DEVELOPMENT OF A NEW XY COMPLIANT PARALLEL MANIPULATOR FOR MICROMANIPULATION

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ABSTRACT

This paper deals with the development of a new XY compliant parallel manipulator (CPM) for micromanipulation in precision engineering. The XY CPM is actuated by two non-contact electromagnetic (EM) actuators through a low-cost 8-bit Arduino controller. The XY CPM has a stiffness of 380 N/mm, a natural frequency of 63 Hz and a motion range of 325 *u*m along each axis, which can achieve a higher resolution of up to 0.32 *u*m if a better displacement sensor is used. An open-control system and GUI control interface are also developed along with open-loop control testing results.

KEYWORDS: Compliant Mechanisms; Manipulator; Micromanipulation; Open-loop Control

1. INTRODUCTION

XY compliant parallel manipulators (CPMs) have been used in a variety of applications such as the atomic force microscope [1, 2], micro-assembly [3] and data storage [4], which transfer motion/load through the deformation of compliant links and are parallel-type manipulators. Their merits include eliminated backlash and friction, no need for lubrication, reduced wear and noise, and monolithic configuration [5]. An XY CPM is usually composed of a fixed base and a motion stage connected by compliant members and the motion stage of which only translates in the XY plane by the forces from actuators.

For the XY CPM using leaf beams under a large payload or out-of-plane vibration, one needs to increase the out-of-plane thickness (height of beams) of planar XY CPMs to enhance the out-of-plane stiffness [6]. However, the above approach will increase the primary motion stiffness and also increase the cost or even cause machining difficulty. Alternatively, spatial compliant mechanisms composed of wire beams can be used to improve the out-of-plane stiffness without the above negative issues [7, 8].

A wire beam not only has a large motion range in the DOF (degree of freedom) directions due to the distributed compliance but also has a very high stiffness along the wire axial direction, a DOC (degree of constraint) direction. This will result in the high stiffness (usually out-of-plane stiffness) of the resulting spatial compliant mechanism in the directions along the wire-beam axis. Moreover, spatial compliant mechanisms using wire beams cannot result in very

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large primary stiffness. This enables the use of the electromagnetic (EM) actuator since a larger primary stiffness will require a bulkier electromagnetic actuator to produce a higher peak force and therefore a quadratic larger heat creation. The use of the EM actuator benefits from large range of motion, linear model, and force-control along with hysteresis free, frictionless and cog-free motion.

Based on the above advances, this paper aims to propose a new XY CPM using the wire beams and develop an open-loop control system. This paper is organised as follows. Section 2 proposes the new XY CPM including the theoretical analysis for primary stiffness and motion range. Electronics and control are detailed in Section 3 followed by further discussions in Section 4. Conclusions are drawn finally in Section 4.

2. DESING OF NEW XY CPM

2.1 Description of XY CPM

The proposed XY CPM is shown in Fig. 1. It is composed of an XY motion stage actuated by two EM actuators and sensed by two displacement sensors (dial gauges). The two EM actuators are controlled by a low-cost 8-bit Arduino controller through two 10-bit DAC circuits and two power MOSFET drive circuits.

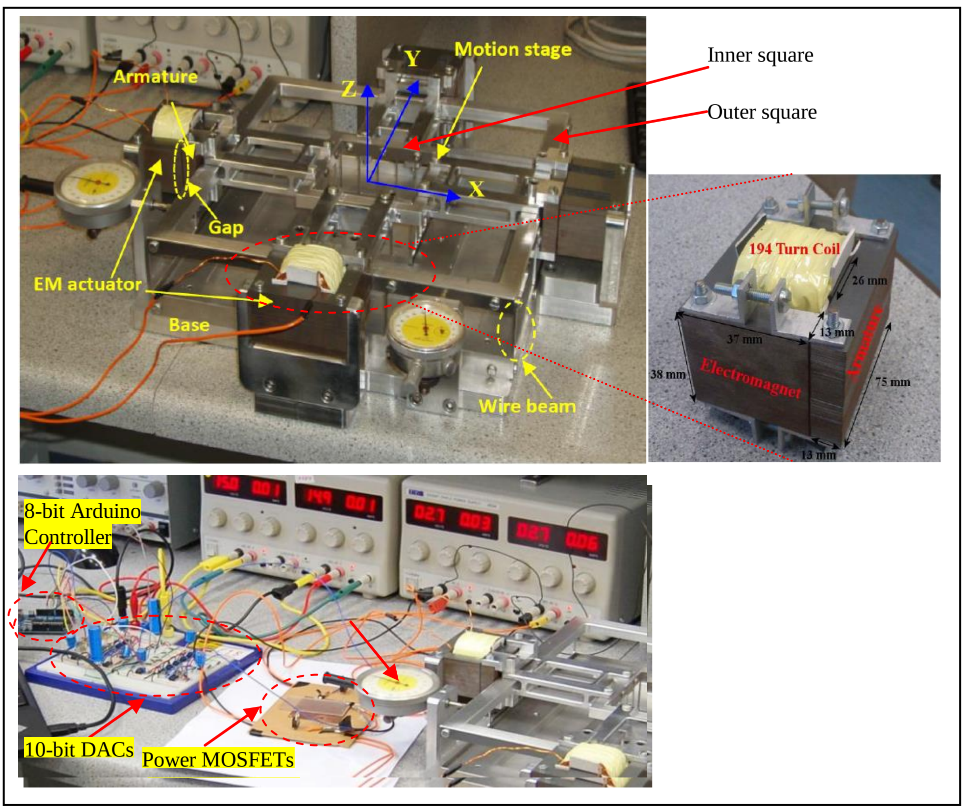


Fig.1 Embodiment of XY CPM.

The XY motion stage, with a desktop-size dimension of 300 mm × 300 mm, is a compliant parallel mechanism consisting of 32 parallel identical wire beams to support the motion stage. Each wire beam has a uniform and square cross-section with a length of 31 mm and thickness of 1.5 mm. Here, 20 beams and 12 beams uniformly distribute along an inner square and an outer square, respectively. The inner and outer squares are rigidly connected to form a motion stage where the side length of the inner square is 89 mm. The material chosen for the wire beams is AL6082-T6 with Young's modulus of 70 Gpa and yield strength of 250 Mpa. All wire beams are fabricated by CNC milling machining from eight pieces of plates with thickness of 1.5 mm where four pieces consist of the outer/inner square of the XY motion stage. The other rigid parts are fabricated separately before the final assembly.

Each EM actuator is an E-core actuator with AWG 18 coil of 194 turns. Two armatures are mounted to the motion stage. The gap width between the E-core actuator and the armature is setup to 1 mm. When the current flows into the coil of the EM actuator, the produced magnetic force will attract the armature to reduce the gap width so that the XY motion stage will translate. The details for the electronics and control will be discussed in Section 3.

2.2 Theoretical Analysis

The primary stiffness along each motion axis (X or Y-axis) can be derived as follows:

$$K=32\times 12EI/\mathrm{L}^3, \tag{1}$$

where "32" is the total number of beams, E is the Young's modulus, L is the wire beam length, and $I=T^4/12$ is the second moment of the wire beam cross-section. Here, T is the wire beam thickness.

The substitution of all the above assigned parameters into Eq. (1) yields

$$K=380 \text{ N/mm}.$$

In addition, based on maximal shear stress theory, the single-axis motion range of the XY CPM must meet the following condition to avoid the material yield:

$$\varDelta_1\leq(1/3)(\sigma_s/E)(L^2/T), \tag{2}$$

where σ_s is the material yield strength.

Substituting all the above assigned parameters in Section 2.1 into Eq. (2), one can obtain the motion range:

$$\varDelta_1\leq 0.763 \text{ mm}.$$

It is noted that the force-displacement characteristic of the EM actuator also affects the motion range of the XY CPM as detailed in Fig. 2. In order to make the magnetic force from the actuator balance the stiffness of the XY motion stage over the whole motion range, the motion range cannot exceed 0.325 mm (at the gap width of 0.675 mm when the EM actuator curve with the current of 2.16 A is just tangent to the XY motion stage curve), i.e.

$$\varDelta_2\leq 0.325 \text{ mm}. \tag{3}$$

Comparing Eqs. (2) and (3), it can bed concluded that the maximal motion range of the XY motion stage is

$$\varDelta_{max}=\min(\varDelta_1, \varDelta_2)=0.325 \text{ mm}.$$

In addition, the first-two order natural frequencies of the XY motion stage have been simulated by Solidworks, which are both equal to about 63 Hz.

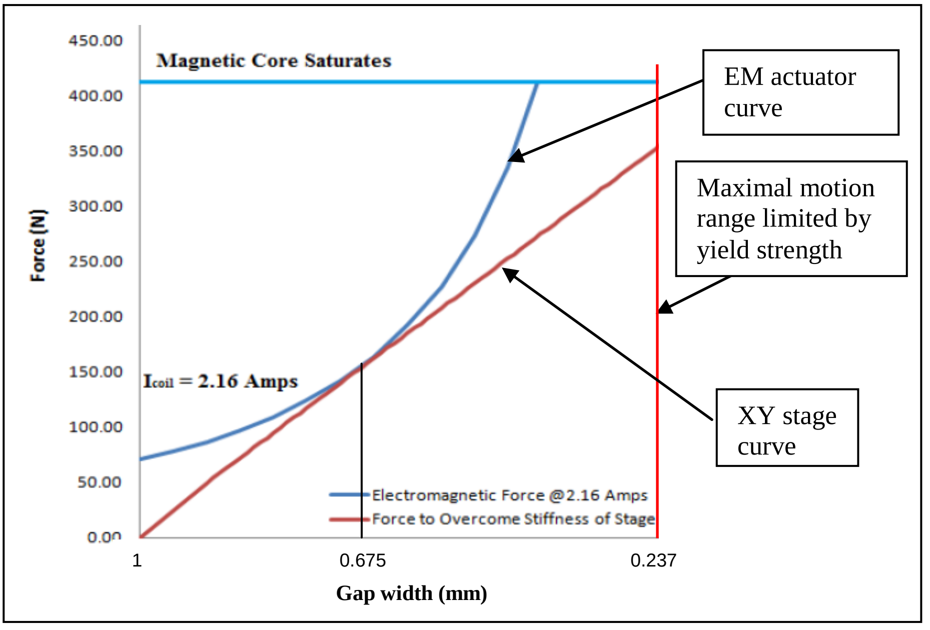


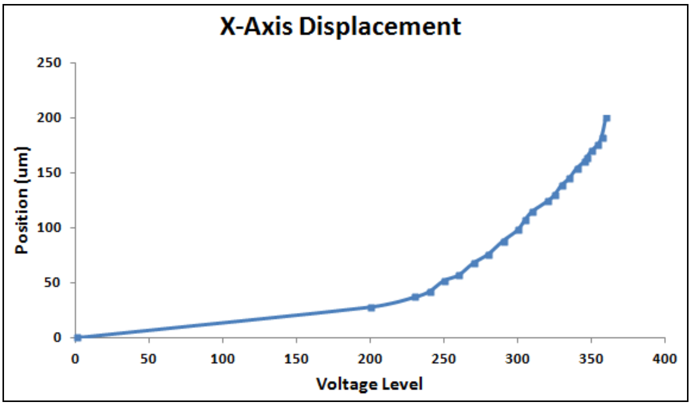
Fig.2 Comparison of force-displacement relationships between the EM actuator and the XY motion stage.

3. ELECTRONICS AND CONTROL

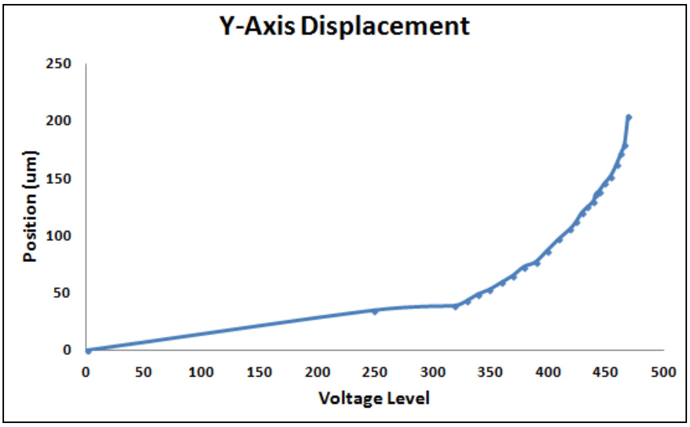
In order to control the current through the coils of the two EM actuators, two "PHT6N06LT" power MOSFET drive circuits (Fig. 1) are adopted. The maximal continuous current rating for the MOSFET is 2.5 A which is more than the maximal current (2.16 A) to drive the EM actuator for producing large enough forces. For safety reasons, the flyback diode is used in the drive circuit. A soldered copper plate as heat sink is also employed to keep the MOSFET's temperature down.

Due to the fact that the 8-bit Arduino microcontroller can only provide 256 discrete voltage levels, which cannot achieve a resolution of at least 1*u*m over the motion range of 325 *u*m, two 10-bit DAC circuits are thus designed. The final circuit can achieve 1024 separate voltage levels in a range of 1.4 to 2.6 V, therefore a resolution of 325/1024 *u*m can be realized if no limitation from others.

Before a sophisticated closed-loop control system can be implemented, an initial open-loop control is done in the work of this paper. The open-loop control testing results in two displacement-voltage graphs (Fig. 3), which relate values for the displacements of the motion stage to the voltage output levels from the Arduino controller. Here, the dial gauge with a 2 *u*m resolution is used to sense the displacement. It can be observed from Fig. 3a that the nonlinearity is apparent after the voltage level of 200, which makes the precise control more difficult. It is also noted that the X-axis displacement-voltage characteristic is slightly different from the Y-axis, which may be attributed to the manufacturing/assembly error for the actuators



(a) Open loop X-axis results



(b) Open loop Y-axis results

Fig. 3 Open-loop control testing results.

The *Processing complier* is used to communicate with the Arduino microcontroller through the serial port of a PC. This compiler uses java which is different than the Arduino using C++. Using results taken from the open-loop testing (Fig. 3), a library database of voltage levels and there corresponding motion stage position results is created. The program works by allowing the user to input a position value between 0 and 300 μm with the keyboard of the PC. The inputted position is then compared to the library of positions. The voltage level corresponding to the open-loop result position that is closest to the input value is then selected. This voltage level value is sent to the Arduino. When the Arduino receives the value, it processes this and also sends back the same voltage level to the PC. This is just to ensure that the Arduino receives the value and doesn't come across any problems. The Processing program then takes the received value, and prints onto the GUI on the PC screen. Figure 4 shows an image of the GUI created using *Processing*.

The two-axis motion can be controlled by pressing X for the X-axis and Y for the Y-axis on the keyboard. This sends an X or Y character to the Arduino and allows it to swap between the two drive circuits so each actuator can be controlled separately. The axis on the GUI also changes to let the user know what axis is being controlling. In this way, the XY CPM has an open loop control of both axes.

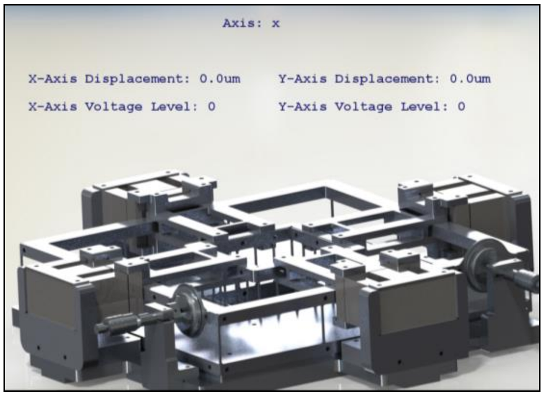


Fig. 4 Open-loop control GUI of XY CPM.

4. DISCUSSIONS

There are some unique advantages for the proposed XY CPM. The non-contact control (due to the gap) can prevent the heat from the EM actuators from dissipating to the XY motion stage so that the deformation of wire beams is only controlled by the actuation force. The proposed design has a very desirably high out-of-plane stiffness which can support a very high payload or be used for other purposes. Due to the fact that the output stage acts as the input stage as well, no lost motion exists and fewer displacement sensors are needed.

However, some disadvantages remain. On the one hand, there are undesired parasitic translation along the Z-axis and parasitic rotations about the X- and Y-axis accompanying the two primary translations [8]. On the other hand, although the in-plane parasitic rotational yaw about the Z-axis cannot be produced by the two actuation forces from the EM actuators and the adopted two-square strategy can further enhance the Z-axis rotational stiffness [8], the motion stage can still have non-negligible rotation under some circumstances on the second hand. For example, if a small external force exerting on the outer edge of the XY motion stage forms a large rotation arm regarding the motion stage center, a large rotational moment can be therefore caused to generate an appreciable parasitic rotation about the Z-axis.

The currently-used two EM actuators can only attract the XY motion stage to cause translation along the uni-direction in each axis. If four EM actuators can be used (i.e. two in each axis), the motion range of the XY CPM can be extended to 650 *u*m in total in each axis.

The presented XY CPM in Fig. 2 has only a resolution of 2 *u*m which is limited by the dial gauge used. In order to improve the resolution, a better displacement sensor, which can tolerate the cross-axis motion, is needed.

5. CONCLUSIONS

A XY CPM for micromanipulation in precision engineering has been reported in this paper. The XY CPM has a stiffness of 380 N/mm with first-two order natural frequencies of 63 Hz, a motion range of 325 *u*m with a 2 *u*m resolution. An open-control system and GUI control interface have been developed. It is hoped that a sophisticated closed-loop control system can be conceived in the near future for the XY CPM.

6. REFERENCES

[1] Schitter, G., Thurner, P.J, and Hansma, P.K., 2008, "Design and Input-Shaping Control of a Novel Scanner for High-Speed Atomic Force Microscopy", *Mechatronics*, 18:282-288.

[2] Werner, C., Rosielle, P.C.J.N., and Steinbuch, M., 2010, "Design of a Long Stroke Translation Stage for AFM", *International Journal Machine Tools and Manufacture*, 50(2):183-190.

[3] Gorman, J.J., and Dagalakis, N.G., 2003, "Force Control of Linear Motor Stages for Microassembly", *ASME International Mechanical Engineering Conference and Exposition*, Washington, DC, Nov. 15–21, USA.

[4] Vettiger, P., Despont, M., Drechsler, U., Durig, U., Haberle, W., Lutwyche, M.I., Rothuizen, H. E., Stutz, R., Widmer, R., and Binnig, G. K., 2000, "The Millipede—More Than One Thousand Tips for Future AFM Data Storage", *IBM Journal of Research and Development*, 44(3):323–340.

[5] Howell, L.L., 2001, *Compliant Mechanisms*, Wiley, New York.

[6] Hao, G., and Kong, X. 2012, "A Novel Large-Range XY Compliant Parallel Manipulator with Enhanced Out-of-Plane Stiffness", *Journal of Mechanical Design*, 134:061009.

[7] Hao, G., Kong, X., and Reuben, L.L., 2011, "A Nonlinear Analysis of Spatial Compliant Parallel Modules: Multi-Beam Modules", *Mechanism and Machine Theory*, 46(5):680-706.

[8] Hao, G., and Kong, X., 2014, "Nonlinear Analytical Modelling and Characteristic Analysis of Symmetrical-Beam Based Composite Compliant Parallel Modules for Planar Motion", *Mechanism and Machine Theory*, 77: 122-147.