2010 American Control Conference
Marriott Waterfront, Baltimore, MD, USA
June 30-July 02, 2010

Robust Adaptive Control of a Micro Telemanipulation System Using Sliding Mode-Based Force Estimation

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Abstract— **Piezoelectric actuators are widely used in micro manipulation applications. However, hysteresis nonlinearity limits the accuracy of these actuators. This paper presents a novel approach for utilizing a piezoelectric nano-stage as the slave manipulator of a teleoperation system based on a sliding mode controller. The Prandtl-Ishlinskii (PI) model is used to model actuator hysteresis in feedforward scheme to cancel out this nonlinearity. The presented approach requires full state and force measurements at both the master and slave sides. Such a system is costly and also difficult to implement. Therefore, sliding mode unknown input observer (UIO) is proposed for full state and force estimations. Furthermore, the effects of uncertainties in the constant parameters on the estimated external forces should be eliminated. So, a robust adaptive controller is proposed and its stability is guaranteed through the Lyapunov criterion. Performance of the proposed control architecture is verified through experiments.**

I. INTRODUCTION

Telemanipulation defines the idea of a user interacting with and manipulating a remote environment and has led to applications ranging from space-based robotics to telesurgery [1]. Beside several applications of teleoperation systems, there is a new application area which is called macro-micro teleoperation. Man has restriction to sense or manipulate micro objects directly. Macro-micro teleoperation can enable human to manipulate tasks in micro world. Note that not all of these applications consider force feedback, though systems using force feedback are important in this work. In this paper, a piezoelectric-actuated stage was used as the slave manipulator of a macro–micro teleoperation system. A piezoelectric actuator is an excellent choice as a micro positioning actuator because of its high resolution, fast response and capability of producing high forces.

The hysteresis effect of piezoelectric actuators, which is revealed in their response to an applied electric field, is the main setback in precise position control [2]. In this study, a modified Prandtl–Ishlinskii (PI) model is applied and its inverse is used to cancel out the hysteresis effect in a feedforward scheme. Hysteresis-compensated model can be considered as a second order linear system [3].

One of the challenges associated with micro-teleoperation is the scaling between the human hand and micro parts. Fine motion control in teleoperation is generally achieved through position control with de-amplification from the master to the slave. Higher transparency is accomplished by tracking of scaled force of the slave on the master side. A method has been proposed to derive scaling factors based on Llewellyn's criterion [4].

The work presented here uses the position-force architecture, where the master sends its position and velocity to the slave side. The slave sends only the force exerted on it by the environment to the master. Comparing with the position-position architecture [5], this architecture provides perfect force tracking and avoids the reflection of large reaction forces, due to differences between the master and slave position in free motion, to the operator. Nevertheless, it requires force sensing at the slave side. From a performance point of view, the increased transparency of the position-force architecture motivates research into teleoperation systems where the forces are measured. However, force sensors are costly, can be unreliable, and provide noisy signals. Thus, this work develops an approach that has the benefits of a teleoperation architecture using force sensors, without the need to measure the forces. The unknown input observer for state estimation under unknown (non-white or non-Gaussian) inputs has been intensively studied recently [6].

In teleoperation systems, a robot has usually a control input and a force input applied to the robot by an external environment. The control input is clearly a known input, but without a force sensor, the external force input may be viewed as an unknown input. Thus, unknown input observers are used as external force estimators.

The disturbance identification algorithms are output feedback in nature and are based on the concept of inverse dynamics. Since the inverse of physical systems is usually noncausal, derivatives of the output signal will help the reconstruction of the disturbance input [7]. If the output signals are contaminated by noise, accurate output derivatives may be difficult to obtain. This has been a common problem for many output feedback disturbance observers. However, in the approach proposed in this work, only the position needs to be measured and derivatives of the output signals are no longer required.

Another problem is that a robust controller drops a portion of its performance to compensate for disturbances originated from parametric uncertainties. Furthermore, without eliminating the effects of uncertainties in the constant parameters, the unknown input observers estimate the external forces and the disturbances caused by uncertainties altogether. As a result, the external forces cannot be estimated correctly. To remedy this problem, a Lyapunov-

Manuscript received October 6, 2009.
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based robust adaptive controller is proposed in this article in order to adapt the uncertain parameters, improve the tracking transparency, and estimate the external forces accurately.

II. Macro-Micro Telemanipulation System

Fig. 1 shows the master-slave system for a micro telemanipulation setup. To design an efficient controller for this system the dynamics equations of motion of the teleoperation system are first derived.

A. Dynamic Modeling for the Master Robot

In this research the master is a 1-DOF manipulator which utilizes a DC servo motor. A load cell is installed on the shaft of the motor to measure the force exerted on the master. Dynamic model of the motor can be considered as,

$$j_m\ddot{x}_m(t) + b_m\dot{x}_m(t) + k_m x_m(t) = u_m(t) + L_m F_h(t) \tag{1}$$

where x_m denotes the rotation angle. j_m, b_m and k_m are moment of inertia, damping constant and spring constant, respectively. F_h is the force exerted by human operator and L_m is the effective length between the force and motor shaft. u_m is the control signal that is applied to the master robot.

B. Dynamic Modeling for the Slave Robot

The slave manipulator consists of a 1-DOF stage actuated by a piezo stack actuator. For the sake of precise positioning, a dynamic model which describes the hysteresis behavior should be developed. In many investigations, a second-order linear dynamics has been utilized for describing the system dynamics. As shown in Fig. 2, this model combines mass-spring-damper ratio with a nonlinear hysteresis function appearing in the input excitation to the system. The following equation defines the model,

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = H_F\big(v(t)\big) \tag{2}$$

where $x_s(t)$ is the salve position. m_s, b_s and k_s are mass, damping constant and spring constant, respectively. $H_F\big(v(t)\big)$ denotes the hysteretic relation between input voltage and excitation force. Piezoelectric actuators have very high stiffness, and consequently, possess very high natural frequencies. In low-frequency operations, the effects of actuator damping and inertia could be safely neglected. Hence, the governing equation of motion is reduced to the following static hysteresis relation,

$$x_s(t) = \frac{1}{k_s} H_F\big(v(t)\big) = H_x\big(v(t)\big) \tag{3}$$

Equation (3) facilitates the identification of the hysteresis function $H_F\big(v(t)\big)$. This is performed by first identifying the hysteresis map between the input voltage and the actuator displacement, $H_x\big(v(t)\big)$. It is then scaled up to k_s to obtain $H_F\big(v(t)\big)$. By inserting the force F_e, exerted by the environment, into the model, the dynamics of the slave manipulator can be written as follows,

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = k_s H_x\big(v(t)\big) - F_e \tag{4}$$

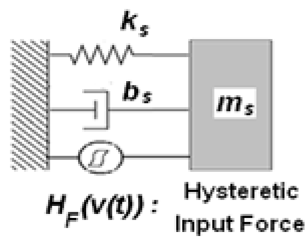

Fig.2. Equivalent dynamic model of the piezo actuator.

C. Hysteresis Modeling

In this paper, the PI model is utilized to cancel out hysteresis nonlinearity. It is known that the PI model consists of both play and stop operators [8]. Considering the difficulty of the determination of the parameters for PI model, the elementary operators of the simplified PI model are only backlash operators. The hysteresis can be described by a sum of weighted backlash operators with different thresholds and weight values. This model can approximate the hysteresis loop accurately and its inverse could be obtained analytically. Therefore, it facilitates the inverse feedforward control design. [9] proved that PI and inverse model of PI are Lipschitz continuous and thus input-output stable.

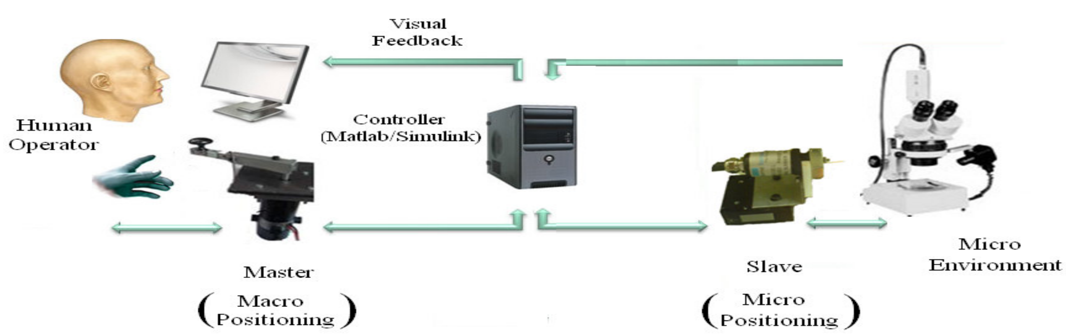

Fig.1. Micro telemanipulation setup.

D. *Feedforward Hysteresis Compensation*

The structure of inverse feedforward hysteresis compensation is shown in Fig. 3. The key idea of an inverse feedforward controller is to cascade the inverse hysteresis operator H_x^{-1} with the actual hysteresis represented by the hysteresis operator H_x. In this manner, an identity mapping between the desired actuator output $x_d(t)$ and actuator response $x(t)$ is obtained (Fig. 4).

The inverse of PI operator H_x^{-1} uses $x_d(t)$ as input and transforms it into a control input $v_{H_x^{-1}}(t)$ which produces $x(t)$ in the hysteretic system that closely tracks $x_d(t)$.

III. Unknown Input Sliding Mode Observer

Unknown input observers are useful when estimation is being performed for a plant that is subject to unknown disturbances [10]. In a classical observer these disturbances would affect the estimate of the state, but unknown input observers provide a framework to generate accurate state estimates despite the presence of disturbances. Consider a second order mass spring damper plant of the form,

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{k}{m}x_1 - \frac{b}{m}x_2 + \frac{1}{m}u + \frac{1}{m}F \\ y &= x_1 \end{aligned} \tag{5}$$

where m, b, and k are the mass, damping constant, and spring constant of the system, u represents a known input, and F represents an unknown input. A step by step sliding mode observer for this plant may be designed as [11],

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + \alpha_1 sgn(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 &= -\frac{k}{m}\hat{x}_1 - \frac{b}{m}\hat{x}_2 + \frac{1}{m}u + \alpha_2 sgn(\tilde{x}_2 - \hat{x}_2) \end{aligned} \tag{6}$$

where $\hat{x}_1$ and $\hat{x}_2$ are the estimate position and velocity, respectively, and $\tilde{x}_2 = \hat{x}_2 + (\alpha_2 sgn(x_1 - \hat{x}_1))_{eq.}$. The notation $(.)_{eq}$ is used to denote a low pass filtering operation on the discontinuous switching term to obtain the equivalent output injection [12]. The equivalent output injection is analogous to the notion of equivalent control in sliding mode control. The observer estimates will converge to the true states in finite time and the unknown input may also be obtained from the observer for large enough choices of the sliding gains α_1 and α_2.

IV. Problem Statement

Consider the following modified dynamics for the slave manipulator,

$$\begin{aligned} (\hat{m}_{s0} + \Delta m_s)\ddot{x}_s + (\hat{b}_{s0} + \Delta b_s)\dot{x}_s + (\hat{k}_{s0} + \Delta k_s)x_s \\ = u_s - F_e \end{aligned} \tag{7}$$

where $\hat{m}_{s0}$, $\hat{b}_{s0}$ and $\hat{k}_{s0}$ being approximate values of mass, damping constant and spring constant, respectively. Likewise, Δm_s, Δb_s and Δk_s are the parametric uncertainties of mass, damping constant and spring constant, respectively. u_s is the slave control input, and F_e is the force exerted on the slave by the environment.

Now, let us gather the parametric uncertainties, the unmodeled dynamics and the external disturbances all in one perturbation term. A robust control method can compensate the effect of this term for the sake of precision tracking. However, the external force cannot be decoupled from other disturbances when a disturbance observer is utilized.

Consequently, the disturbance observer estimates the external force and parametric uncertainties altogether. To solve this problem, a parameter adaptation law is used that includes the unknown parameters m_s, b_s and k_s. In this way, the parametric uncertainties will be no more included in the external force estimation.

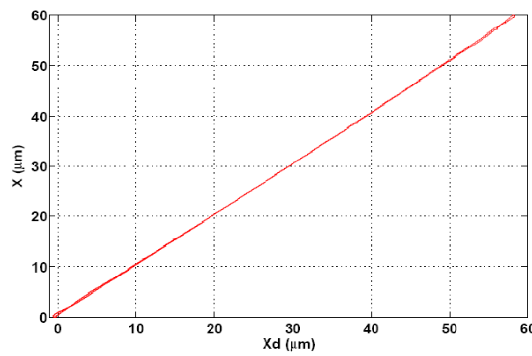

Fig. 4. x_d vs. x after compensation.

V. Adaptive Sliding Mode Control Design

In this section, an impedance controller is used at the master side to give the master manipulator a desired characteristic impedance. An adaptive sliding mode controller is developed at the slave side. By introducing unknown input sliding mode observers, the full state of both the master and slave as well as the external forces acting on each manipulator can be estimated by position measurements only. In this teleoperation approach, the goals involve ensuring that the slave manipulator position tracks the master position and remains stable. The master sends its position and velocity to the slave side. The slave sends only the force exerted on it by the environment to the master. e_1 and e_2 are defined as the master- slave position and velocity

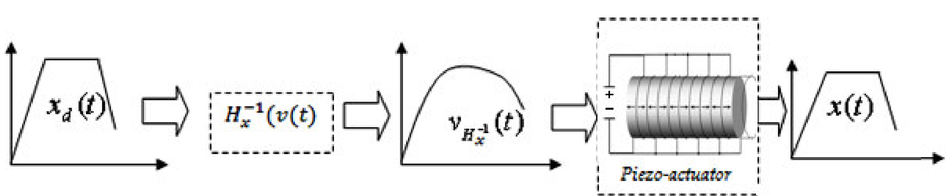

Fig.3. Inverse feedforward hysteresis compensation.

tracking errors, respectively,

$$e_1 = k_p x_{m1} - x_{s1}$$
$$e_2 = k_p x_{m2} - x_{s2} \tag{8}$$

where, x_{m1} is the master position, x_{m2} is the master velocity, x_{s1} is the slave position, and x_{s2} is the slave velocity. k_p is the position scaling factor. The master's position and velocity are transformed from rotational to linear units. The objective of the sliding mode control is to design asymptotically stable hyperplanes to which all system trajectories converge and slide along their path until the desired zones are obtained. To simultaneously satisfy tracking control and robustness requirements, the sliding hyperplane is selected as,

$$s = e_2 + \lambda e_1 = 0 \tag{9}$$

where $\lambda > 0$ is a control gain.

However, this work examines output feedback control. In order to estimate the master states and human input force, the following step by step sliding mode observer for the master side is proposed,

$$\dot{\hat{x}}_{m1} = \hat{x}_{m2} + \alpha_{m1} sgn(x_{m1} - \hat{x}_{m1})$$
$$\dot{\hat{x}}_{m2} = -\frac{k_m}{j_m}\hat{x}_{m1} - \frac{b_m}{j_m}\hat{x}_{m2} + \frac{1}{j_m}u_m + \alpha_{m2} sgn(\tilde{x}_{m2} - \hat{x}_{m2}) \tag{10}$$

where $\tilde{x}_{m2} = \hat{x}_{m2} + (\alpha_{m2} sgn(x_{m1} - \hat{x}_{m1}))_{eq.}$. α_{m1} and α_{m2} are sliding mode gains. The slave observer dynamics are as given,

$$\dot{\hat{x}}_{s1} = \hat{x}_{s2} + \alpha_{s1} sgn(x_{s1} - \hat{x}_{s1})$$
$$\dot{\hat{x}}_{s2} = -\frac{\hat{k}_s}{\hat{m}_s}\hat{x}_{s1} - \frac{\hat{b}_s}{\hat{m}_s}\hat{x}_{s2} + \frac{1}{\hat{m}_s}u_s + \alpha_{s2} sgn(\tilde{x}_{s2} - \hat{x}_{s2}) \tag{11}$$

where $\tilde{x}_{s2} = \hat{x}_{s2} + (\alpha_{s2} sgn(x_{s1} - \hat{x}_{s1}))_{eq.}$. α_{s1} and α_{s2} are sliding mode gains. $\hat{m}_s$, $\hat{b}_s$ and $\hat{k}_s$ are adapted values of slave's mass, damping constant and spring constant, respectively.

The master side impedance controller is expressed as,

$$u_m = \left(k_m - \frac{j_m}{\bar{J}_m}\bar{k}_m\right)\hat{x}_{m1} + \left(b_m - \frac{j_m}{\bar{J}_m}\bar{b}_m\right)\hat{x}_{m2} + \left(\frac{j_m}{\bar{J}_m} - 1\right)\hat{F}_h - \frac{j_m}{\bar{J}_m}.k_f.\hat{F}_e \tag{12}$$

where $\bar{J}_m$, $\bar{b}_m$ and $\bar{k}_m$ represent the desired moment of inertia, damping constant and spring constant, respectively. k_f is the force scaling factor. This control law is a modification of the master control law presented in [13] that makes use of the estimated plant states and forces. The estimated forces $\hat{F}_h$ and $\hat{F}_e$ are obtained from the sliding mode observers as follows,

$$\hat{F}_h = j_m(\alpha_{m2} sgn(\tilde{x}_{m2} - \hat{x}_{m2}))_{eq.}$$
$$\hat{F}_e = -m_s(\alpha_{s2} sgn(\tilde{x}_{s2} - \hat{x}_{s2}))_{eq.} \tag{13}$$

An output feedback version of the sliding surface is defined as,

$$\hat{s} = \hat{e}_2 + \lambda \hat{e}_1 = 0 \tag{14}$$

where

$$\hat{e}_1 = k_p \hat{x}_{m1} - \hat{x}_{s1}$$
$$\hat{e}_2 = k_p \hat{x}_{m2} - \hat{x}_{s2}. \tag{15}$$

Taking the time derivative of (14) yields,

$$\dot{\hat{s}} = \dot{\hat{e}}_2 + \lambda \dot{\hat{e}}_2 = k_p \dot{\hat{x}}_{m2} - \dot{\hat{x}}_{s2} + \lambda \hat{e}_2 = k_p \dot{\hat{x}}_{m2} + \lambda \hat{e}_2 + \frac{1}{m_s}(k_s \hat{x}_{s1} + b_s \hat{x}_{s2} - u_s - \alpha_{s2} sgn(\tilde{x}_{s2} - \hat{x}_{s2})) \tag{16}$$

Theorem: For the system described by (4), if the variable structure control law is given by,

$$u_s = \hat{m}_s\left(k_p \dot{\hat{x}}_{m2} + \lambda \hat{e}_2\right) + \hat{b}_s \hat{x}_{s2} + \hat{k}_s \hat{x}_{s1} + \rho_1 \hat{s} + \rho_2 sgn(\hat{s}) \tag{17}$$

where ρ_1 and ρ_2 are positive control gains, and the parameter adaptation laws are given by,

$$\hat{m}_s(t) = \hat{m}_{s0} + \frac{1}{c_1}\int_0^t \hat{s}(\tau)\left(k_p \dot{\hat{x}}_{m2}(\tau) + \lambda \hat{e}_2(\tau)\right)d\tau$$
$$\hat{b}_s(t) = \hat{b}_{s0} + \frac{1}{c_2}\int_0^t \hat{s}(\tau)\hat{x}_{s2}(\tau)d\tau$$
$$\hat{k}_s(t) = \hat{k}_{s0} + \frac{1}{c_3}\int_0^t \hat{s}(\tau)\hat{x}_{s1}(\tau)d\tau \tag{18}$$

with c_1, c_2, and c_3 being adaptation gains and $\hat{m}_{s0}$, $\hat{b}_{s0}$, and $\hat{k}_{s0}$ being approximate parameter values, then, asymptotically tracking of the system is guaranteed in the sense that $\hat{e}_1$ is bounded.

Proof: For analyzing the stability of the proposed control scheme, let us first define the following parametric error signals and take their time derivative to obtain,

$$\tilde{m}_s(t) = m_s - \hat{m}_s(t);\ \dot{\tilde{m}}_s(t) = -\dot{\hat{m}}_s(t)$$
$$\tilde{b}_s(t) = b_s - \hat{b}_s(t);\ \dot{\tilde{b}}_s(t) = -\dot{\hat{b}}_s(t)$$
$$\tilde{k}_s(t) = k_s - \hat{k}_s(t);\ \dot{\tilde{k}}_s(t) = -\dot{\hat{k}}_s(t) \tag{19}$$

Now, the positive definite Lyapunov function is selected as,

$$V = \frac{1}{2}\left(m_s \hat{s}^2 + c_1 \tilde{m}_s^{\ 2} + c_2 \tilde{b}_s^{\ 2} + c_3 \tilde{k}_s^{\ 2}\right) \tag{20}$$

The derivative of V with respect to time can be obtained as,

$$\dot{V} = m_s \hat{s}\dot{\hat{s}} + c_1 \tilde{m}_s \dot{\tilde{m}}_s + c_2 \tilde{b}_s \dot{\tilde{b}}_s + c_3 \tilde{k}_s \dot{\tilde{k}}_s \tag{21}$$

By substituting (16), (17) and (19) in (21) one can obtain,

$$\dot{V} = \tilde{m}_s\left(\hat{s}\left(k_p\dot{\hat{x}}_{m2} + \lambda\hat{e}_2\right) - c_1\dot{\hat{m}}_s\right) + \tilde{b}_s\left(\hat{s}\hat{x}_{s2} - c_2\dot{\hat{b}}_s\right)$$
$$+\tilde{k}_s\left(\hat{s}\hat{x}_{s1} - c_3\dot{\hat{k}}_s\right) - \rho_1\hat{s}^2 - \rho_2 sgn(\hat{s})\hat{s}$$
$$-\hat{s}\alpha_{s2}sgn(\tilde{x}_{s2} - \hat{x}_{s2}) \quad (22)$$

By taking the time derivatives of adaptation laws given by (18) and substituting them into (22), the coefficients of parametric error signals become zero. So,

$$\dot{V} = -\rho_1\hat{s}^2 - \rho_2 sgn(\hat{s})\hat{s} - \hat{s}\alpha_{s2}sgn(\tilde{x}_{s2} - \hat{x}_{s2})$$
$$= -\rho_1\hat{s}^2 - \rho_2|\hat{s}| - \hat{s}\alpha_{s2}sgn(\tilde{x}_{s2} - \hat{x}_{s2}) \quad (23)$$

If the condition $|\alpha_{s2}sgn(\tilde{x}_{s2} - \hat{x}_{s2})| \leq \rho_2$ is applied for all $t > 0$, then $-\rho_2|\hat{s}| \leq \hat{s}\alpha_{s2}sgn(\tilde{x}_{s2} - \hat{x}_{s2})$, and this leads to,

$$\dot{V} \leq -\rho_1\hat{s}^2 \leq 0 \quad (24)$$

(24) depicts that time derivative of the positive definite Lyapunov function V is negative definite. Thus stability of the system is guaranteed. Essentially (24) states that the squared distance to the sliding surface, as measured by $\hat{s}^2$ decreases along all system trajectories. Chattering phenomena is the main problem of sliding mode control and must be eliminated for the controller to perform properly. For this purpose, instead of utilizing low pass filters, controller discontinuity can be smoothed out by replacing the hard switching term $sgn(\hat{s})$ with a softer switching method using the saturation function $sat\left(\hat{s}/\varphi_s\right)$, where φ_s is boundary layer thickness. Therefore, the control law (17) can be written as,

$$u_s = \hat{m}_s\left(k_p\dot{\hat{x}}_{m2} + \lambda\hat{e}_2\right) + \hat{b}_s\hat{x}_{s2} + \hat{k}_s\hat{x}_{s1}$$
$$+\rho_1\hat{s} + \rho_2 sat(\hat{s}/\varphi_s) \quad (25)$$

The same soft switching approach is applicable to sliding mode observers, as well.
One can also prove the finite time convergence of the state estimates to the true states and the availability of the environmental force estimate. However, this proof is omitted here due to space constraints.

VI. EXPERIMENTAL RESULTS

In this section, the experimental results of the macro-micro teleoperation system are presented.

A. *Experimental setup*

As shown in Fig. 5, a Physik Instrumente PZT-driven nanopositioning stage (PI 611.1s) with high resolution strain gage position sensor is used as the slave manipulator. The E500 module includes E501 piezo driver, and E503 strain gage amplifier which carry out experimental data. A rigid needle is mounted on the stage. A hi-precision load cell is used to measure the environmental force. A dSpace1104 board is used as the interface element between MATLAB Real-Time Workshop and equipments. The controllers are developed in Simulink and implemented in real time using MATLAB Real-Time Workshop and through Control Desk software. To effectively implement the controller, the sampling frequency is set to $10\,KHz$. The master manipulator consists of a DC servo motor which is equipped with a high resolution encoder. A load cell is installed on the motor shaft to measure the force exerted on the master (Fig. 6). A Digital Motor Controller is used for driving the DC servomotor.

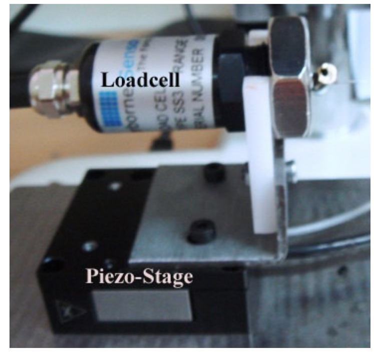

Fig.5. Nanopositioning stage as the slave robot.

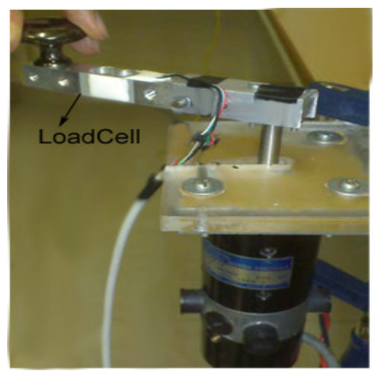

Fig.6. DC-servo motor as the master manipulator.

B. *Results*

For verification of the proposed controllers and observers, human operator manipulates the master end-effector to generate a desired position trajectory. The human desired trajectory is then transferred to the slave side with position scaling gain $k_P = \frac{1e^{-5}}{2\pi}$, such that with the master rotating 360°, the piezo-stage moves $100\,\mu m$.
The motion of the slave end-effector contains two stages:
1) Free motion when the slave end-effector does not contact with the environment.
2) Interaction stage, when the end-effector exerts an interaction force on the external environment and also moves forward. The contact force is then transferred to the master side with force reflecting gain $k_f = 100$.

After contact, the end-effector moves forward. It then keeps the master position for some seconds before returning to the home position. Figs. 7 and 8 show the experimental results for position and force tracking, respectively. The proposed scheme shows good tracking performance. In spite of contact with the environment, the slave can still track the master's desired position (Fig.7), while force reflected back to the master side is increasing (Fig. 8). The controllers are capable of achieving both position tracking and force tracking. Since the operator tries to keep the master in a fixed position, hand chattering is inevitable. This leads to a noisy force signal (Fig. 8).

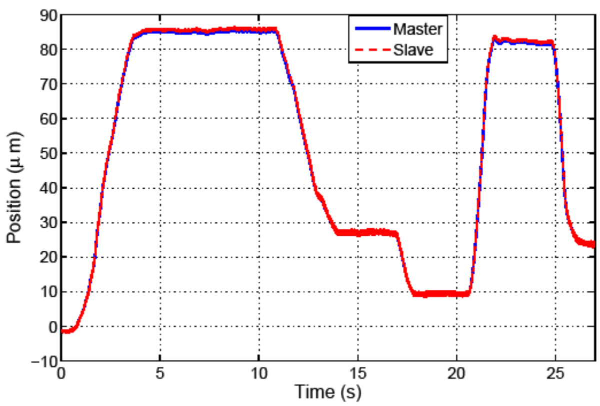

Fig. 7. Scaled Master/ Slave position signals.

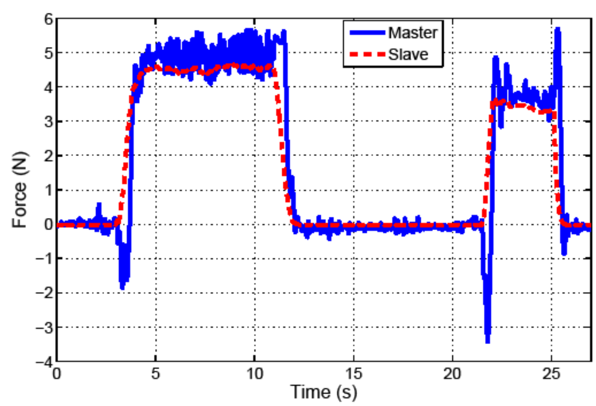

Fig. 8. Master/ Scaled Slave force signals.

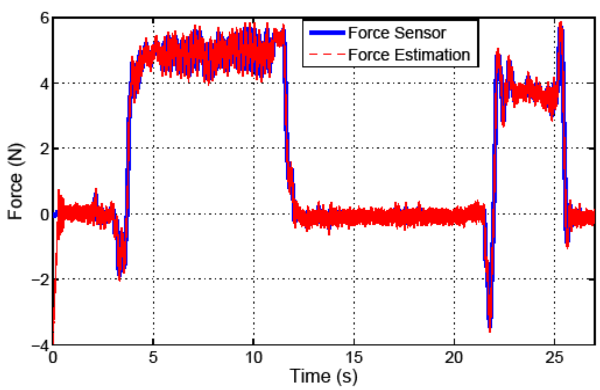

Fig. 9. Actual/Estimated human force.

The human force and its estimate are shown in Fig. 9. This figure depicts that the master force observer gives an accurate estimate of the actual human force. Likewise, the environmental force exerted on the slave is estimated accurately. To select the gains in the adaptation laws, a number of trial and error experiments are required. Table I shows the selected gains.

TABLE I
GAINS OF ADAPTATION LAWS AND SLIDING MODE CONTROLLER

c_1	c_2	c_3	ρ_1	ρ_2	λ
100	5×10^{-6}	8×10^{-7}	800	300	500

VII. CONCLUSIONS

In this paper, a macro-micro teleoperation was implemented using a piezoelectric actuator as the slave manipulator. An inverse model-based feedforward controller was then proposed and implemented to compensate the hysteresis of the piezoelectric actuator. Instead of using force sensors, sliding mode unknown input observers were utilized to estimate the human and environmental forces. An adaptive sliding mode control scheme was proposed to eliminate the adverse effects of parametric uncertainties and ensure perfect position tracking and accurate force estimation. The experimental results verified the validity of the proposed approaches; human and environmental forces were estimated accurately and precision tracking of master and slave were achieved, as well.

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