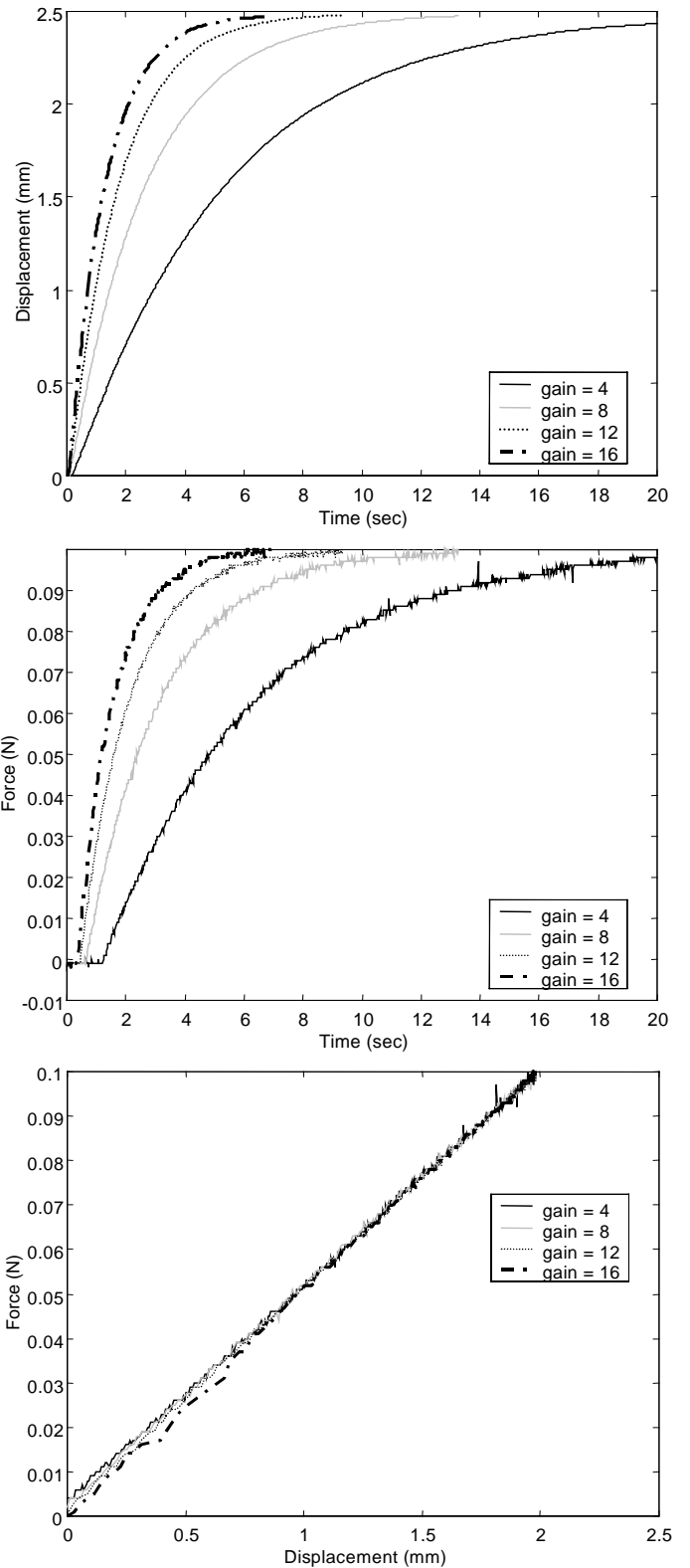


Figure 8: Experimental Force Control Performance in Contact with Linear Environment Compliance: Tool-tip force versus time (top); Displacement versus time (middle); Force versus Displacement (bottom). Desired force is a 0.10 Newton step function at $t=0$. Results are shown for different values of force-feedback gain k_f .

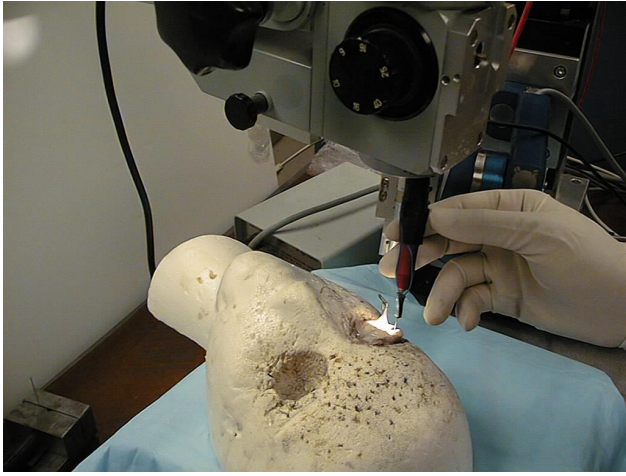


Figure 9: Experimental Setup for Tissue Contact (Nonlinear Compliance) Experiments. Photographs show the steady-hand robot arm, force-instrumented retinal pic, retinal tissue sample, and stereo microscope.

We have experimented with a variety of force feedback gains, and desired force profiles. Figure 10 shows the results of step response tests in which the desired force profile was a 0.10 Newton step at $t=0$. Results are plotted for several different values of force feedback gain. The top graph of Figure 10 shows the reference force and measured tool-tip force versus time. The middle graph shows the displacement versus time. These two graphs demonstrate that the response of this system is stable, but not linear. The bottom graph shows force versus displacement. This graph verifies that the overall compliance, comprising both the linear robot compliance and the nonlinear tissue compliance, is non-linear.

4.3 Steady-Hand Force Scaling Performance

How does the system perform in actual “steady hand” haptic force scaling tasks? We have experimented using the simple 1-DOF force control law (8) with the desired force specified in real time by the user’s haptic input per (11). We have tested force-scaling ratios from $\alpha = 1.0$ to $\alpha = 0.02$ for contact with both linear elastic steel whiskers and non-linear porcine eye tissues. The force feedback gain k_f was empirically set to 8 m/(N-sec) for these experiments.

Figure 11 shows the haptic force input and tool-tip force response for contact with the compliant steel whisker at a force scaling ratio of 25 ($\alpha = 0.04$) – thus a 1 N user haptic input force results in a 0.04 N tool-tip force. The handle force trajectories shown are the actual forces exerted on the tool handle by the user during operation, but are scaled by a factor $\alpha = 0.04$ to permit both the handle force and tip force to be plotted together. This force scaling ratio enhances the kinesthetic force perception of the user, enabling safer and less difficult manipulation of delicate compliant tissues.

Figure 12 shows the corresponding experiment tool-tip for contact with porcine eye tissue.

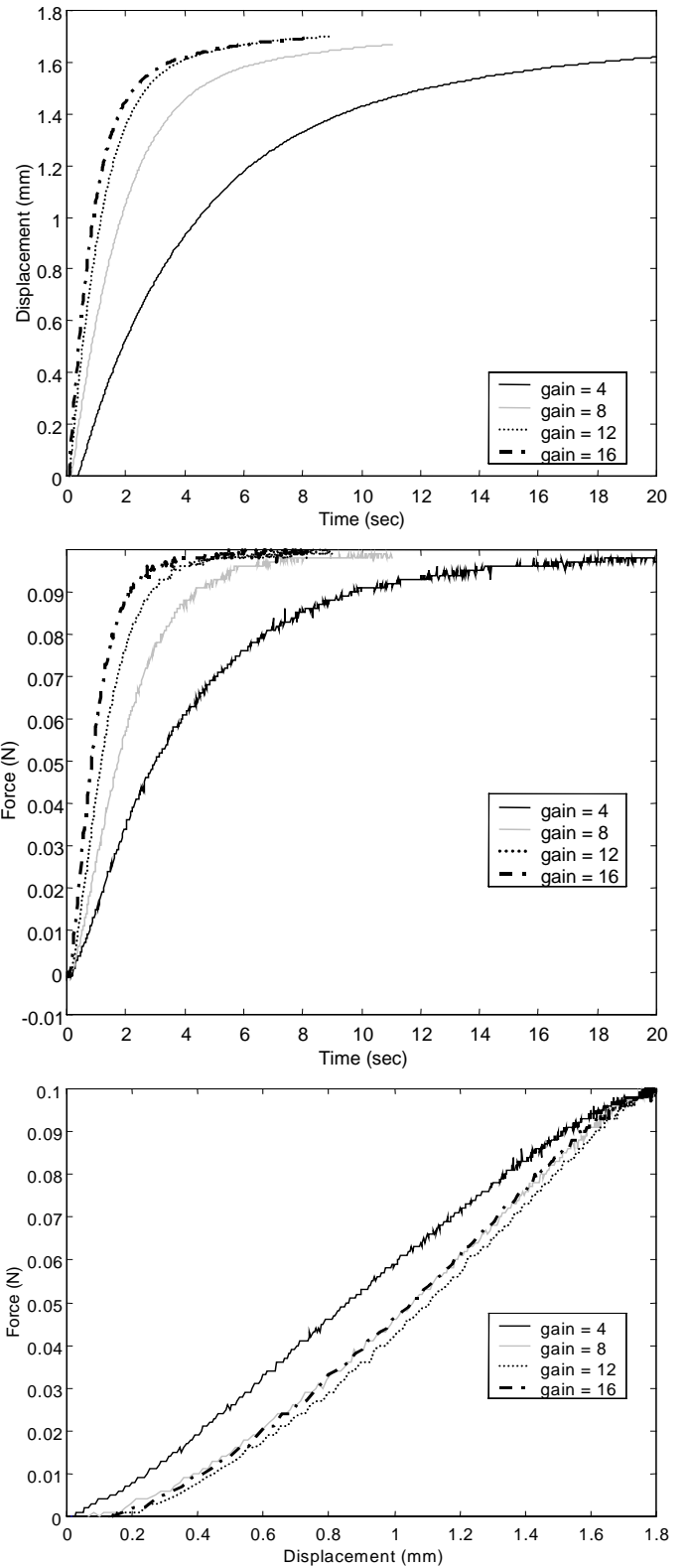


Figure 10: Experimental Force Control Performance in Contact with Porcine Retinal Tissue: Tool-tip force versus time (top); Displacement versus time (middle); Force versus Displacement (bottom). Desired force is a 0.10 Newton step function at $t=0$. Note nonlinear retinal tissue compliance.

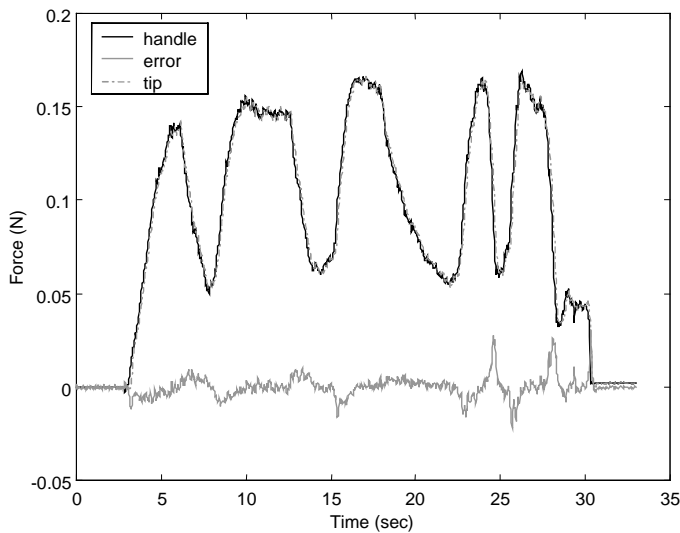


Figure 11: Steady-hand force scaling with whisker environment: Handle to tool tip force scaling ratio is 0.04 – a 25:1 ratio. Figure shows actual tool-tip force, scaled-down user haptic handle force, and force tracking error.

In both cases, the measured tool tip force tracks the scaled operator force trajectories with transient errors of less than 0.02 Newton. The delay of the force response is perceived by the user as viscous drag. This degree of viscosity in the steady-hand system response may greatly reduce the hand tremor typical in microsurgery.

5 Conclusion

This paper has reported a robot system designed to implement “steady-hand” manipulation – a novel paradigm in human/machine augmentation of micro-manipulation. A preliminary version for a force-instrumented microsurgical end-effector, the retinal pic, for retinal surgery is reported.

A simple first-order force control algorithm for low-bandwidth control of tool tip forces was reported. This algorithm is specific to the highly geared position-controlled manipulators that we anticipate will become common in surgical robotic applications. Preliminary experimental results with a 1-D implementation of this control law show stable force tracking and stable steady-hand force scaling when in contact with both linear and nonlinearly compliant (retinal tissue) environments. The experimental performance with both linear and nonlinear environments is consistent with simple theoretical models. The experimental results also suggest that this approach might provide sufficient data for real-time *in-vivo* estimation of tissue mechanical properties.

We are presently completing instrumentation to implement and test the full multi-axis version of steady-hand manipulation. A 3-axis force instrumented pic is under development. A multi-axis version of (8) is being implemented. Our immediate goal is to quantify the extent to which this type of robot/human augmentation improves microsurgical manipulation tasks.

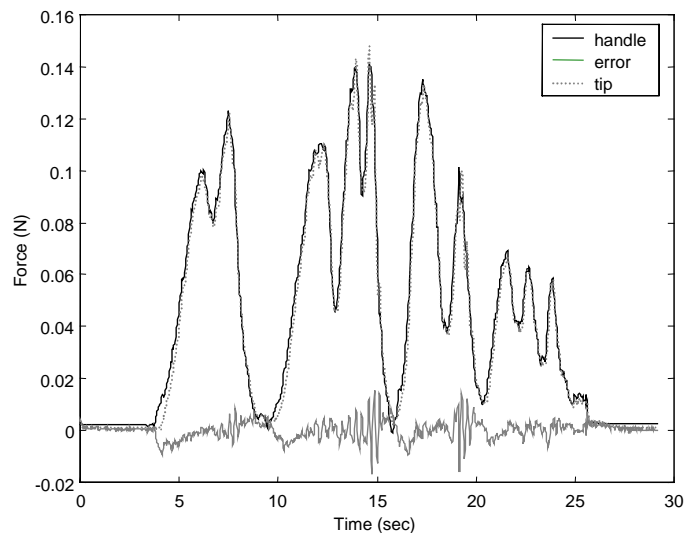


Figure 12: Steady-hand force scaling with porcine eye environment: Handle to tool tip force scaling ratio is 0.04 – a 25:1 ratio. Figure shows actual tool-tip force, scaled-down user haptic handle force, and force tracking error.

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