A Micro-positioning Parallel Mechanism Platform with 100-degree Tilting Capability

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Abstract
This paper presents a micro-positioning platform based on the unique parallel mechanism recently developed by the authors. The platform has a meso-scale rectangular shape whose size is 20 x 23 mm. The stroke is 5 mm for both the *x*- and *y*-axis and 100 degrees for the *α*-axis (the rotational axis along the *x*-axis). The platform is actuated by the three sets of two-stage linear actuators: a linear motor for rough positioning and a piezo actuator for fine positioning. The platform is already assembled. The detailed design issues, including the kinematic analysis, and the experimental results of the positioning measurements and control performance, are presented.

Keywords: Parallel mechanism, Kinematic analysis, Micromanipulator

1 INTRODUCTION

Micro-mechanical devices, microelectronics and optics require components of complex three-dimensional shape from a few millimeters to sub millimeters with high accuracy. The demands for miniaturized manufacturing systems have been growing because of the space savings, energy savings, easy transportation and less environment problems [1]. Serial mechanism machines are commonly used in miniaturized manufacturing [2].

To manufacture, assemble or manipulate these three-dimensional precise components, a positioning device with sub-micron accuracy and high mobility (rotational capability) over a large workspace is required. One method to achieve this sub-micron accuracy in a large workspace is to use the dual stage system (coarse and fine actuators) [3].

Takeda [4] presented a parallel mechanism platform, which can achieve sub-micron accuracy by using the dual stage systems. However, the mobility of the platform is only ±10 degrees.

This paper presents a unique parallel mechanism micro-positioning platform with the dual stage system, whose mobility is ±50 degrees. This platform has a meso-scale rectangular shape whose size is 20 x 23 mm. The overall size of the machine is 280(w) x 200(d) x 408(h) mm, which is approximately the desktop size.

The platform has three degrees-of-freedom (DOF): two translational motions in the *x*- and *y*-axis and a rotational motion in the *α*-axis (a rotation along the *x*-axis). The stroke is 5 mm for both the *x*- and *y*-axis and ±50 degrees for the *α*-axis. The target positioning accuracy is within 0.5 μm in the *x*- and *y*-axis, respectively, and within 1.0 μm in the *α*-axis on the basis of the extreme outer edge of the rotating platform.

The machine has three sets of two-stage linear actuators: a linear motor for rough positioning and a piezo actuator for fine positioning. The actuation directions of the coarse and fine actuators are vertical with each other to maximize the platform mobility and resolution [5, 6].

Another uniqueness of the platform is that the position control is executed by the full-feedback control. The three linear sensors directly sense the final position of the platform. The whole machine is already assembled and under detail performance evaluation.

The paper is organized as follows. In Section 2, the kinematic analysis of the parallel mechanism is presented. Section 3 describes the main design features of the real micro-postioning platform that has been assembled. In Section 4, experimental results on the positioning control performance will be presented. Finally, some concluding remarks follow in Section 5.

2 KINEMATIC ANAYSIS OF THE PARALLEL MECHANISM

The micro-positioning platform is based on a new spatial 3-DOF parallel mechanism, which has the distinct advantage of high mobility. The 3-DOF parallel mechanism consists of a base plate, a movable platform, and three legs that connect the base plate and the movable platform. Each leg is connected to the actuator combination of coarse and fine actuators.

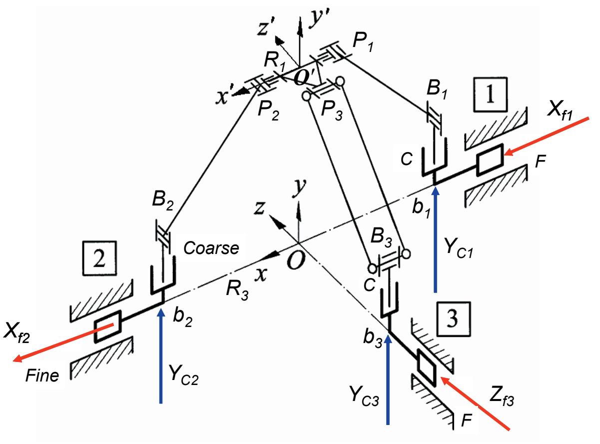
A kinematics model of the manipulator is shown in Figure 1. The first and second legs have identical chains, each of which consists of a link connected to the movable platform by a universal joint, and to the base plate by a passive revolute joint. The third leg has a different chain, which consists of a planar four-bar parallelogram connected to the movable platform and the base plate by universal joints.

The combination of three legs leaves the mechanism with two translational DOF in *O-xy* plane and one rotational DOF about *x*-axis.

The kinematic constraint of the mechanism is that the length of each link is constant as shown in equation (1).

$$\| P_i - B_i \| = L \text{ , where } i = 1, 2, 3 \tag{1}$$

Three scalar equations can be generated from equation (1) for the three links, respectively, as follows:



O-xyz : Fixed global reference frame
O'-x'y'z' : Movable top frame
P_1, P_2, P_3 : Movable platform joints
B_1, B_2, B_3 : Base joints
b_1, b_2, b_3 : Vertices of base plate
L or (P_iB_i) : Length of link for each leg
R_1 or ($O'P_i$) : Radius of moving platform
R_3 or (Ob_i) : Radius of base plate
Y_{c1}, Y_{c2}, Y_{c3} : Coarse actuator inputs
X_{f1}, X_{f2}, Z_{f3} : Fine actuator inputs

Figure 1 : A parallel mechanism of the micro-positioning platform.

$$(x - R_1 + R_3 - X_{f1})^2 + (y - Y_{c1})^2 = L^2 \qquad (2)$$

$$(x + R_1 - R_3 - X_{f2})^2 + (y - Y_{c2})^2 = L^2 \qquad (3)$$

$$(-R_1 \cos\alpha + R_3 - Z_{f3})^2 + x^2 + (R_1 \sin\alpha + y - Y_{c3})^2 = L^2 \qquad (4)$$

Forward kinematics is to obtain the position (*x, y* and *α*) from the value of each actuator. In these equations, there are three values of end effector and six values of actuator. The equations for forward and backward kinematics are shown in Table 1. Table 2 explains the definitions of parameters, which are used in the equations of forward and backward kinematics.

Backward kinematics is to obtain the six values of each actuator from the three values of end effector. A problem arises when solving the backward kinematics of the mechanism, since six unknown values of actuator exist while only three constraint equations are available. By fixing three values of actuator, all six unknown values are determined.

The workspace analysis is performed based on the backward and forward kinematics. The result of workspace analysis is shown in Figure 2. The stroke in the *x*-axis is ±2.5 mm and that in the *y*-axis is from 0 to 5 mm. This satisfies the 5 x 5 mm workspace. In any point of (*x, y*) of this workspace, the tilting angle in the *α*-axis satisfies 100-degree requirement. The minimum and maximum tilting angles in this workspace are 112 and 139 degrees, respectively.

The singularity analysis is also performed. It is found that there exists no singularity in the workspace.

3 MICRO-POSITIONING PLATFORM

The micro-positioning platform is designed and assembled. An overview of this platform is shown in Figure 3. The whole size of the machine is 280(w) x 200(d) x 408(h) mm.

Forward Kinematics
$x = m\left(\dfrac{-f \pm \sqrt{f^2 - 4eg}}{2e}\right) - n$
$y = \dfrac{-f \pm \sqrt{f^2 - 4eg}}{2e}$
$\alpha = 2\tan^{-1}\left(\dfrac{A \pm \sqrt{A^2 + B^2 - C^2}}{B + C}\right)$
Backward Kinematics
$X_{f1} = x - R_1 + R_3 \pm \sqrt{L^2 - (y - Y_{c1})^2}$
$X_{f2} = x + R_1 - R_3 \pm \sqrt{L^2 - (y - Y_{c2})^2}$
$Z_{f3} = -R_1 \cos\alpha + R_3 \pm \sqrt{L^2 - x^2 - (R_1 \sin\alpha + y - Y_{c3})^2}$
$Y_{c1} = y \pm \sqrt{L^2 - (x - R_1 + R_3 - X_{f1})^2}$
$Y_{c2} = y \pm \sqrt{L^2 - (x + R_1 - R_3 - X_{f2})^2}$
$Y_{c3} = R_1 \sin\alpha + y \pm \sqrt{L^2 - x^2 - (-R_1 \cos\alpha + R_3 - Z_{f3})^2}$

Table 1 : Kinematics of the parallel mechanism.

$e = 1 + m^2$	$f = 2m(R_3 - R_1 - n - X_{f1}) - 2Y_{c1}$
$g = (R_3 - R_1 - n - X_{f1})^2 + Y_{c1}^2 - L^2$	
$m = \dfrac{Y_{c1} - Y_{c2}}{-2R_1 + 2R_3 - X_{f1} + X_{f2}}$	
$n = \dfrac{X_{f1}(2R_1 - 2R_3 + X_{f1}) + X_{f2}(2R_1 - 2R_3 - X_{f2}) + Y_{c1}^2 - Y_{c2}^2}{2(-2R_1 + 2R_3 - X_{f1} + X_{f2})}$	
$A = 2R_1(y - Y_{c3})$	$B = 2R_1(Z_{f3} - R_3)$
$C = L^2 - x^2 - R_1^2 - (R_3 - Z_{f3})^2 - (y - Y_{c3})^2$	

Table 2 : Definition of the parameters in Table 1.

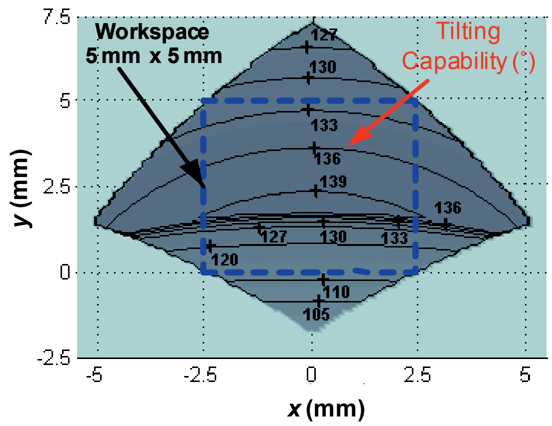


Figure 2 : Tilting capability distribution in the workspace.

Each link has unique ball joint, which is shown in the upper right corner of Figure 3. This ball joint has two independent rotational axes with low friction. It has a ϕ5 mm ball which is surrounded by 48 small balls whose diameter is 0.8 mm.

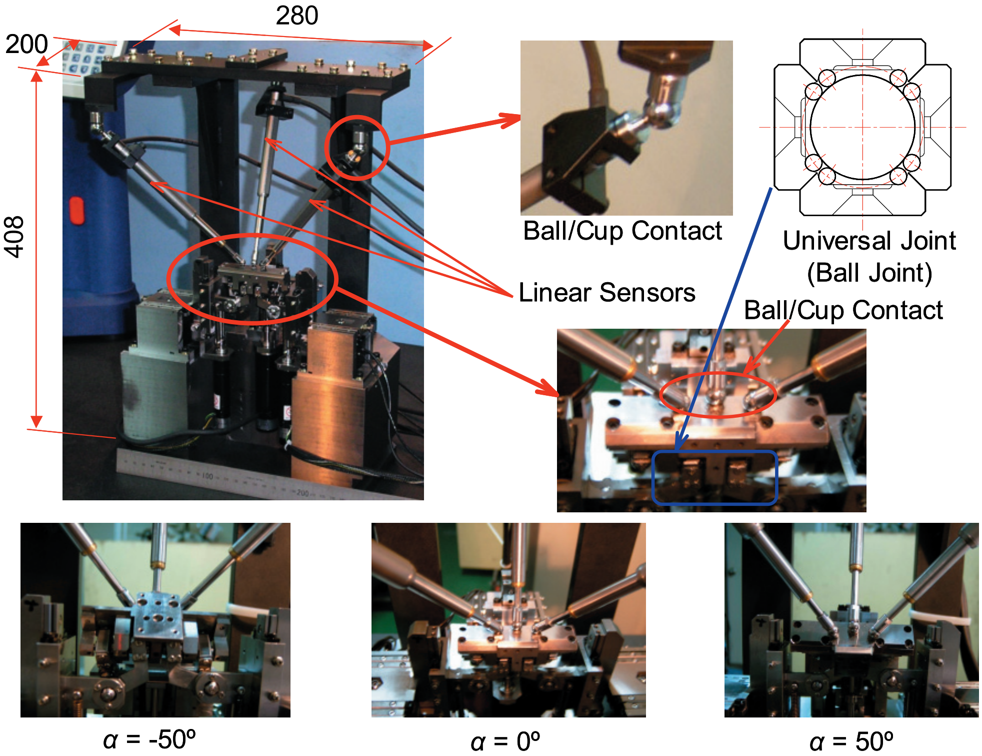


Figure 3 : Photo of the micro-positioning parallel mechanism platform.

In Figure 3, it can be found that three linear sensors are attached to the movable platform. Since the three linear sensors directly sense the final position of the platform, the full-feedback control is possible.

In the bottom of Figure 3, there are three photos that show the tilting capacity of the movable platform. Each photo shows the tilting posture of the platform at -50, 0 and 50 degrees, respectively.

4 EXPERIMENTS: POSITIONING CONTROL

The machine has three sets of two-stage linear actuators: a linear motor for rough positioning and a piezo actuator for fine positioning. The uniqueness is that the actuation directions of the coarse and fine actuators are vertical with each other to maximize the platform mobility and resolution [Please refer to the references 5 and 6 for detail discussion.].

Another unique feature is that the position control is executed by the full-feedback control. The three linear sensors directly sense the final position of the platform (please refer to three linear sensors in Figure 3.).

Figure 4 shows the control block diagram of the controller. It has the dual servo control algorithm block, which is operated by the switching function. At every control sampling period, the dual servo control algorithm block selects three coarse actuators first and execute the positioning control of the three coarse actuators simultaneously. If the positioning accuracy is within 5 μm (x- and y-axis) and 0.01 degree (α-axis), then the dual servo control algorithm block selects three fine actuators in sequence and execute the the positioning contol of the three fine actuators simultaneously. If the positioning accuracy is within 0.1 μm (x- and y-axis) and 0.002 degree (α-axis), then the controller waits for the next reference signals. The sampling period is 100 msec.

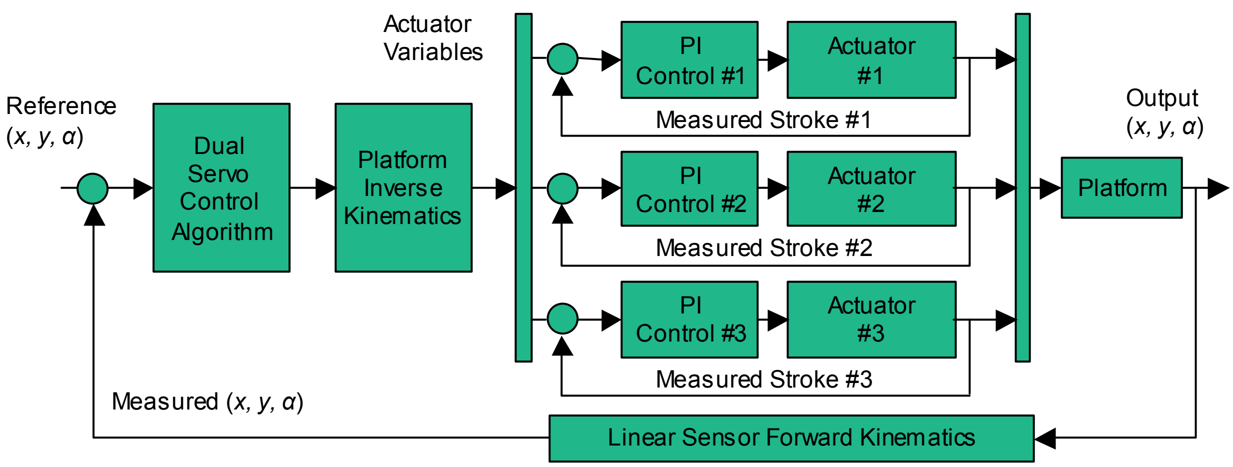


Figure 4 : Control block diagram – dual-servo and full-feedback control.

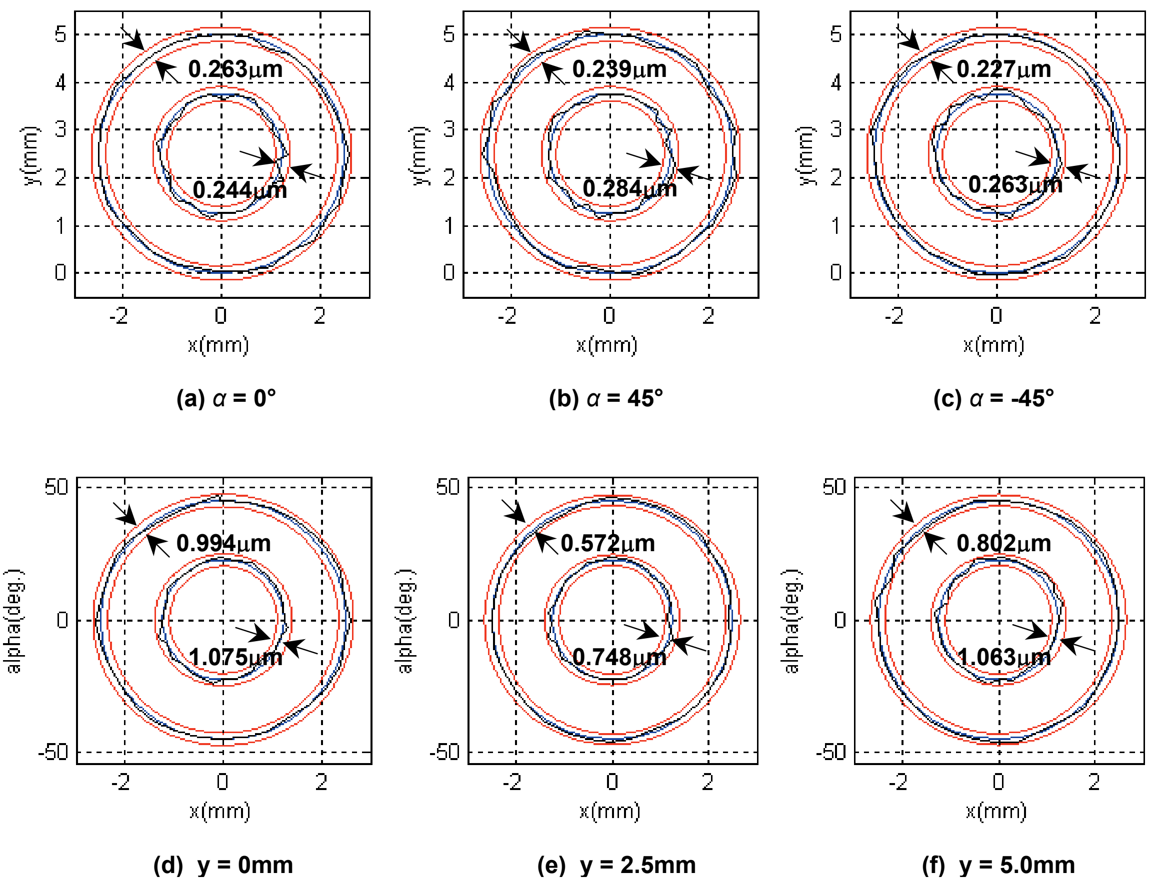


Figure 5 : Positioning capability of the micro-positioning parallel mechanism platform.

Since a PI controller is used for each positioning control of the three coarse actuators, respectively, total six controller gains have to be tuned. Taguchi methodology has been used for control gain tuning. The PI controller gains for the three fine actuators are set according to the recommended values of the manufacturer of the fine actuators.

Figure 5 presents the experimental result for verifying the positioning control capabilities of the developed micro-positioning platform. The (a), (b) and (c) in Figure 5 shows the contouring accuracy of the platform in the *x-y* plane at three typical tilting angles of *α* = 0, 45 and -45 degrees, respectively. The overall accuracy is within 0.3 μm.

The (d), (e) and (f) in Figure 5 shows the tilting capacity of the platform in the *α*-axis. The tilting angle range of ±50 degrees in the *α*-axis is achieved with the contouring accuracy within 1.1 μm on the basis of the extreme outer edge of the rotating platform, whose relative accuracy in μm unit is compatible with the contouring accuracy in the *x*- and *y*-axis. The feedrate in the *x*- and *y*-axis is 6 mm/min, respectively, and that in the *α*-axis is 48 degrees/min.

5 CONCLUSIONS

A three degrees-of-freedom parallel mechanism micro-positioning platform with the 100-degree tilting capability has been presented. It is controlled by a dual-stage controller. The two unique features of the dual-stage controller are that the actuation directions of the coarse and fine actuators are in vertical with each other and that it has the full-feedback control loop. The positioning accuracy of the platform in within 0.3 μm in 5 mm stroke.

The on-line calibration study of the linear sensors is in progress, and the dynamic control problem in the more rapid movement is also being studied.

6 ACKNOWLEDGMENTS

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