Inverse Control of a Piezoelectric Actuator for Precise Operation of a Micro-motion Stage

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Abstract

The inverse control of a piezoelectric actuator for precise tracking operation of a three degree of freedom (DOF) micro-motion stage is presented in this paper. This stage, which provides translational motion in X and Y directions and rotation about the Z-axis, is actuated using three stack type piezoelectric actuators. Although capable of resolution in micrometres to sub-nanometres, the actuators exhibit a significant amount of hysteresis and creep, which may lead to substantial errors if the stage was used in a tracking application. Thus, for the stage to provide precise operation, it is necessary to mitigate the effects due to hysteresis and creep. To minimize these effects, an inverse, feed-forward, control strategy is presented in this paper. Experimental results are presented to display the effectiveness of this control strategy in precise operation of the stage over a wide band of amplitudes and frequencies.

1 Introduction

A piezoelectric actuator is formed of ceramic material, which is ferroelectric in nature; a property that causes expansion or contraction of the actuator when a input signal is applied. The resolution of a piezoelectric actuator is dependent only on the amount of the disturbance noise in the input signal and the resolution of a sensor used to measure the resulting displacement. Other than being highly efficient and compact in size, which leads to low power consumption, a piezoelectric actuator is capable of micrometre / sub-nanometre resolution in displacement, has high stiffness, provides fast response times and high force output and, therefore, has been commonly used in many applications, such as the three degree of freedom (DOF) mobile robotics [Yan et al., 2006], fuel flow control in internal combustion engines [Rauznitz et al., 2006] and for vibration cancellation in disk drives [Ma and Ang, 2000].

Piezoelectric actuators have also been used to actuate micro-motion stages, which have been used to position scanning tunnelling microscopes (STM) [Wiesendanger, 1994] and atomic force microscopes (AFM) [Croft et al., 2001], to position samples in scanning electron microscope (SEM) and to track trajectories [Handley 2006], for optical alignment [Rihong et al., 1998], in lithography [Vettiger, 1996], for positioning of semiconductor objects [Verma et al., 2005], for DNA injection and cell extraction in microbiology [Zhang et al., 2002] and in micro-robotic applications [Goldfarb and Celanovic, 1997], to name but a few.

Being easy to implement, a piezoelectric actuator is normally driven using voltage [Goldfarb and Celanovic, 1997]. However, a voltage driven piezoelectric actuator exhibits non-linear hysteresis and creep, which affect its positioning accuracy [Goldfarb and Celanovic, 1997]. This in turn affects the tracking performance of a micro-motion stage that is driven using a piezoelectric actuator. Therefore, to precisely position a micro-motion stage, it is important to implement a technique that could assist in minimization of hysteresis and creep.

The remainder of this paper is organized as follows: The hysteresis and creep non-linearities as well as the techniques used to minimize them are presented in the background study in Section 2. In Section 3, the inverse control of the hysteresis and creep in a piezoelectric actuator is presented. The experimental setup, used to test the control algorithm, is presented in Section 4 and the results obtained from this investigation are presented in Section 5. Finally, the concluding remarks follow in Section 6.

2 Background

Various techniques have been researched to minimize the amount of hysteresis and creep and, thus, to precisely position a micro-motion stage. This section not only provides an insight into the exisiting techniques, but also highlights the drawbacks in them.

2.1 Micro-motion stage

Micro-motion stages have emerged as an important technological advancement in the past twenty-five years. The significance of this advancement is highlighted in many applications (refer to Section 1) where positioning of components within micrometre or sub-nanometre accuracy is required. The design of most of the micro-motion stages is based on the concept of a compliant mechanism actuated by a piezoelectric actuator [Handley, 2006]. Compliant mechanisms generate their motion through elastic deformation of a flexure like structure and are machined from a single piece of material. Since there are no moving and sliding joints in such mechanisms, the problems related to wear, backlash, friction is eliminated. Overall, the use of a jointless compliant mechanism to provide motion transfer means that the accuracy of such stages depends only on the accuracy with which the piezoelectric actuator functions.

2.2 Hysteresis and creep

When a voltage signal is applied to a piezoelectric actuator in open-loop mode, a non-linear displacement response due to hysteresis and creep can be observed. Hysteresis, caused by the polarization of microscopic ferroelectric particles, leads to a non-linear relationship between the input voltage and the output displacement [Damjanovic, 2005] of the actuator. An example of a traditional hysteresis curve is shown in Figure 1. This hysteresis curve was obtained by driving a Tokin model AE0505D16 piezoelectric stack type actuator using a -20 to 100 volts sine wave output from a voltage amplifier. The amount of hysteresis was approximately 20 % (2.4 micrometre) at 50 % voltage swing (40 volts in this case).

Hysteresis is not only dependent on the amplitude but also on the frequency of the input voltage. While the amount of hysteresis increases with an increase in the amplitude of the input voltage (see Figure 2), the shape of the hysteresis curve changes as the frequency of the input voltage is varied (see Figure 3). Moreover, hysteresis also depends on a combination of the current as well as on some past values of the input voltage. Thus, when a voltage driven piezoelectric actuator is operated in open-loop, the maximum positioning error due to hysteresis could be as much as 10-15% of the operating range of a piezoelectric actuator [Ge and Jouaneh, 1996]. The effect of hysteresis, which is more pronounced as the operating range increases, can be minimized by driving the actuator in a linear range by keeping the amplitude and frequency of the input voltage constant and as small as possible. However, in such a case the actuator's ability to be displaced over a long range with high precision needs to be sacrificed.

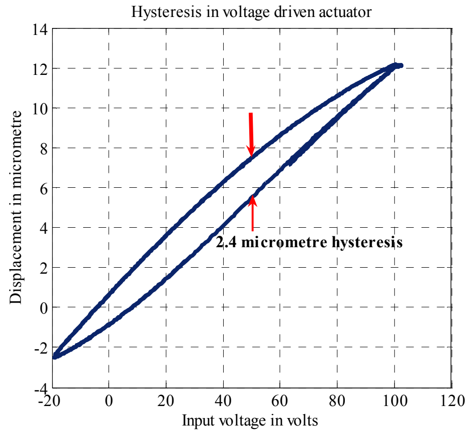

Figure 1: Hysteresis in a voltage driven piezoelectric actuator.

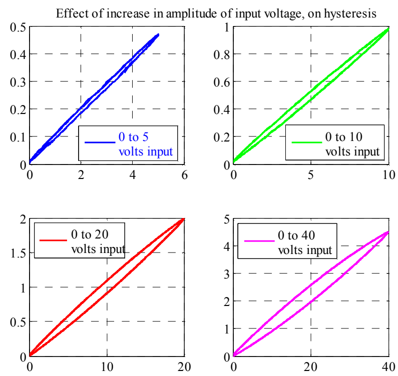

Figure 2: Effect of increase in amplitude of input voltage, on the amount of hysteresis in displacement response; where x-axis is input voltage and y-axis is displacement in micrometre.

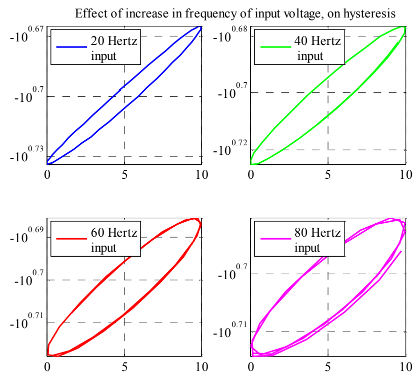

Figure 3: Effect of increase in frequency of input voltage, on the shape of hysteresis loop; where x-axis is input voltage and y-axis is displacement in micrometre.

Creep, a slow eccentric drift in the displacement of a piezoelectric actuator [Ru and Sun, 2005], is caused by remanent polarization which continues to change over time even after the input voltage has reached a constant value. An example of a traditional creep curve, exhibited by a piezoelectric actuator, is shown in Figure 4. The creep curve, in Figure 4, was obtained by driving a Tokin model AE0505D16 piezoelectric stack type actuator using a 100 volts step input. The step input was applied at 10 seconds. As shown in Figure 4, the initial response of the actuator is very fast. However, then onwards the actuator slowly drifts away from the final value of 11 micrometre; the error due to creep is approximately 9.1% (1 micrometre). Creep, more prominent in low bandwidth applications, could affect the positioning precision of a piezoelectric actuator in a quasi-static application. Operating a piezoelectric actuator fast enough can help reduce the drifting effect caused by creep.

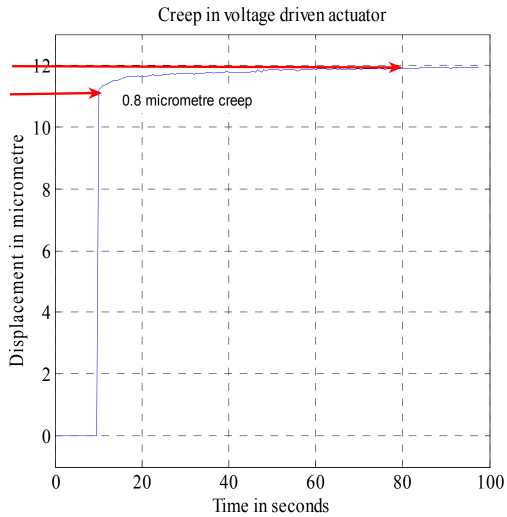

Figure 4: Creep in a voltage driven piezoelectric actuator

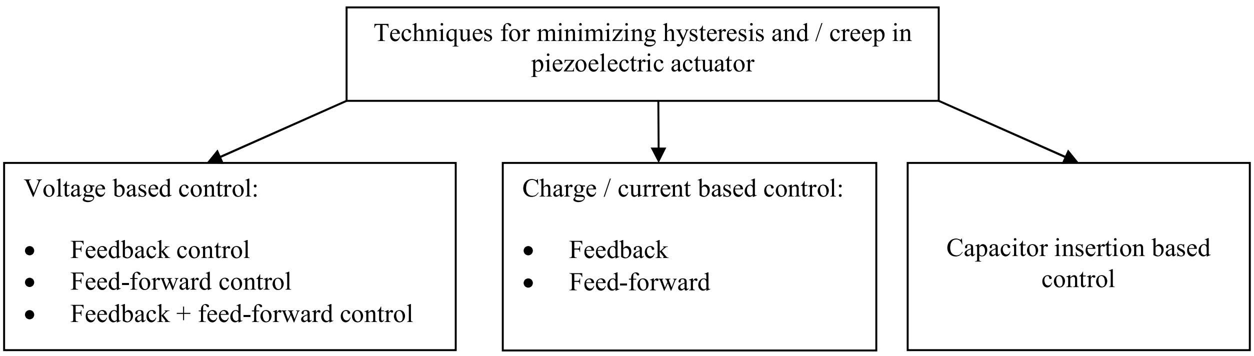

Figure 5: Techniques for minimizing hysteresis and / creep in a piezoelectric actuator.

2.3 Techniques for Minimizing Hysteresis and Creep

The combined effect of hysteresis and creep could lead to inaccuracy in open-loop control [Ge and Jouaneh, 1996] and / instability in closed-loop control [Leang et al., 2009]. To achieve fast and accurate reference tracking of a micro-motion stage it is therefore important to implement a technique that could assist in minimization, if not elimination, of hysteresis and creep. As shown in Figure 5, the control techniques for minimizing hysteresis and / creep can be divided into three main categories: Voltage, Charge/current and Capacitor insertion based.

A charge / current based approach could lead to the minimization of hysteresis and, thus, the approximate linearisation of a piezoelectric actuator's displacement response under dynamic operating conditions [Fleming and Moheimani, 2005]. However, creep cannot be minimized when using this approach and, thus, one would need to design a feedback or a feed-forward controller for the minimization of creep. The capacitor insertion method [Kaizuka and Siu, 1988] is an easy way of reducing the amount of hysteresis and creep in a piezoelectric actuator. Depending on the size of the inserted capacitor, this method leads to minimization of hysteresis in static and dynamic operations. The amount of creep in a piezoelectric actuator can be nearly eliminated as well. A detailed comparison between the voltage, charge and capacitor insertion based driving techniques [Minase et al., 2010] shows that, although a voltage driven piezoelectric actuator exhibits hysteresis and creep that requires precise modelling and control, it would remain the first choice method for driving a piezoelectric actuator due to the advantages it provides over the other two techniques.

Various analytical approaches have been proposed for the modelling of hysteresis [Wen, 1976; Goldfarb and Celanovic, 1997] as well as creep [Vieira, 1986] in a voltage driven actuator. Since these approaches are static in nature, various identification approaches [Adly and Hafiz, 1998; Yeh et al., 2006], which update these analytical models, have been implemented for the prediction of hysteresis and creep.

Based on the above approaches, numerous model based, feedback [Choi et al., 2002; Salapaka et al., 2002] as well as feed-forward [Ru and Sun, 2005; Leang et al., 2009] control schemes have been implemented to precisely position a piezoelectric actuator. In addition, feedback plus feed-forward approaches [Ge and Jouaneh, 1996; Ru and Sun, 2005] have also been proposed to minimize the error due to uncertainties or un-modelled dynamics of the actuator.

2.4 Drawbacks in Existing Techniques

Although many control schemes have been derived and implemented, major performance issues still exist in the form of precise positioning / tracking of piezoelectric actuator driven micro-motion stage. This has been caused not only by the in-effectiveness of above mentioned schemes in certain scenarios but also by new designs of high-speed micro-motion stages that have constantly kept pushing the boundaries of achievable operating speeds as well as positioning resolution and / tracking performance.

On comparing the control approaces listed above, it can be seen that feedback plus feed-forward approach outperforms the feedback as well as the feed-forward approach. However, this comes with the added cost of a feedback sensor. The feed-forward control approaches have not only shown promising results; by reducing the positioning / tracking error to between 2 - 5 % of the operating range, but are also cost effective. However, for the feed-forward approach to be implemented on a micro-motion stage that aims to provide a resolution in the range of micrometre to sub-nanometre or so, a error between 2-5% is still quiet large. Therefore, it is necessary to improve the exisiting feed-froward control approaches before it could be implemented on a micro-motion stage.

3 Inverse Control of Hysteresis and Creep

This section provides the details of the inverse control strategy that was implemented to minimize hysteresis and creep in the piezoelectric actuator. In this strategy (see Figure 6), the control input, u_c, is determined by inverting the dynamic model identified using the Unscented Kalman Filter (UKF) [Wan and Merve, 2001] based adaptive identification algorithm. This input is then used to drive the actuator so that hysteresis and creep is minimized and a desired trajectory is tracked.

The UKF based identification algorithm (see Figure 7); details of which can be found in Minase et al (2010), integrates a nominal dynamic model of the piezoelectric actuator with its measured displacement response such that the dynamics of the actuator can be precisely identified; there by leading to accurate prediction of hysteresis and creep. While a second-order linear parametric model (refer to Eq. (1)) coupled with the Bouc-Wen model [Wen, 1976] in Eq. (2) was used to define the nominal dynamics of hysteresis, the Logarithmic model [Vieira, 1986] in Eq. (3) was used to define the nominal dynamics of creep.

$$m_p \ddot{x} + b_p \dot{x} + k_p x = k_p [cv - h] \quad (1)$$

$$\dot{h} = \mu c \dot{v} - \tau |\dot{v}| h - \delta v |h| \quad (2)$$

$$L(t,u) = L_0 \left[1 + \gamma(u) \log_{10}\left(\frac{t}{0.1} \right) \right] \quad (3)$$

In Eq. (1), x is the output displacement of the piezoelectric actuator, m_p, b_p, k_p and c are the mass, damping, stiffness and piezoelectric coefficient of the piezoelectric actuator, h is the output variable of the dynamic model of non-linear hysteresis behaviour, and v is the applied voltage signal. In Eq. (2), μ, τ and δ are the constants that affect the shape of the hysteresis curve. In Eq. (3), $L(t, u)$ is the displacement of the actuator for any constant voltage, u, L_0 is the displacement 0.1 seconds after u is applied, $\gamma(u)$ is the creep factor and t is the time.

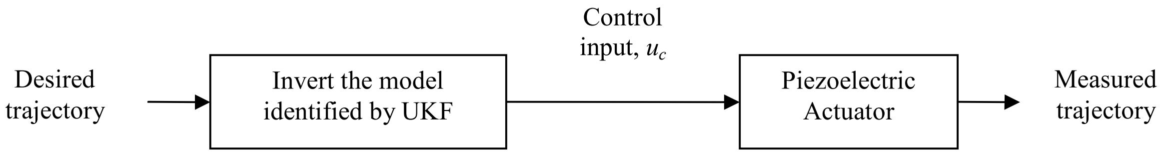

Figure 6: Inverse (Feed-forward) control algorithm

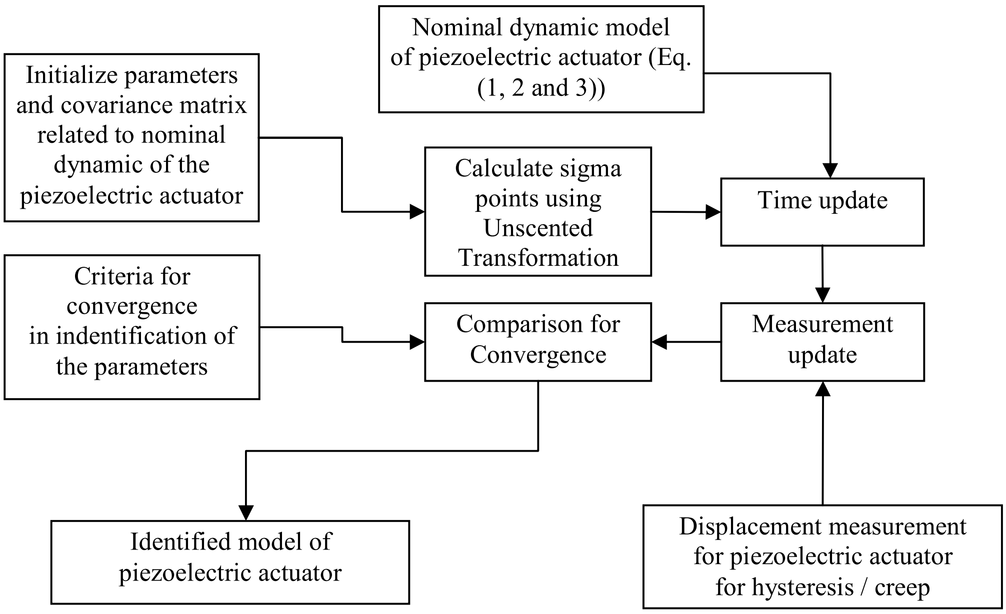

Figure 7: Unscented Kalman Filter based adaptive identification algorithm

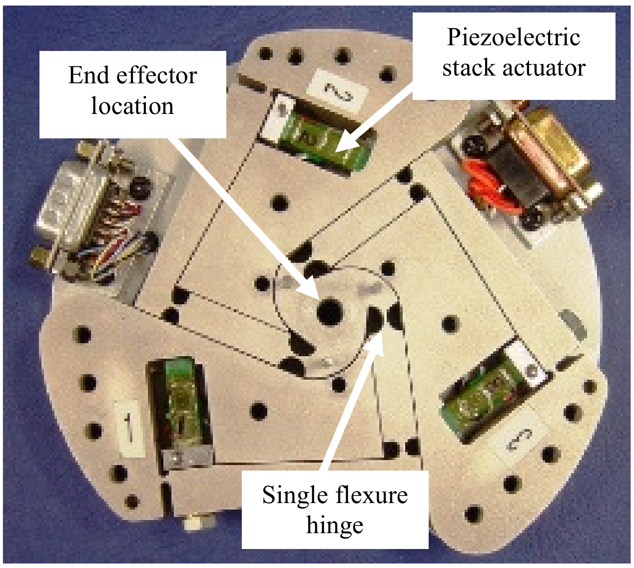

Figure 8: Three degree of freedom micro-motion stage designed by Handley (2006).

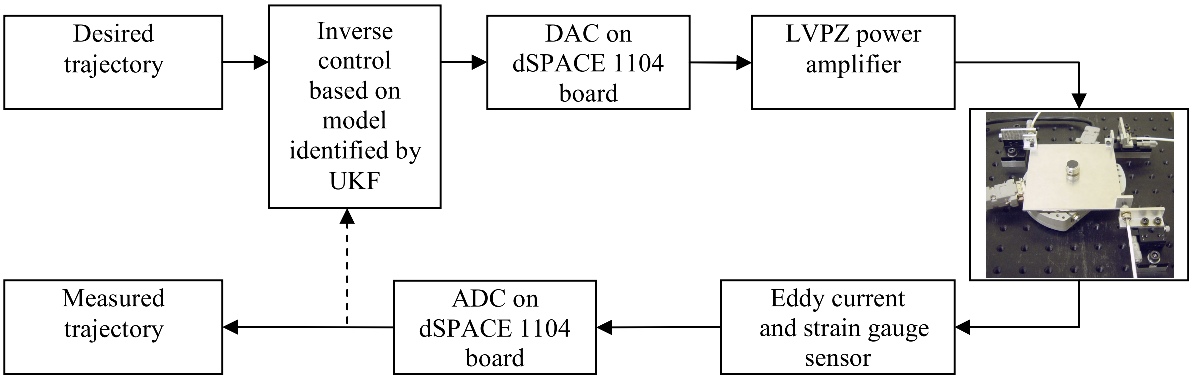

Figure 9: Block diagram of the experimental setup that was used to test the inverse control strategy

4 Experimental Setup

A block diagram representation of the experimental setup, which was used to test the inverse control strategy on the three degree-of-freedom (DOF) micro-motion stage (shown in Figure 8), which was designed and developed by Handley (2006), is shown in Figure 9. The stage, which has planar motion along the X and Y axis and rotation about the Z axis, has a large reachable workspace of approximately 103 micrometre and its first natural frequency of resonance is 630 Hertz. The stage is a parallel compliant mechanism with three revolute-revolute-revolute (RRR) flexure hinges. Each of the three RRR linkages uses three circular profile notch flexure hinges. Each flexure hinge provides predominantly rotational motion about one axis. While the parallel compliant mechanism gives rigidity and light link mass to the stage, the use of flexure hinge assists the stage in providing finest accuracy motion. The stage is actuated using three Tokin model AE0505D16 piezoelectric stack type actuators. Each AE0505D16 stack actuator generates a large force of up to 850 Newtons, has a maximum displacement of approximately 12 micrometre and most importantly its first natural frequency of resonance is very high; 69 kilo Hertz, which makes it suitable in high frequency applications. These actuators are each driven by a low voltage piezo (LVPZ) power amplifier from Physik Instrumente (PI), which provides a bi-polar voltage ranging from -20V to 120V. The amplifier has a maximum output power of 30W. While the displacement of the end-effector, in X-direction, is measured using Micro-Epsilon eddyNCDT 3700 eddy-current sensor, the displacement of the actuators are measured using strain gauge sensors, which are mounted in the form of full bridge for precise measurements. A dSPACE DS1104 controller board interfaces the stage with the computer.

5 Results

In order to test the success of the inverse control algorithm, which was presented in Section 3, the stage was subject to two different inputs. While the first input was a sine wave, the second input was a staircase. As mentioned previously, hysteresis is both frequency and amplitude dependent. Therefore, to test the ability of the inverse control, to compensate hysteresis, a sine wave, of changing frequency and amplitude, was selected as one of the input. Since creep is time dependent, a staircase input was selected so that the effects of hysteresis and creep could be visualized as well as the ability of the control algorithm, to compensate hysteresis and creep, could be tested.

In Figure 10, the experimental result for tracking a sine wave are presented. It can be seen that the “X” motion of the stage precisely tracks a desired trajectory; the sine wave. For a total displacement of 100 micrometre, the maximum tracking error is 1.5 micrometre (1.5% of the total displacement). In Table 1, a comparison of the maximum percentage error (in micrometre as well as %), between the controlled and the un-controlled case, is presented for different inputs. From Figure 10 as well as Table 1 we can conclude that the implementation of the inverse control algorithm leads to a substantial reduction in the maximum tracking error caused by hysteresis in the actuator.

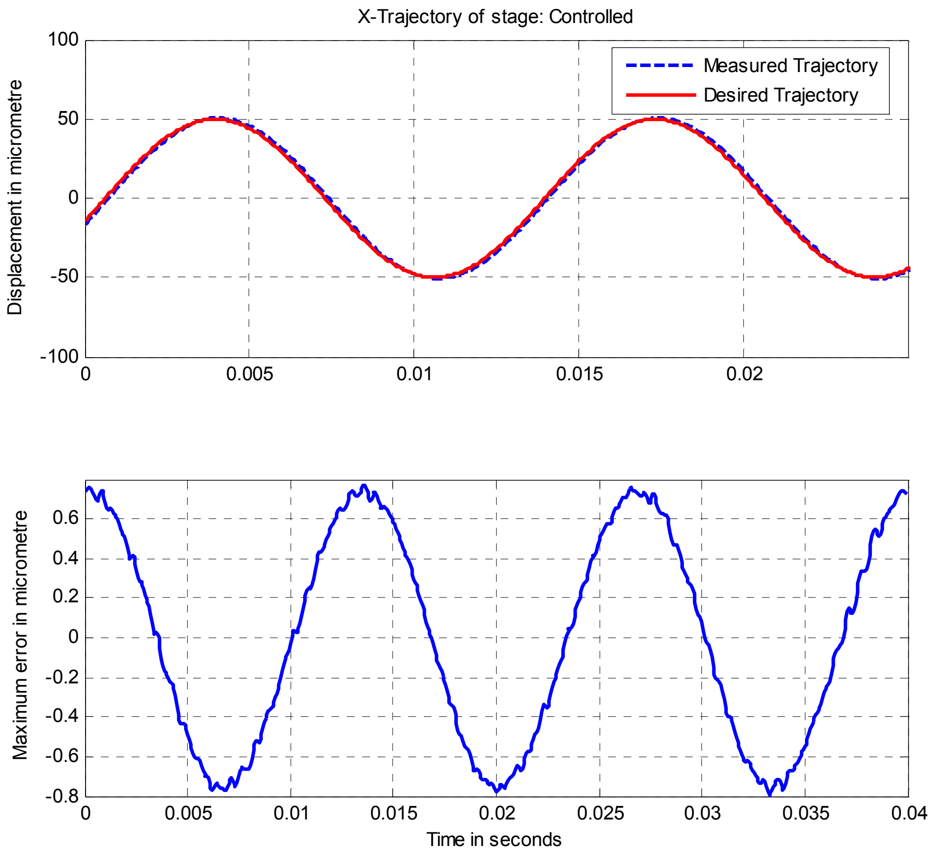

Figure 10: Tracking of a sine wave trajectory using inverse control - compensation of hysteresis.

Table 1: Maximum tracking error when using hysteresis compensation for tracking desired trajectory.

Sr. No	Frequency of desired trajectory in Hertz	Amplitude of desired trajectory in micrometre	Maximum tracking error in micrometre / % (un-controlled)	Maximum tracking error in micrometre / % (controlled)
1	20	± 20	1.8 / 4.5	0.08 / 0.2
		± 30	5.52 / 9.2	0.45 / 0.75
		± 50	16.5 / 16.5	1 / 1
2	75	± 20	3.2 / 8	0.28 / 0.7
		± 30	7.26 / 12.1	0.6 / 1
		± 50	18.6 / 18.6	1.5 / 1.5

The results for the second experiment, which was conducted on tracking a staircase trajectory, are presented in Figure 11 and Figure 12. In Figure 11, it can be seen that in the absence of the inverse control algorithm, the effect due to hysteresis and creep prevent the "X" motion of the stage from precisely tracking the desired trajectory. Figure 12 shows that in the presence of the inverse control, the desired trajectory is tracked precisely. Therefore, we can conclude that the implementation of the inverse control algorithm leads to a substantial reduction in the maximum tracking error caused by the hysteresis and creep in the actuator.

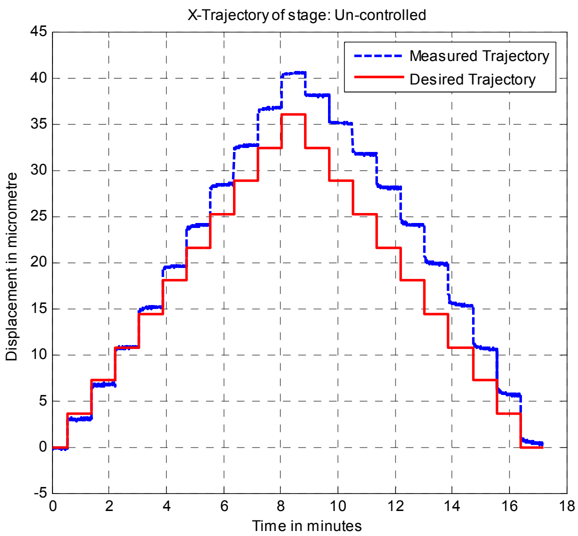

Figure 11: Tracking of a staircase trajectory without inverse control - presence of hysteresis and creep

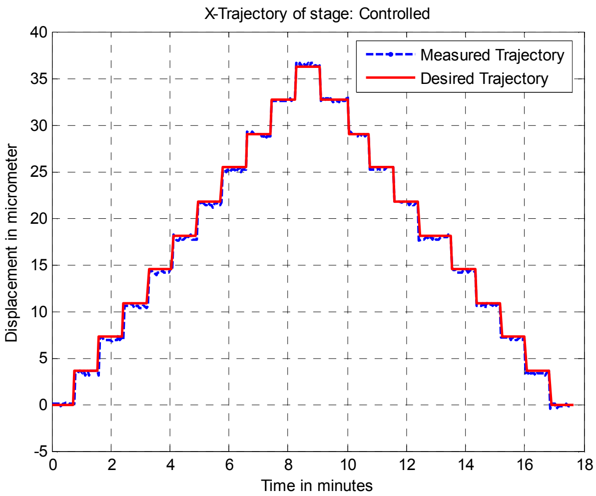

Figure 12: Tracking of a staircase trajectory using inverse control - compensation of hysteresis and creep.

6 Conclusion and Future Work

The main contribution of this paper is the successful implementation of an inverse control approach for precise operation of a piezoelectric actuator drive three degree of freedom micro-motion stage over wide band of input amplitudes as well as frequencies. The results presented in Section 5 show that a substantial improvement in the tracking performance of the stage is achieved. Furthermore, the performance of the controller also justifies that the UKF based identification technique can precisely predict the hysteresis and creep in a piezoelectric actuator.

Although the errors are very much in the acceptable range, it can be seen that the maximum tracking error in the X-direction increases with the frequency and the amplitude of the input. This is because of the un-controlled high frequency dynamics of the stage. Therefore, in order to reduce the maximum tracking error, in higher frequency applications, the authors are currently investigating a similar identification and control approach for implementation on the stage.

Acknowledgement

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