**Control and Cybernetics**

vol. **38** (2009) No. 3

# Robust impedance control of a piezoelectric stage under thermal and external load disturbances*

by

**Mohammad Zareinejad[1], Seyed Mehdi Rezaei[1], Saeed Shiry Ghidary[2], Amir Abdullah[1] and Mohammad Motamedi[1]**

[1] Department of Mechanical Engineering, Amirkabir University
Tehran, Iran

[2] Department of Computer Engineering, Amirkabir University
Tehran, Iran

**Abstract:** Piezoelectric actuators are widely used in micromanipulation tasks such as atomic force microscopy and cell manipulation. However, the hysteresis nonlinearity and the creep reduce their fidelity and cause difficulties in the micromanipulation control procedure. Besides, variation of temperature and external loads could change the model parameters identified for the piezo actu-ator. In this paper, a novel feedforward-feedback controller is proposed. The modified Prandtl-Ishlinskii model is utilized to linearize the actuator hysteresis in feedforward scheme and a sliding mode based impedance control with perturbation estimation is used to cancel out the thermal and external load disturbances in feedback scheme. The efficiency of the proposed controller is verified by experiments.

**Keywords:** piezoelectric actuator, sliding mode, impedance control, hysteresis.

## 1. Introduction

Piezoceramics hold great promise for smart sensors and actuators in a variety of applications. Micro manipulation, civil structures, aerospace, machine tools and bio-medical systems for im-proving performance and augmenting stability are examples. It is well known that a piezoelectric actuator has many advantages such as: (1) no moving parts; (2) capacity of producing large forces; (3) almost unlimited resolution; (4) high efficiency; (5) fast response. The major limitation of piezoceramic actuators is their nonlinear hysteretic behavior, leading to performance degradation in precision positioning applications, Ge (1969). The maximum error due to hysteresis is found to be as much as 10-15% of the path

*Submitted: October 2008; Accepted: May 2009.

covered if the actuators are run in an open-loop fashion. This error affects system performance in general and is particularly undesirable for structural shape control purposes. Reliable predictions of system output taking into account the hysteresis characteristics would be a proper tool when the piezoceramic actuators are employed as part of a closed loop system for purposes of motion and position control.

To deal with the effect of hysteresis, feedforward and feedback techniques have been proposed. In the open-loop technique (feedforward), a model with high precision is needed in order to model the hysteresis. The key idea of a feedforward controller is to cascade the inverse of the hysteresis model with the actual hysteretic plant. In this manner, an identity mapping between the desired output and actuator response can be provided.

Preisach (Ge and Jouaneh, 1995; Hughes and Wen, 1997; Gorbet, Morris and Wang, 2001), and Prandtl-Ishlinskii (Krejci and Kuhnen, 2001) are the well-known feedforward models. Implemen-tation complexity is the major setback of the Preisach model. Prandtl-Ishlinskii (PI) is less com-plex and its inverse can be computed analytically. Identification of PI model is performed for a single loop. Therefore, in feedforward scheme, any deviation from the identified loop leads to hysteresis compensation error. Hysteresis loop deviation due to external disturbances is investigated in this paper.

In this study a modified PI model (see Kuhnen and Fabio, 2003) is applied and its inverse is used to cancel out the hysteresis effect. The nonlinear piezoelectric actuator is linearized using feedfor-ward inverse hysteresis. The linearized uncertain model is used to design the controller (Bashash and Jalili, 2007). To deal with the influence of parametric uncertainties, external disturbance effects and PI identifi-cation error, a perturbation term is considered in linearized model. For proper trajectory tracking, a sliding mode based impedance control with perturbation estimation is proposed. In order to evaluate the proposed approach, performance of the piezoelectric actuator in trajectory tracking under thermal and load disturbances is investigated.

## 2. Piezo stage and hysteresis modeling

### 2.1. Dynamic modeling for the piezo stage

The piezo stage consists of a 1-DOF stage actuated by a piezo stack actuator. Development of a dynamic model, describing hysteretic behavior is very important for improvement of control per-formance of the piezo-positioning mechanism. In many investigations, second-order linear dynamics has been utilized for describing system dynamics. As shown in Fig. 1, this model combines mass-spring-damper ratio with a nonlinear hysteresis function, appearing in the input excitation to the system.

Following equation defines the model:

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = H_F(v(t)) \tag{1}$$

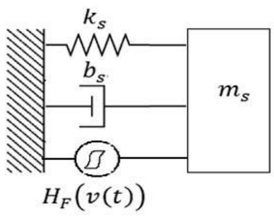


Figure 1. The piezoelectric actuator

where $x_s(t)$ is the stage position, $m_s$, $b_s$ and $k_s$ are stage mass, viscous coefficient and stiff-ness, respectively, and $H_F(v(t))$ denotes the hysteretic relation between input voltage and excitation force.

Piezoelectric actuators have very high stiffness, and so 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 be-tween the input voltage and actuator displacement:

$$x_s(t) = \frac{1}{k_s} H_F(v(t)) = H_x(v(t)) \quad \{m_s\ddot{x}_s(t) \ll b_s\dot{x}_s(t) \ll k_s x_s(t)\}. \tag{2}$$

Equation (2) facilitates the identification of the hysteresis function $H_F(v(t))$ between the input voltage and the excitation force. This is performed by first identifying the hysteresis map between the input voltage and the actuator displacement, $H_x(v(t))$. It is then, scaled up to $k_s$ to obtain.

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) + k_s H_x(v(t)). \tag{3}$$

To consider the influence of parametric uncertainties, unmodeled dynamics and identification error, a perturbation term is added to the stage model. Thus, model (1) can be rewritten as:

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s = H_F(v(t)) + P(t) = k_s H_x(v(t)) + P(t). \tag{4}$$

To consider the interaction with environment, the force $F_\epsilon$ exerted by the environment is inserted into the model. Therefore, the dynamic model of piezo stage can be written as follows:

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = k_s H_x(v(t)) + P(t) - F_\epsilon \tag{5}$$

### 2.2. Hysteresis modeling

We use the Prandtl-Ishlinskii (PI) model to cancel out hysteresis nonlinearity. It is known that the PI model consists of both play and stop operators, Kuhnen and Fabio (2003). 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 approx-imate the hysteresis loop accurately and its inverse could be obtained analytically. Therefore, it facilitates the inverse feedforward control design.

Graphically, the inverse is the reflection of the resultant hysteresis loop about the 45° line. Kuhnen and Fabio (2003) proved that PI and inverse PI are Lipschitz continuous and thus input-output stable.

### 2.2.1. Feedforward hysteresis compensation

The structure of inverse feedforward hysteresis compensation is shown in Fig. 2. 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. 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.

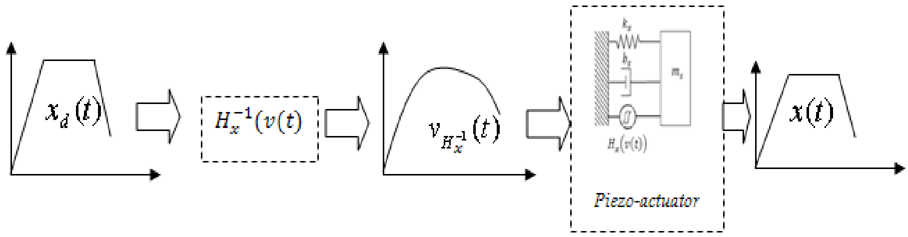


Figure 2. The feedforward inverse control

## 3. The temperature effect analysis

In the temperature effect analysis, two effects must be considered:

A. *Linear thermal expansion*: Thermal stability of piezoceramics is better than that of most other materials. Actuators and positioning systems consist of a combination of piezoceramics and other materials and their overall behavior differs accordingly.

B. *Temperature dependency of the piezo effect*: Piezo translators work in a wide temperature range. The piezo effect in PZT ceramics is known to function down to almost zero Kelvin. But the magnitude of the piezo coefficients is temperature dependent. Also, the closed-loop piezo positioning systems are less sensitive to temperature changes than open-loop systems. Optimum accuracy is achieved if the operating temperature is identical to the calibration temperature. At liquid helium temperature, piezo gain drops to approximately 10–20% of its room temperature value which causes a displacement error of more than $10\mu m$ in the micromanipulation system.

It is well known that as the temperature increases, the creep is amplified. For the representation of this phenomenon in the piezoelectric actuator, a step voltage is applied and the displacement is monitored for about four minutes. As shown in Fig. 3, the creep is considerably amplified. This behavior decreases the accuracy of the micro-positioning system.

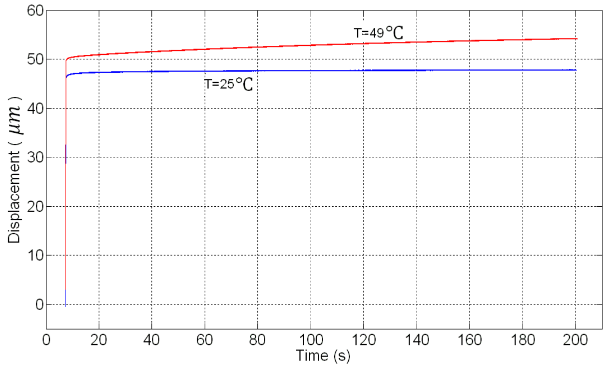


Figure 3. The effect of thermal disturbance on creep

Temperature variation affects hysteresis as well. To observe that, a sine voltage of 60 of amplitude is applied to the piezoelectric actuator. The resultant hysteretic loops are plotted for two temperatures (T = 26°C and T = 55°C). Fig. 4 shows how temperature variations affect hysteretic behavior.

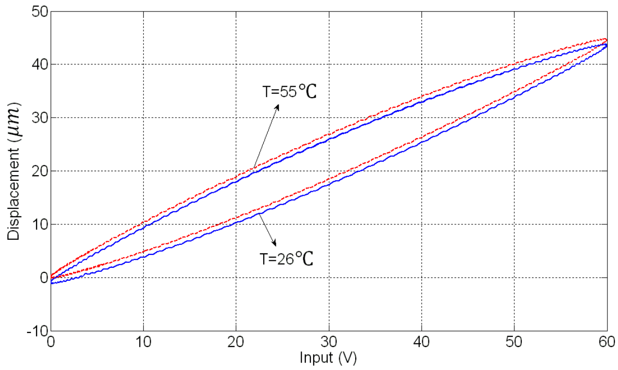


Figure 4. The effect of thermal disturbance on hysteresis

*Effect of load on the hysteresis loop*

Fig. 5 depicts experimental voltage-to-displacement hysteresis in a PEA when the external mechanical load changes according to Fig. 6. As shown in

Fig. 5, external mechanical load affects the inclination of the hysteresis curve. The effect of the load on the hysteresis curve obviously increases as the load increases.

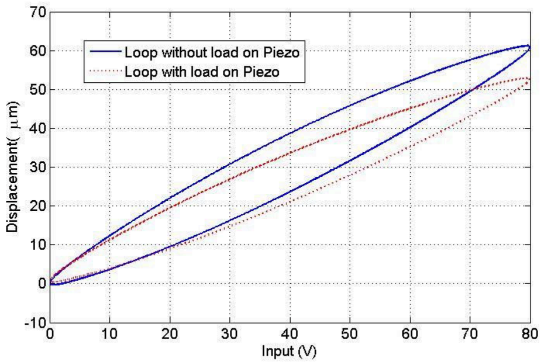


Figure 5. The effect of load applied to the piezo stage on the shape of hysteresis loop

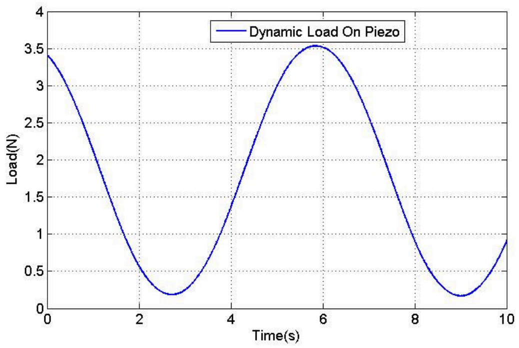


Figure 6. Dynamic load signal applied the piezo stage

## 4. Impedance control for the piezoelectric actuator with sliding mode based perturbation estimation

### 4.1. Impedance control

Control of manipulators interacting with their environment has received considerable attention. The most efficient method of controlling interaction between a manipulator and its environment is impedance control. It enables to regulate response properties of the manipulator to external forces by modifying the mechanical impedance parameters. In position-based impedance control, the impedance controller alters the position for any force applied to the manipulator end-point. The control problem is to asymptotically drive the system state to implement the target impedance (6).

The desired dynamic for the piezo stage is considered as follows:

$$\bar{m}_s\ddot{\tilde{x}}(t) + \bar{b}_s\dot{\tilde{x}}(t) + \bar{k}_s\tilde{x}(t) = -F_\epsilon \tag{6}$$

where $\bar{m}_s$, $\bar{b}_s$ and $\bar{k}_s$ are the desired mass, viscous damping coefficient and stiffness of piezo-actuator, respectively; $\tilde{x}(t) = x_s - x_d$ is position error and $x_d$ is desired trajectory. The control law for the piezo stage is obtained by combining (6) and (1):

$$\begin{aligned} u_s(t) = H_F^{-1}\Big\{ & -\frac{m_s}{\bar{m}_s}[b_s\dot{\tilde{x}}(t) + k_s\tilde{x}(t) + F_\epsilon(t)] \\ & +F_\epsilon(t) + b_s\dot{x}_s(t) + k_s x_s(t) + m_s\ddot{x}_d - P_{est}\Big\} \end{aligned} \tag{7}$$

To deal with the influence of parametric uncertainties, unmodeled dynamics and PI identification error, estimation of perturbation term $P_{est}$ is added to the piezo stage model. In next section the procedure for estimation of $P_{est}$ is presented.

### 4.2. Perturbation estimation

Elmali and Olgac (1992, 1996) proposed a perturbation estimation scheme, embedded in the traditional Sliding Mode Control (SMC) design. The main advantage of this methodology is that a priori knowledge of the upper-bounds of perturbation is not required. The general class of nonli-near dynamics is considered as:

$$x^{(n)} = f(x) + \triangle f(x) + [B(x) + \triangle B(x)]u + d(t) \tag{8}$$

where $X_i = [x_i, \dot{x}_i, ..., x_i^{(n-1)}]^T \varepsilon R^n$, $i = 1, 2, ..., m$ is the state subvector and $x_i$, $i = 1, 2, ..., m$ are independent coordinates; $\triangle B(x)$ is perturbation of control gain and $d(t)$ is system disturbance vector. Perturbations and disturbance are gathered into a variable named perturbation vector:

$$\psi(X,t)_{actual} = \triangle f(x) + \triangle B(t)u + d(t). \tag{9}$$

If all the components in the dynamics show slower variations with respect to the loop closure (or sampling) speed, $\psi(X,t)$ can be estimated as:

$$\psi(X,t)_{estimated} = x^{(n)}_{calculated} - f - Bu(t-\delta) \tag{10}$$

where $\delta$ is the control interval or sampling time in the digital controller. In practice, sampling time is selected high enough to ensure $u(t) = u(t-\delta)$. As shown in (10), the class of perturbation estimators is based on the simple intuition that if all the states are available, the perturbation of the plant can be effectively estimated using the nominal model and one step delayed input signals. Additionally, in the absence of measurements of $x^{(n)}$, the approximation used is

$$x^{(n)} = \frac{x^{(n-1)}(t) - x^{(n-1)}(t-\delta)}{\delta} \tag{11}$$

### 4.3. Sliding mode based impedance control for piezo stage using perturbation estimation

A modified version of system (1) could be written as:

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = H_F(v(t)) + P_{est}(t) - \tilde{P}(t) \tag{12}$$

where $\tilde{P}(t) = P_{est}(t) - P(t)$ is the error signal between the system perturbation and its estima-tion. Based on the perturbation estimation technique, an estimation of the perturbation function given in (12) is obtained as:

$$P_{est}(t) = m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) - H_F(v(t-\delta)). \tag{13}$$

Substituting $H_F(v(t))$ by $k_s H_x(v(t))$, using (4), one can obtain:

$$P_{est}(t) = m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) - k_s H_x(v(t-\delta)). \tag{14}$$

Sliding surface can be defined as follows:

$$s(t) := \frac{1}{\bar{m}_s}\int_0^t I_e(t)dt \tag{15}$$

where $I_e$ is the impedance error, that is:

$$I_e : \ddot{m}_s\dot{\tilde{x}}(t) + b_s\dot{\tilde{x}}(t) + \bar{k}_s\tilde{x}(t) - (-F_e(t)). \tag{16}$$

THEOREM 1 *For the system described by (5), if the control law is given by:*

$$v(t) = u_s(t) = H_F^{-1}\Big\{\frac{m_s}{\bar{m}_s}[b_s\dot{\tilde{x}}(t) + k_s\tilde{x}(t) + F_e(t)] + F_e(t) + b_s\dot{x}_s(t) + k_s x_s(t) + m_s\ddot{x}_d - \gamma sgn(S) - \lambda S - P_{est}\Big\} \tag{17}$$

*where $sgn(.)$ represents the sign function and $\gamma$ and $\lambda$ are the positive scalars, then asymptotical tracking of the system is guaranteed.*

*Proof.* For analyzing the stability of the proposed control scheme, a Lyapunov function candidate is defined as:

$$V = \frac{S^2}{2} \tag{18}$$

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

$$\dot{V} = S\dot{S} \tag{19}$$

By substituting (16) in (15) one can obtain:

$$\dot{V} = S\dot{S} = S\left[\ddot{\tilde{x}}(t) + \frac{\bar{b}_s}{\bar{m}_s}\dot{\tilde{x}}(t) + \frac{1}{\bar{m}_s}(\bar{k}_s\tilde{x}(t) + F_e(t))\right] \tag{20}$$

Utilizing (12) for substituting $\ddot{\tilde{x}}(t) = \ddot{x}_s - \ddot{x}_d$ in (20), yields:

$$\begin{aligned}\dot{V} =& S\left[-\ddot{x}_d + \frac{\bar{b}_s}{\bar{m}_s}\dot{\tilde{x}}(t) + \frac{1}{\bar{m}_s}(\bar{k}_s\tilde{x}(t) + F_e(t))\right] \\ &+ \frac{1}{m_s}[-b_s\dot{x}_s - k_s x_s + H_F(v(t)) + P_{est} - F_e - \tilde{P}(t)]\end{aligned} \tag{21}$$

Substituting $v(t)$ from (17) in (21) yields:

$$\dot{V} = S\dot{S} = S = -\frac{\lambda}{m_s}S^2 - \frac{1}{m_s}\gamma|S| - \frac{\tilde{P}(t)}{m_s}S \tag{22}$$

If the gain $\gamma$ is selected such that condition $\gamma > |\tilde{P}(t)|$ is satisfied, (22) leads to:

$$\dot{V} \le -\frac{\lambda}{m_s}S^2 \le 0. \tag{23}$$

Equation (22) shows that time derivative of the positive definite Lyapunov function $V$ is negative definite. Thus, stability of the system is guaranteed. Essentially, (23) states that the squared distance to the sliding surface, as measured by $S^2$ 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, controller discontinuity can be smoothed out by using a superposition function $sat(S/\varphi)$ instead of $sgn(S)$, where $\varphi$ is boundary layer thickness. Therefore, control law (17) can be rewritten as follows:

$$\begin{aligned}u_s(t) = H_F^{-1}\Big\{&\frac{m_s}{\bar{m}_s}[b_s\dot{\tilde{x}}(t) + k_s\tilde{x}(t) + F_e(t)] + F_e(t) + b_s\dot{x}_s(t) + k_s x_s(t) \\ &+ m_s\ddot{x}_d - \gamma sat(^S/_\varphi) - \lambda S - P_{est}\Big\}\end{aligned} \tag{24}$$

To achieve a good tracking and chattering free control signal, the desired impedance and controller parameters for the piezo stage are chosen as shown in Table 1.

Notice that (16) requires acceleration measurement. To deal with this measurement noise, accele-ration and velocity are estimated, by a linear observer, introduced in the next section.

Table 1. Piezo stage impedance parameters

| | | | |
|---|---|---|---|
| $\bar{m}_s$ | 0.8 kg | $m_s$ | 2.17 kg |
| $\bar{b}_s$ | 5 N.s/m | $b_s$ | 1078 N.s/m |
| $\bar{k}_s$ | 1e$^5$ N/m | $k_s$ | 3e$^5$ N/m |
| $\lambda$ | 0.3 | $\gamma$ | 250 |
| $\varphi$ | 0.05 | | |

### 4.4. Velocity and acceleration observer

Consider the observable system (25) and (26) described in state space:

$$\dot{x} = Ax + Bu \tag{25}$$

$$y = Cx \tag{26}$$

where $x \in R^n$ denotes the state of the system, $y$ is the measured output, $u$ is the control input, $B \in R^{nxn}$, contains system parameters and $C \in R^{mxn}$ is used to select the $m$ outputs (see Kailath, 2000). The state x of (25) can be estimated by means of linear observers. A full order linear ob-server is designed as follows:

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}) \tag{27}$$

$$\hat{y} = C\hat{x} \tag{28}$$

where $\hat{x}$, $\hat{y}$ denote the estimated state and the estimated output, $L \in R^n$ is the observer gain vector that can be chosen such that the polynomial characteristic of $(A - LC)$ is Hurwitz. Substituting for the output vector, we obtain the differential equation describing the observer error $\dot{e}$, which is given by:

$$\dot{e} + (A - LC)e \dot{=} \bar{A}e \tag{29}$$

To prove that the estimation error tends to zero asymptotically let us consider (29) together with the following Lyapunov equation:

$$P\bar{A} + \bar{A}^T P = -Q$$

where $P$ and $Q$ are positive definite symmetric matrices, with the Lyapunov candidate function $v = \frac{1}{2}e^T Pe$ whose time derivative is:

$$\dot{V} = 2e^T P\dot{e} = 2e^T P\bar{A}e = e^T P\bar{A}e + e^T \bar{A}^T Pe = -e^T Qe \leq -\lambda_{min} Q||e||^2 \tag{30}$$

From (30), it is obvious that the estimation error tends asymptotically to zero. Considering the piezo-stage, $x_s$ is the measured output. In this manner, with an appropriate choice of, $\hat{x}_s \to x_s$ and $\dot{\hat{x}}_s \to \dot{x}_s$ $at\ t \to \infty$.

## 5. Experimental setup

A PZT-driven nanopositioning stage with high resolution strain gage position sensor was used to perform the experiments. The E500 Module includes E501 Piezo driver and E503 Strain gage amplifier to realize experimental data. A rigid adjustable end effector is mounted on the stage. A load cell is used to measure external force. A data acquisition controller (dSPACE 1104) board is used as interface element between MATLAB Real Time Workshop and the equipment. The con-trollers are developed in Simulink and implemented in real-time using MATLAB Real Time Workshop and through Control Desk software. A Heater is used to change the environment tem-perature between 25 and 60°C. A $T40$ sensor is also utilized for temperature monitoring (Fig. 7).

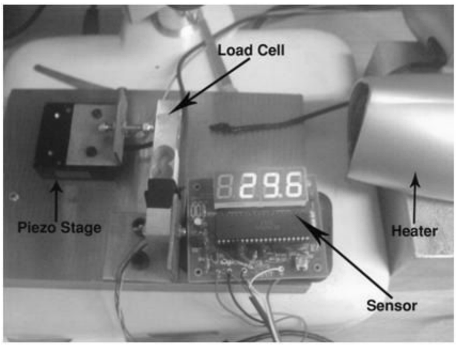


Figure 7. The experimental setup

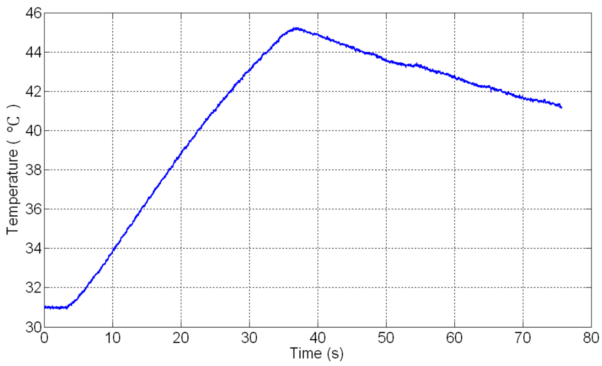


Figure 8. The temperature variation

## 6. Experimental results

Environment temperature was increased from 31°C to 45°C and then reduced to 41°C in 75 seconds (Fig. 8).There is a space between the piezo stage and the load cell. Hence, when the alter-native input signal is applied, the piezo stage contacts the load cell intermittently and generates an alternative force (Fig. 9). In Fig. 10a, the tracking of the reference signal by the proposed controller is shown for temperature of 45°C. The tracking error is plotted in the same figure. The tracking of the reference signal by the PID controller is also investigated and the tracking error is calculated (Fig. 10b).The results show that via utilizing the proposed robust controller, the tracking error decreases noticeably. Table 2 shows the measured performances of the PID and the proposed controllers in tracking of the desired trajectory. Fig. 11 shows performance of the proposed controller in higher frequency trajectory tracking.

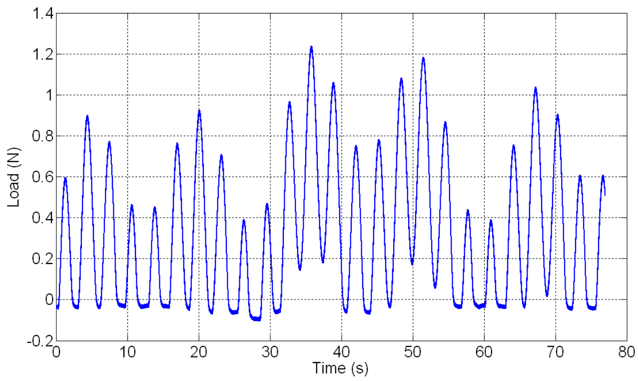


Figure 9. The external load variation

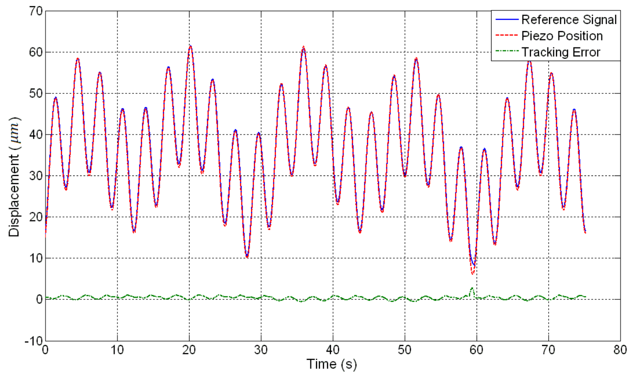


Figure 10a. Tracking of the reference signal by the proposed controller

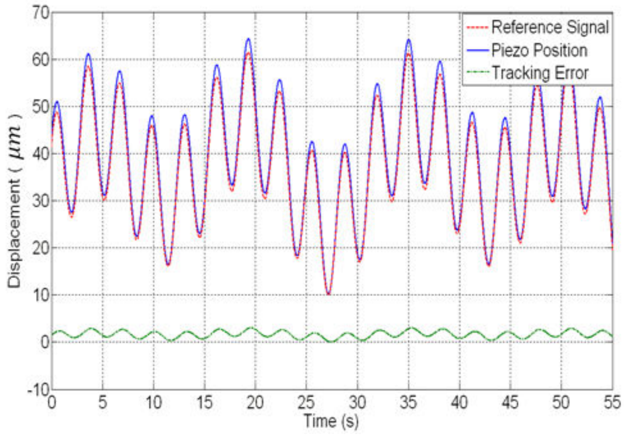


Figure 10b. Tracking of the reference signal by the PID controller

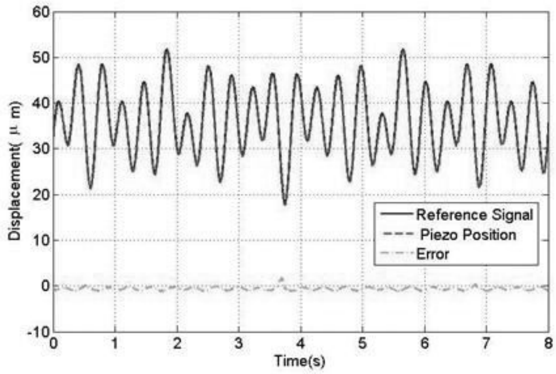


Figure 11. Tracking of a higher frequency reference signal by the proposed controller

Table 2. Performance of the PID and the proposed controllers

| *Controller* | $e_{\max(\mu m)}$ | $RMS(\mu m)$ |
|---|---|---|
| *PID* | 3.1 | 1.76 |
| *Proposed Controller* | 1.5 | 0.35 |

## 7. Conclusion

Hysteresis is the main drawback of using piezoelectric actuators in precision positioning applica-tions. Moreover, environmental temperature and external load variations worsen also the accuracy of a micromanipulation system. In this paper, the Prandtl-Ishlinskii model is used for the actuator hysteresis in feed-forward scheme to cancel the hysteretic nonlinearity. A robust controller is also utilized in a feedback manner to compensate for the thermal and external load disturbance effects. By implementation the proposed controller, the required tracking performance in micromanipulation is fulfilled.

## References

Bashash, S. and Jalili, N. (2007) Robust multiple frequency trajectory tracking control of piezoelec-trically driven micro/nanopositioning systems. *IEEE Trans. Control Syst. Technol.* **15** (5) 867-878.

Elmali, H. and Olgac, N. (1992) Sliding mode control with perturbation estimation (SMCPE): A new approach. *Int. J. Control* **56**, 923–941.

Elmali, H. and Olgac, N. (1996) Implementation of sliding mode control with perturbation estima-tion (SMCPE). *IEEE Trans. Control Syst. Technol.* **4** (1) 79–85.

Ge, P. and Jouaneh, M. (1995) Modeling hysteresis in piezoceramic actuators. *Precision Engineering* **17** (3) 211-21.

Ge, P. and Jouaneh, M. (1996) Tracking control of a piezoceramic actuator. *IEEE Trans. Control Syst. Technol.* **4** (3) 209-215.

Ge, P. and Jouaneh, M. (1997) Generalized Preisach model for hysteresis nonlinearity of piezoelec-tric actuators. *Precision Engineering* **20**, 99-111.

Hughes, D. and Wen, J.T. (1997) Preisach modeling of piezoceramic and shape memory alloy hysteresis. *Smart Mater. Struct.* 287-300.

Gorbet, R.B., Morris, K.A. and Wang, D.W.L. (2001) Passivity-based stability and control of hysteresis in smart actuators. *IEEE Transactions Control Syst. Technol.* **9**.

Kailath, T., Sayed, A.H. and Hassibi, B. (2000) *Linear Estimation.* Prentice Hall, New Jersey.

Krejcí, P. and Kuhnen, K. (2001) Inverse Control of Systems with Hysteresis and Creep. *IEE Proceedings Control Theory and Applications.*

Kuhnen, K. and Fabio, P. (2003) Modeling, identification and compensation of complex hysteretic nonlinearities: A modified Prandtl-Ishlinskii approach. *European Journal of Control*, 407-421.