A Six-degree-of-freedom Micro Parallel Kinematic Stage for Multi-axis Positioning

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Abstract

This paper describes the concept, design and development of a six-degree-of-freedom (6-DOF) micro parallel kinematic stage for multi-axis positioning. The stage consists of six piezoelectric elements (piezos) and six electromagnets. The stage can move in the five directions by the principle of an inchworm, and can elevate a platform in z-direction by the principle of a parallel mechanism. Some preliminary experiments indicate the 6-DOF motion of the proposed stage.

1 Introduction

We previously developed a long travel range stage using the piezos[1]. The parallel mechanism using ultrasonic vibration realized the linear and rotational motion. The tilt motion of the platform however was very small. This paper proposes a 6-DOF micro parallel kinematic stage for multi-axis positioning. The ultimate goal of this project is to develop a precise stage capable of high resolution over long travel range in six directions (x, y, z, θ_x, θ_y and θ_z).

In high precision metrology and process equipment, it is desirable to have high resolution and large working area. The parallel kinematic stage has several positive characteristics, which are desirable for a positioning stage: low inertia, high stiffness, and no error accumulation. A typical example is the Stewart-platform driven by six prismatic joints. Although the Stewart-platform has some outstanding features, its working range is limited by the prismatic joints.

A piezo motor using the principle of an inchworm is an actuator with long travel range. The inchworm is controlled by a cyclic signal. Two clutch elements are excited alternatively, and a displacement element is synchronized with the clutch elements. The piezo motor has some outstanding features: high resolution, high driving force, and simple structure. An individual inchworm however is a one-dimensional actuator.

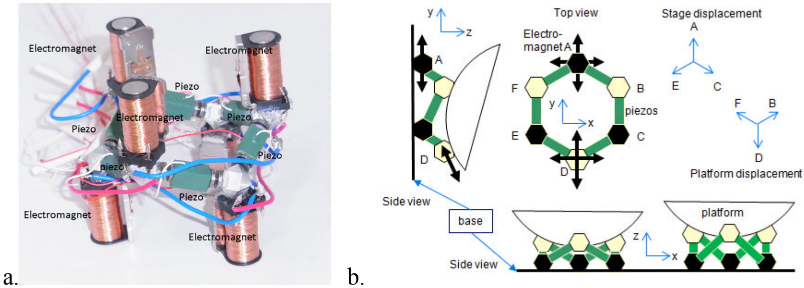


Figure 1: (a) Photo of the 6-DOF stage and (b) schematic diagram of the stage

2 Concept and Design

The stage described in this paper is similar to the Stewart-platform combined with the inchworm. The structure of the stage imitates the structure of a cyclohexane molecule in chair conformation. Prismatic joints correspond to chemical bonds in a ball-and-stick model, and connectors correspond to atoms in the organic compounds. The angle of the prismatic joints is 109.5 degrees.

Figure 1 shows the photo and schematic diagram of the stage which consists of six piezos as the prismatic joints and six electromagnets as the connectors. The platform supported by the stage moves in six directions, realizes sub-micron preciseness, and has an unlimited traveling range. The proposed stage does not have a fixed base. Three electromagnets A, C, E can connect the stage with the base. The other three electromagnets B, D, F can connect the stage with the platform.

While all the electromagnets are excited, the stage is identical with the Stewart-platform. The inverse kinematics determines the piezos' deformations. The travel range of the platform is as large as the piezo deformation.

The principle of an inchworm helps overcome the problem of poor working range. While five out of six electromagnets are excited, the other electromagnet that is not excited moves by the deformation of the piezos. The piezos deform in the longitudinal direction and thrust the electromagnet. The electromagnet A, C, E moves on the base and the electromagnet B, D, F slides in the tangential direction of the platform. In Figure 1(b), the moving directions of the electromagnets A and D are indicated as examples. The electromagnets and piezos are controlled synchronously, and they rotate and tilt a hemispherical platform.

Table1: Displacement, electromagnet controlled, and principle

Displacement	Electromagnet						Principle	Fig.
	A	B	C	D	E	F		
z	on	on	on	on	on	on	Parallel mechanism	3
x, y	on/off	on	on/off	on	on/off	on	Inchworm	4
θ_x, θ_y, θ_z	on	on/off	on	on/off	on	on/off	Inchworm	5

3 Experiment

The stage consists of 10 mm long multilayer piezos which deform 6.1 μm by 100 V_{DC}. We assume that the piezo deformation is in proportional to the applied voltage. The maximum voltage is 100 V, and one control cycle is 0.2 s. The moving directions are expressed by the electromagnets A-F, as shown in Figure 1(b). The electromagnetic force is about 5 N at 10 V. The piezos and electromagnets are fixed with adhesives. Metal parts bond the piezos in 109.5 degrees.

Experimental conditions are summarized in Table 1. The stage realizes the minute z-displacement by the parallel mechanism using piezos, while all the electromagnets are excited. The stage moves forward by the inchworm motion, when the electromagnets B, D, F keep excited and the stage is fixed to the platform. The stage rotate the platform in θ_x, θ_y, and θ_z directions by the inchworm motion, when the electromagnets A, C, E enable the stage to hold the base.

In the experiment, we used a flat iron plate (100 mm x 100 mm x 2 mm) instead of a hemispherical platform. Although the flat platform moves in the linear directions, its linear displacement is essentially identical to the rotational displacement of a hemispherical platform.

4 Results

Figure 2 shows the z displacement caused by the parallel mechanism, which is in proportional to the applied voltage to the piezos. Figure 3 indicates the stage displacement obtained by the inchworm motion. The stage moves linearly on a flat surface, although the insufficient electromagnetic force can not fix the stage. Figure 4 shows the linear and rotational displacement of the flat plate platform. By reducing the voltage applied to the piezo, we can obtain the 10 nm linear displacement and 100 nrad rotational displacement.

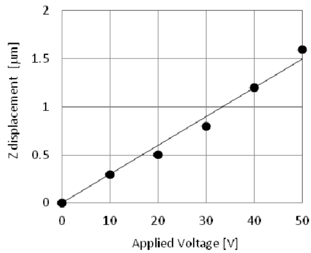


Figure 2: Z-displacement

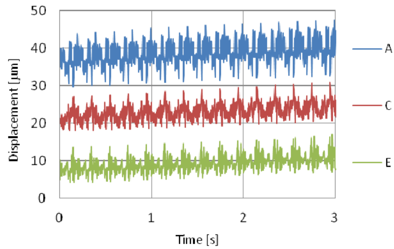
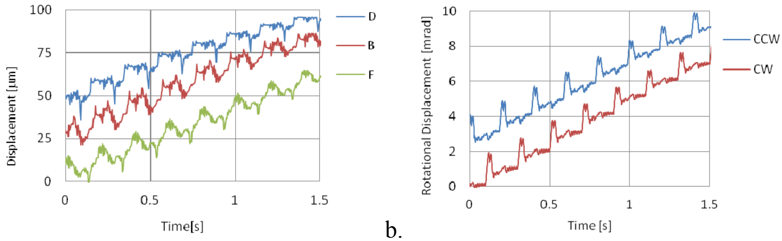


Figure 3: Linear stage displacement



a. b.

Figure 4: Platform displacement in (a) linear directions corresponding to θ_x and θ_y, and (b) rotational direction θ_z in CW and CCW

5 Summary

This research showed a 6-DOF stage for multi-axis positioning. The new concept of the stage design was introduced. It moved in x, y, θ_x, θ_y, θ_z directions by the principle of an inchworm, and elevated a platform by the parallel mechanism. These results show that the stage can realize not only 6-DOF minute motion by the parallel mechanis but also the 5-DOF incremental motion by the inchworm. The stage described in this paper is used in a scanning probe microscope.

Acknowledgements:

This project was financially supported by the Japan Society for the Promotion of Science (JSPS), “Grant-in Aid for Scientific Research (C), No. 23560302”.

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