2004 8th International Conference on
Control, Automation, Robotics and Vision
Kunming, China, 6-9th December 2004

Position Control of a 3 DOF Compliant Micro-Motion Stage

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ABSTRACT

This paper focuses on the open-loop and closed-loop position control of a three degree-of-freedom (DOF) compliant micro-motion stage with flexure hinges. This micro-motion stage has a parallel structure for better stiffness and accuracy than serial structures and is driven by three PZT stack actuators. It was discussed in the authors' previous paper that due to the limitation of current modeling methods for compliant mechanisms the derived kinematic model is not able to accurately describe the behavior of the investigated micro-motion stage. Therefore, an experimentally determined constant Jacobian matrix is used to relate the extensions of PZTs and the end-effector movement for position control. With the use of the experimentally determined Jacobian in open-loop control, the micro-motion stage is proved able to achieve good positioning accuracy. Nevertheless, the positioning accuracy is significantly improved by incorporating end-effector closed-loop control.

1. INTRODUCTION

During the past two decades considerable research has been conducted to develop micro-motion devices for applications including biological cell manipulation in biotechnology and micro-component assembly in micro-technology. One common need is to manipulate micro scale objects and to perform very small motions, say less than 100 μm, with good positioning accuracy. Conventional technologies based on servomotors, ball screws, and rigid linkages struggle to fulfill these requirements due to inherent problems, such as clearance, friction and backlash. Therefore, compliant mechanisms with parallel structures and novel actuators, such as piezoelectric actuators, have been adopted in many designs of micro-motion devices[1-4].

Compliant mechanisms generate their motions through elastic deformations and replace the joints in rigid mechanisms by flexure hinges. These mechanisms are advantageous over the rigid-link designs in applications requiring micro-motion[5] because problems such as friction, wear, backlash and lubrications are eliminated. Furthermore, compliant mechanisms contain fewer components compared to rigid-body mechanisms, thus allowing for savings in weight. Using a parallel structure all the actuators can be located at the base, thus reducing the active mobile mass[6] and leading to higher loading capacity. Parallel structures also have higher mechanical stiffness, faster manipulation and higher positioning accuracy[7].

To efficiently deal with position control of micro-motion stages for low frequency operations, accurate kinematic models are required. However, it is proved in this study that the derived kinematic model is not accurate enough to predict the behavior of the miro-motion stage. Therefore, experiments were conducted to collect data that relates the extensions of PZT with the end-effector movement. The experimental data is used to derive a constant Jacobian matrix and subsequently the Jacobian matrix is used for both open-loop and closed-loop position control rather than the derived kinematic model.

This paper firstly presents the 3RRR compliant micro-motion stage and its theoretical constant Jacobian matrix[8]. The experimental set-up of this compliant micro-motion system for the derivation of experimentally determined Jacobian matrix and the derived Jacobian matrix are then described. It is followed by the presentation of open-loop and closed-loop control schemes. Then, the positioning accuracy of the open-loop and closed-loop controlled end-effector using both theoretical and experimental Jacobian matrices respectively are compared and discussed. Finally, conclusions are drawn and future work is presented.

2. THE MICRO-MOTION STAGE DESIGN

The micro-motion system presented in this study is a three degree-of-freedom (DOF) parallel micro-motion stage (also known as 3RRR compliant mechanism). It is a monolithic compliant mechanism utilising flexure hinges. The stage is actuated by three PZT stack actuators as shown in Figure 1 and is designed based on the 3RRR mechanism structure as depicted in Figure 2. The end-effector platform is attached to the ends of the three linkages as illustrated by a triangle in Figure 1. The end-effector translates along x, y-axis and rotates about the z-axis.

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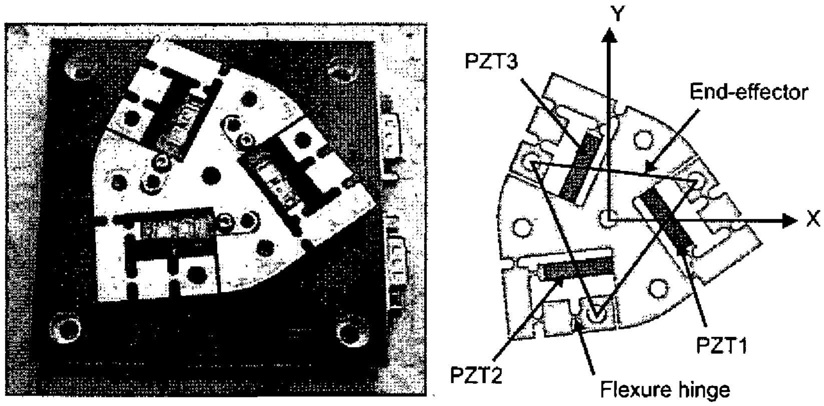


Figure 1: 3RRR compliant micromanipulation device

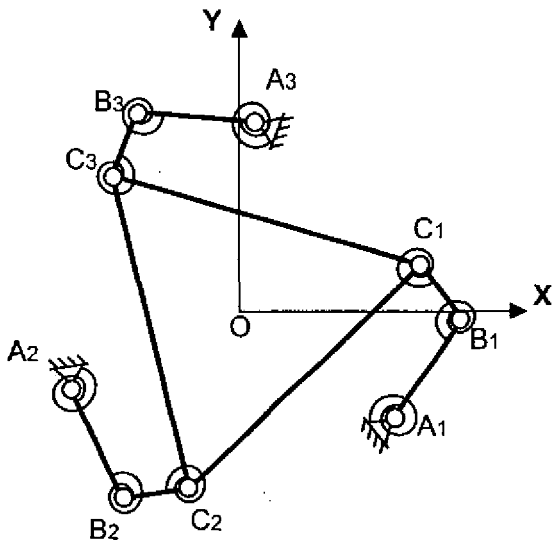


Figure 2: 3RRR compliant mechanism PRBM

The pseudo-rigid-body model (PRBM) approach and loop-closure theory are adopted to derive the linear kinematics of the presented compliant micro-motion stage[8]. The PRBM is used to model the deflections of the flexible members using conventional rigid-link mechanism theory[5]. The PRBM assumes that the flexure hinges in the structure act like revolute joints with torsional springs attached to them. The other parts of the structure are assumed to be rigid. The PRBM of the presented 3RRR compliant mechanism is illustrated in Figure 2. Loop-closure theory incorporates the complex number method to model a mechanism. For each closed-loop in the mechanism, a loop equation is generated[9]. This equation can be expressed in terms of its real and imaginary parts, resulting in two equations per loop[5]. As the angular displacements of the mechanism are small, linear small angle approximations can be used and thus the loop equations are linear. Unknowns can be found by solving these equations simultaneously. The model resulting from this approach has been proved to be as good as the models derived by other researchers using the PRBM approach[8].

A Jacobian matrix is normally used to relate the velocity of an end-effector to the velocity of actuators. However, for the case of compliant micro-motion stages, the Jacobian matrix can be defined as a matrix to relate the end-effector displacement (Δx, Δy, $\Delta \gamma$), to the actuator displacements, (Δl_1, Δl_2, Δl_3)[10]. The displacements of the PZT actuators are small compared to the link lengths and the motions of the 3RRR mechanism are very small. Therefore, the micromanipulation stage is almost configurationally invariant and its Jacobian matrix is assumed to be constant. The Jacobian below has been derived for the 3RRR compliant mechanism presented in this paper[8].

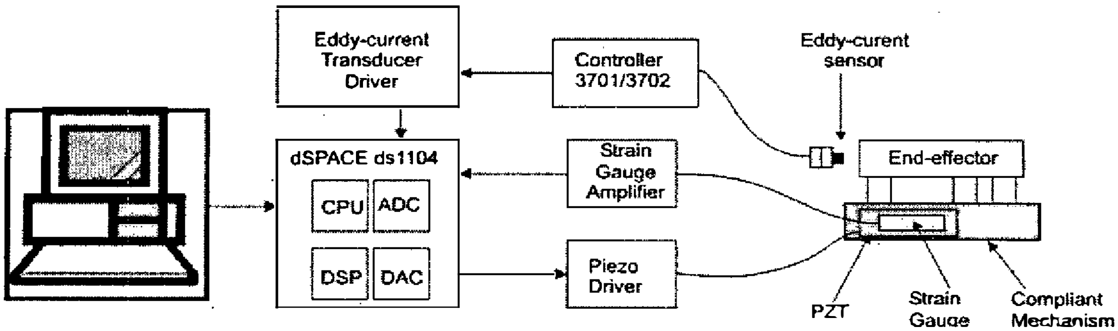
$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta \gamma \end{bmatrix} = J \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \end{bmatrix} \quad \text{where} \qquad (1)$$

$$J_{theoretical} = \begin{bmatrix} 1.905 & -3.220 & 1.315 \\ -2.618 & -0.341 & 2.959 \\ -59.960 & -59.960 & -59.960 \end{bmatrix}$$

With such a simple constant matrix, the calculations for forward and inverse kinematics of the compliant micro-motion stage are more efficient than using any other mathematical models.

3. EXPERIMENTAL SET-UP

The experimental set-up of the micro-motion system consists of 3 Tokin AE0505D16 PZT stack actuators assembled into a flexure hinge, compliant mechanism, as shown in Figure 1. Each unloaded actuator has a maximum displacement of approximately 15 μm. These PZTs are each driven by a Physik Instrumente (PI) PZT



amplifier, which provides a bi-polar voltage ranging from –20V to 120V. The amplifiers have a maximum output power of 30W. Measurement Group EA-06-125TG-350 strain gauges are mounted to the PZTs to determine their displacement. All the strain gauges are connected to a strain gauge conditioner. The end-effector location is measured using three Micro-Epsilon eddyNCDT 3700 eddy-current transducers. The PZT amplifiers, strain gauge conditioning circuitry and eddy-current transducers are connected to a dSPACE DS1104 DSP controller board via inbuilt DAC's and ADC's. A schematic of the experimental set-up is shown in Figure 3.

To validate the theoretical Jacobian matrix derived from the forward kinematics and compare the performance of open-loop with closed-loop control, an experimental constant Jacobian, J_{exp}, was obtained out of the experimental data relating the extensions of PZTs with the end-effector movement. One at a time each PZT actuator was extended to 10μm, while the other two PZTs were kept at 0μm, i.e. Δl_1=10μm, Δl_2=0, Δl_3=0. Actuator feedback was used to control the PZT displacements. For each PZT extension the displacement of the end-effector $(\Delta x, \Delta y, \Delta\gamma)$ was recorded. The $(\Delta x, \Delta y, \Delta\gamma)$ produced by the extension of PZT_1 alone corresponds to the first column of the Jacobian. The appropriate values of J_{exp} were then determined by dividing the $(\Delta x, \Delta y, \Delta\gamma)$ values by Δl_1. Likewise, the $(\Delta x, \Delta y, \Delta\gamma)$ produced by the extensions of PZT_2 and PZT_3 alone were used to determine columns 2 and 3 of J_{exp} respectively. The experimentally derived Jacobian is given below.

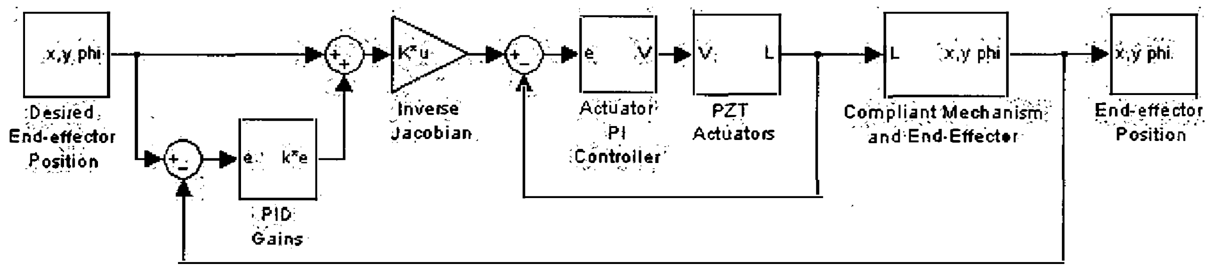
$$J_{\exp} = \begin{bmatrix} 0.668 & -1.298 & 0.734 \\ -1.183 & -0.002 & 1.361 \\ -25.433 & -24.975 & -26.073 \end{bmatrix} \quad (2)$$

4. POSITION CONTROL SCHEMES

A schematic of the controller design is shown in Figure 4. In operation, it is desired to control the x, y position of the end-effector in the Cartesian workspace as well as the orientation, γ of the end-effector. The inverse-Jacobian allows us to calculate the required actuator displacements $(\Delta l_1, \Delta l_2, \Delta l_3)$ to give us a desired $(\Delta x, \Delta y, \Delta\gamma)$. To achieve the required actuator displacements a closed-loop PI controller is used. This controller uses feedback from strain-gauges mounted to the PZT actuators. The PI controller provides adequate response for point-to-point position control. Given that the PZT actuators can now achieve the desired displacement, the accuracy of the end-effector displacement is dependent on the accuracy of the inverse-Jacobian.

However, it is highly possible that there is non-linearity in the kinematics, in which case the constant Jacobian will have some inaccuracy. Without closed-loop feedback from the end-effector, this will result in positioning errors. To compensate for this error, closed-loop end-effector position control was implemented. This uses feedback from the eddy-current sensors and PID gains to compensate for position errors by adjusting the desired input coordinates and orientation of the end-effector.

To demonstrate the performance of the positioning control, the end-effector was manoeuvred to eleven random points within the reachable workspace of the micro-motion system. The input to the controller was a desired x-y coordinate and an orientation, γ. Four experiments were conducted in total for this study and the results are presented and discussed in next section. In the first experiment, the theoretical constant Jacobian is used and end-effector open-loop control is implemented without the feedback from the eddy-current sensors. In the second experiment, the experimental constant Jacobian is used and still the same end-effector open-loop control is implemented. In the third experiment, the theoretical constant Jacobian is used again and end-effector closed-loop control is implemented with the feedback from the eddy-current sensors. In the last experiment, the experimental constant Jacobian is used and end-effector closed-loop control is again implemented.



For end-effector open-loop control, only actuator feedback is used. In this case, the end-effector positioning accuracy is dependent on the accuracy of the Jacobian. In the end-effector closed-loop control case, both actuator and end-effector feedback are used. In this case the positioning accuracy is limited by the accuracy of the eddy-current sensors and the performance of the feedback control system.

5. COMPARISON OF RESULTS

Figure 5 shows the x-y coordinates of the eleven desired points in the workspace and the actual points reached by the end-effector with open-loop control and closed-loop control. Table 1 summaries the average absolute error for x, y and γ for the two controller cases with the use of theoretical Jacobian. Table 2 gives the average absolute error for x, y and γ for the two controller cases with the use of experimental Jacobian.

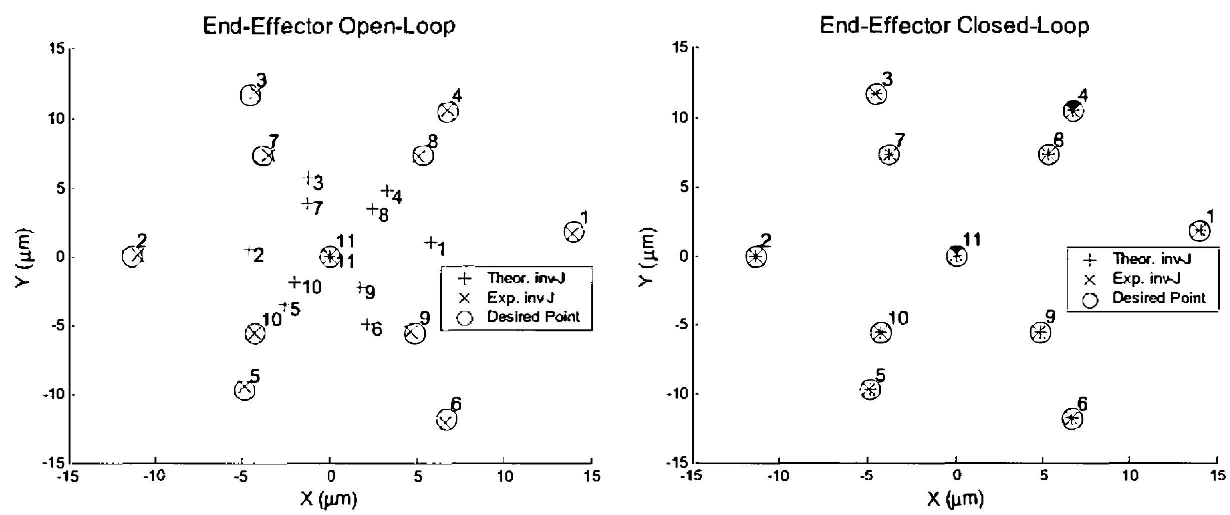
From Figure 5 and Table 1 can be observed the accuracy of the end-effector open-loop controller. This indicates the accuracy of the theoretical and experimental inverse-Jacobian. It is apparent that the theoretical inverse-Jacobian predicts the required relative motion of the actuators but incorrectly predicts the magnitude of end-effector motion. The experimental inverse-Jacobian is far more accurate. It is apparent that a simple linear constant-Jacobian matrix can accurately describe the kinematics of the compliant micro-motion stage. From Figure 5 and Table 2 can be observed the accuracy of the closed-loop controller, using both the theoretical and experimental inverse-Jacobian. In both cases the control system can provide very accurate

Table 1: The average absolute error of x, y and γ for the two controller cases with theoretical Jacobian

Average Absolute Error	End-effector Open-Loop	End-effector Closed-Loop
X (μm)	3.59	0.01
Y (μm)	3.70	0.01
γ (μrad)	212.22	0.07

Table 2: The average absolute error of x, y and γ for the two controller cases with experimental Jacobian

Average Absolute Error	End-effector Open-Loop	End-effector Closed-Loop
X (μm)	0.15	0.01
Y (μm)	0.1	0.01
γ (μrad)	5.48	0.07



positioning, limited only by the sensor hardware. The difference in performance between the two inverse-Jacobian is the response and settling time of the control system. Using the theoretical inverse-Jacobian the response time of the controller is much slower than using the experimental inverse-Jacobian.

6. CONCLUSIONS AND FUTURE WORK

This paper presents the position control of a 3 degree-of-freedom compliant micro-motion stage with flexure hinges. This micro-motion stage has parallel structure and can be implemented for applications requiring motions in micrometers or even nanometres. Possible applications include micro-system assembly, biological cell manipulation and microsurgery. It is demonstrated in this paper that, by using the experimental Jacobian, the presented system has achieved very good position control for applications with the need of only low frequencies. However the positioning accuracy is significantly improved by incorporating end-effector close-loop control. It is also observed through the use of the theoretical Jacobian that the kinematic models that have been derived so far are still inaccurate to predict and analyze the behavior of micro-motion systems. Therefore, one direction of future work is to improve the modelling accuracy while keeping the model as computationally efficient as possible. Another direction is to take the current system further by considering dynamic behaviour for operations requiring higher frequencies.

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