# Trajectory Following with a three-DOF Micro-motion Stage

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## Abstract

This paper presents the position control of a three-DOF (degree-of-freedom) micro-motion stage. This stage provides micro scale planar motion along the x and y axis and rotational motion along the z axis. It uses a 3 RRR (three revolute-revolute-revolute) flexure hinge based compliant mechanism driven by three piezoelectric stack actuators to achieve the micro motion along x, y and z axis. The micro-motion stage with operating frequency up to 1Hz is controlled to follow a prescribed circular trajectory. An analytical Jacobian of the stage is derived to relate the input displacements of the piezo-actuators to the output displacements of the stage. Closed-loop positioning control is achieved using the standard PI controller. The errors related to the position control along the x and y axis are presented.

## 1 Introduction

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 where positioning of components within micrometer or nanometer accuracy is required. For instance, the positioning of samples in a scanning-electron-microscopes, the alignment of fibre-optics and lasers, the positioning of wafers in micro-lithography [Lee and Kim, 1997], the manipulation of cells in micro-biology [Zhang *et al.*, 2002], the manipulation of micro-scale components in micro-assembly and disk drive microactuation.

The design of most of the micro-motion stages is based on the concept of a compliant mechanism being driven by piezoelectric actuators. [Scire and Teague, 1978; Her and Chang, 1994; Handley *et al.*, 2004; Park and Yang, 2005; Kim *et al.*, 2005]. Compliant mechanisms generate their motions through elastic deformation. These mechanisms use flexure hinges to replace the joints in a rigid-link mechanisms; thus avoiding the use of moving and sliding joints. The problems related to wear, backlash, friction and need for lubrication can thus be eliminated. Many actuation principles have been applied to drive the compliant mechanism in a micro-motion stage. Piezoelectric actuators, electrostatic, electromagnetic and shape memory alloy actuators have been utilised to provide fine motions to the micro-motion stages. Since their resolution is dependent solely on the quality of applied voltage signal, piezoelectric actuators are commonly used to provide fine resolution of input displacements in sub-nanometer range. The use of a jointless compliant mechanism to provide motion transfer means that the position accuracy of such micro-motion stage depends only on the accuracy of the piezoelectric actuator and the position sensor. Therefore, the compliant mechanism based micro-motion stage is capable of achieving micrometer or even sub-nanometer positioning resolution.

Piezoelectric stack actuators, hereafter called piezo-actuators, are used as the driving elements in the compliant mechanism-based micro-motion stage presented in this paper.

## 2 The Micro-motion Stage Design

The micro-motion system presented in this paper is a three degree-of-freedom (DOF) micro-motion stage. It is a monolithic compliant mechanism with flexure hinges and is manufactured using the wire-electric-discharge-machining (wire-EDM) technique. This stage is designed for the positioning of samples in a scanning-electron-microscope (SEM). The stage is actuated by three piezo-actuators as shown in Figure 1. The stage has planar motion along the x and y axis and rotation about the z axis.

Micro-motion stages are commonly modelled using the pseudo-rigid-body-model (PRBM) technique. The PRBM technique models the flexure hinges as revolute joint with an attached torsional spring (see Figure 2b). However, it does not model the translational deformations of the hinges (see Figure 2b). The PRBM

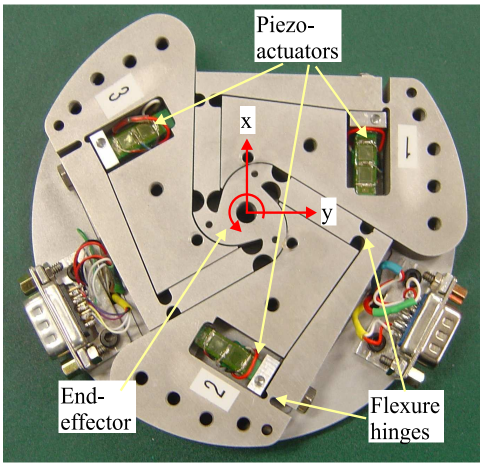


Figure 1: SEM micro-motion stage

technique models flexure hinges to have only one-DOF. Therefore the accuracy of the model generated using the PRBM technique is poor. The inaccuracy of the PRBM is previously reported [Scire and Teague, 1978; Furukawa *et al.*, 1995; Jouaneh and Yang, 2003]. In this paper, the rotational as well as the translational deformations of flexure hinges are considered (see Figure 2c) in order to obtain a more accurate model than that obtained using the PRBM technique.

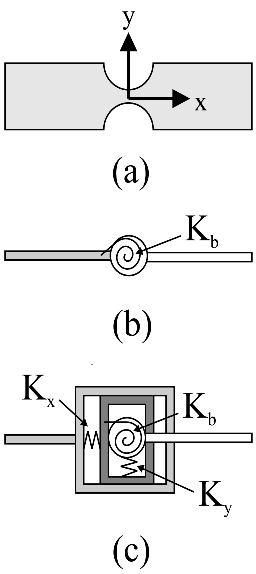


Figure 2: a) Flexure hinge. b) PRBM model. c) 3-DOF model

A Jacobian matrix is normally used to relate the velocity of an end-effector to the velocity of the actuators. However, in case of the compliant micro-motion stages, the Jacobian matrix can be defined as a matrix that relates the end-effector displacements ($\Delta x$, $\Delta y$, $\Delta\gamma$), to the actuator displacements, ($\Delta l_1$, $\Delta l_2$, $\Delta l_3$). The displacements of the piezo-actuators are small as compared to the link lengths. Also, the motions of the stage are very small. Therefore, the micro-motion stage is almost configurationally invariant and its Jacobian matrix is assumed to be constant [Zhang *et al.*, 2002]. The Jacobian matrix presented in this paper considers both the rotational as well as the translational motions of flexure hinges.

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta\gamma \end{bmatrix} = J_{analytical} \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \end{bmatrix} \tag{1}$$

and

$$J_{analytical} = \begin{bmatrix} 3.84 & 1.40 & -5.62 \\ 3.87 & -5.44 & 1.84 \\ -199.77 & -211.90 & -209.42 \end{bmatrix} \tag{2}$$

With such a simple constant Jacobian matrix, the calculation of motions for the compliant mechanism based micro-motion stage are more efficient than using any other mathematical model.

## 3 Experimental Setup

The experimental set-up for the micro-motion system consists of three Tokin AE0505D16 piezo-actuators assembled into a flexure hinge of the compliant mechanism, as shown in Figure 1. Each unloaded actuator has a maximum displacement of approximately 15 $\mu m$. These piezo-actuators are each driven by a Physik Instrumente (PI) piezo amplifier, which provides a bipolar voltage ranging from -20V to 120V. The amplifier has a maximum output power of 30W. Measurement Group EA-06-125TG-350 strain gauges are mounted on the piezo-actuators to determine their displacement. All the strain gauges are connected to a strain gauge conditioner. The end-effector locations are measured using three Micro-Epsilon eddyNCDT 3700 eddy-current transducers. The piezo amplifier, strain gauge conditioning circuitry and eddy-current transducers are connected to a dSPACE DS1104 DSP controller board via inbuilt Digital-Analog (DAC) and Analog -Digital (ADC) converters. A schematic of the experimental set-up is shown in Figure 3.

## 4 Position Control and Trajectory Following

A schematic depicting the two stage position control for trajectory following with a three degree-of-freedom (DOF) micro-motion stage is shown in Figure 4. It

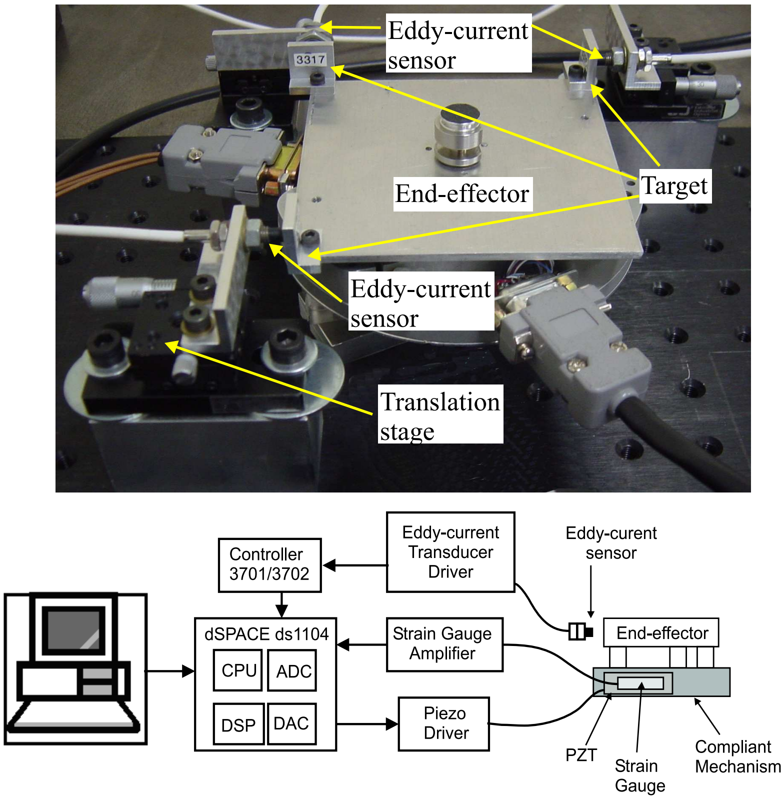


Figure 3: Experimental setup. Top: Photography showing the measurement of displacements using three eddy-current sensors. Bottom: A schematic of the experimental setup

is desired to control the x and y positions of the end-effector, in the Cartesian workspace, to follow a simple circular trajectory. The amount of actuator displacement, ($\Delta l_1$, $\Delta l_2$, $\Delta l_3$) that is required to get a desired ($\Delta x$, $\Delta y$, $\Delta\gamma$), is calculated using the inverse-Jacobian matrix. In stage one a closed-loop Proportional Integral (PI) actuator controller is used to control the voltage input to the piezo-actuators to achieve the desired displacement. The actuator controller uses feedback from strain-gauges mounted on the piezo-actuators to determine the displacement error of the piezo-actuators. The controlled piezo-actuator displacement is translated into the displacement of the end-effector along the x and y axis by the compliant mechanism. The accuracy of the end-effector displacement is thus dependent on the accuracy of the inverse-Jacobian matrix. However, there is an error of around 9% in the derived constant Jacobian matrix. Without a closed-loop feedback from the end-effector, this will result in positioning errors along the x and y axis respectively. To compensate for this error, a second closed-loop end-effector PI controller is implemented. Eddy current sensors, that measure the x and y position, are used to provide feedback to this end-effector PI controller. Tuned up proportional and integral gains help compensate for the position error by adjusting the desired input coordinates of the end-effector. With individual feedback control for the position along the x and y axis, it is possible to accurately track a circular trajectory even with a simple PI control.

To demonstrate the performance of the PI control, the end-effector was manoeuvred to follow a circular trajectory. The input to the controller were the desired coordinates along the x and y axis of the circular trajectory. The controller performance was tested for operating frequencies up to 1 Hz. The results, for 0.5 and 1 Hz frequency value, are presented and discussed in the next section.

## 5 Results and Discussions

Figures 5 show the desired circular trajectories and the actual circular trajectories achieved by the end-effector with closed-loop PI control at operating frequencies of 0.5 and 1Hz respectively. It can be seen that the actual and desired trajectories at both the operating frequencies are quiet similar. Although it is very much evident that at an operating frequency of 1 Hz the error is more than that at the 0.5 Hz frequency. The relative errors along the x and y axis are depicted in Figures 6. These

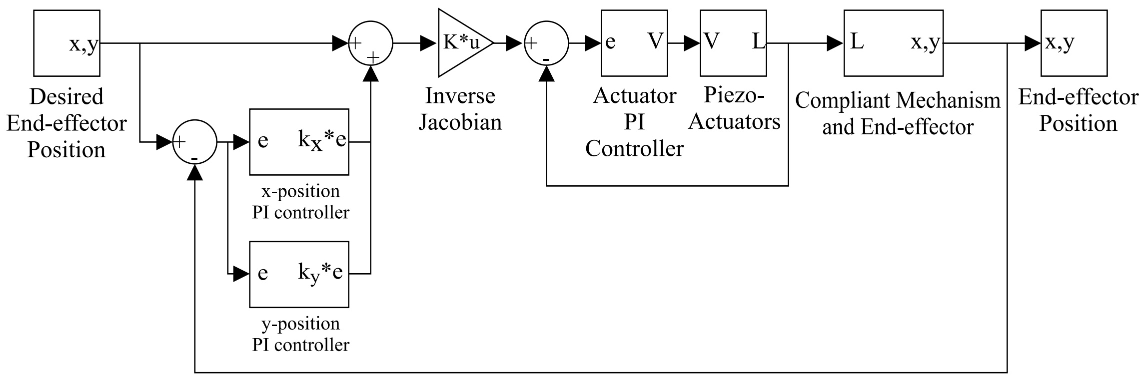


Figure 4: Schematic of the control system

give us a better understanding of the percentage error in tracking the desired circular trajectory. From Figure 6, it is observed that the maximum position error along the x axis is about 2% and the maximum position error along the y axis is about 4% at 0.5Hz. When the micro-motion stage is operated at frequency of 1Hz, the maximum position errors along the x and y axis are approximately 3 and 6 % respectively. Table 1 summarises the average absolute and percentage errors along the x and y axis when the micro-motion stage is operated at a frequency of 0.5 and 1Hz.

| | Average absolute error | | Average % error | |
|---|---|---|---|---|
| | 0.5 Hz | 1 Hz | 0.5 Hz | 1 Hz |
| x ($\mu$m) | 0.04 | 0.06 | 1.3 | 2.0 |
| y ($\mu$m) | 0.08 | 0.12 | 2.7 | 4.0 |

Table 1: Errors of the x- and y-motions operated at 0.5Hz and 1Hz

## 6 Conclusion and Future work

The results show that the three degree-of-freedom (DOF) compliant mechanism based micro-motion stage, with a simple PI control law, is capable of tracking a circular trajectory with precision. It provides precise position control and trajectory following for applications operating in frequency range up to 1 Hz. Although the errors are in an acceptable range, it can be seen that the maximum position errors in the x and y directions increase with the operating frequency. This could be linked to the fact that although the Jacobian matrix based model of the compliant mechanism is easy to compute as compared to other complex mathematical models, the accuracy reduces for high frequency operations. In order to reduce the increase in these position errors, in higher frequency range, the authors are working towards the implementation of a system identification approach to

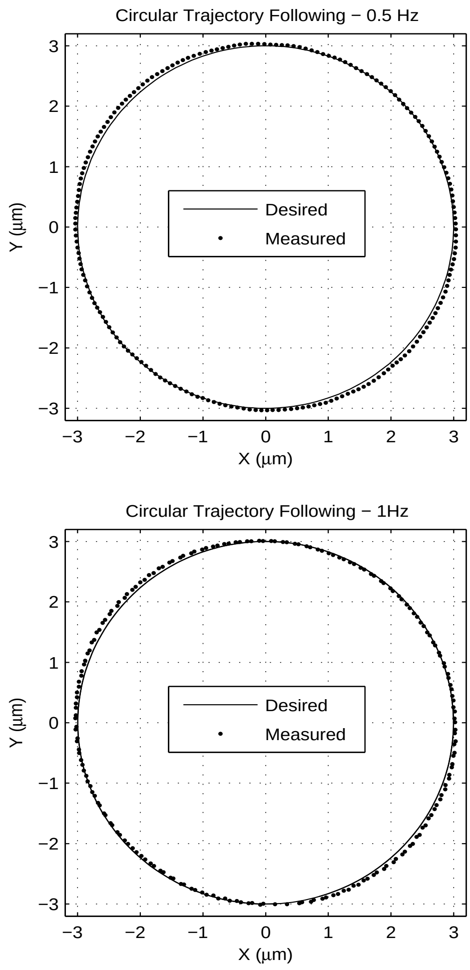


Figure 5: Circular trajectories operating at 0.5 Hz (top) and 1 Hz (bottom)

determine, accurately, the dynamic system model. Also under investigation is a superior model based control law that could follow a trajectory with less that 2% error in higher frequency range.

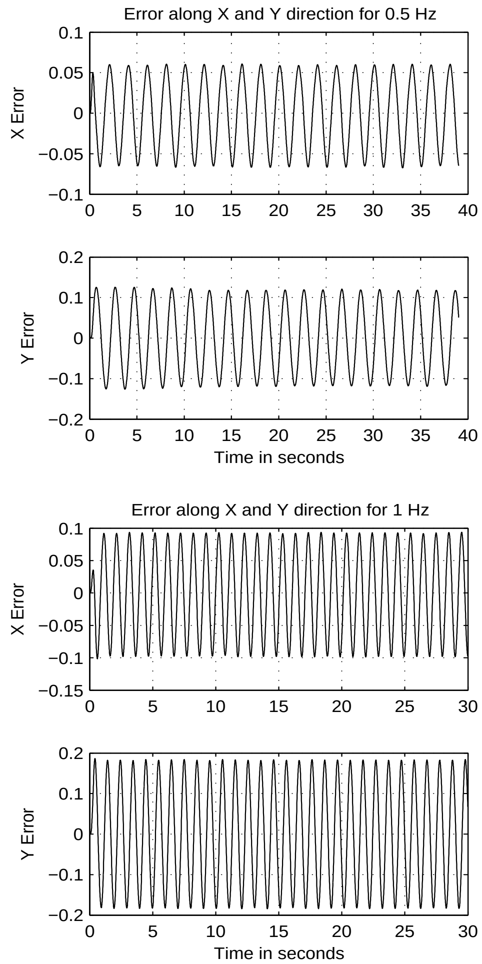


Figure 6: Relative errors between the desired and the measured positions at 0.5 Hz (top) and 1 Hz (bottom)

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