A SIX DEGREE-OF-FREEDOM TRI-LAYER CHEVRON BEAM THERMAL ACTUATOR

Shih-Chi Chen
MIT Department of Mechanical Engineering
77 Massachusetts Avenue, Room 3-446
Cambridge, MA 02139
Tel: 617-452-4957, scchen@mit.edu

Martin L. Culpepper
MIT Department of Mechanical Engineering
77 Massachusetts Avenue, Room 3-449b
Cambridge, MA 02139
Tel: 617-452-2359, culpepper@mit.edu

Keywords: Flexure, compliant mechanism, stiffness, MEMS, manipulation

1 Introduction

In recent years, micro-electro-thermal actuators have been used for single-axis positioning. For example, the bent-beam electro-thermal actuator, developed in 1999, provides 20 µm stroke and more than 100 µN force output. [1, 2]. Although thermally driven micro-manipulators/actuators have a limited operating frequency (generally less than 1 kHz), there are many small-scale, precision alignment and manipulation applications which do not require ultra-high bandwidth. For example micro-photonics alignment is a reasonable candidate. Unfortunately, the state-of-the-art in MEMS electro-thermal actuators is only capable of generating single degree-of-freedom motion [3]. These actuators would be more useful in small-scale precision manipulators if they were capable of multi-axis actuation and high force output. This paper introduces the concept of a multi-axis, tri-layer electro-thermal actuator. The actuator, shown in Fig. 1, has been designed to move in 5 or 6 axes. The actuator exhibits an unexpected motion displacement which affects the precision of its motion. In this paper, we examine a 1st order model used to predict when this phenomenon occurs. This is a necessary first step before we seek to use this actuator in a small-scale precision manipulator.

![Figure 1: A SEM of the tri-layer chevron beam actuator](image1.png)

2 Actuator design concept

As shown in Figure 2A, the tri-layer chevron beam actuator is made of two identical device layers bonded together via a 1 µm thick thermal oxide layer at selected locations (Fig. 2B). Each device layer is 8 µm
thick and comprised of two parallel bi-layer chevron beams of 6µm width. Thus each device layer contains two identical chevron actuators which can be independently or simultaneously actuated. The beams of the actuators connect to the central structure which is 50 µm wide x 1.2 mm long. The beams intersect the central structure at a 10° angle.

![Figure 2: A SEM of the tri-layer chevron beam actuator](image)

**3 Generating displacements in six axes**

The tri-layer actuator has the ability to achieve six-axis displacement by selectively actuating the electro-thermal actuators. Motion generations are explained in Figure 3A - F. The dashed lines represent a driving current through the top layer, and the dotted lines represent current through a bottom layer. To obtain pure y-axis motion, current is supplied to both top and bottom layers as shown in Figure 3A. To obtain z motion, the current is run through both of the chevron beams on the bottom layer. These beams then cause the actuator to buckle out of plane in the z direction. To obtain the angular displacement θx (Fig. 3C), the currents is routed through the top and bottom layer at either the front or back chevron beams. Figures 3D – 3F show how other displacements are achieved.

![Figure 3: Demonstration of six-axis actuation.](image)
4 Modeling out-of-plane motion sensitivity

The ratio of in-plane stiffness to out-of-plane stiffness of the tri-layer actuator is considered to determine the adequate thicknesses and ratios of the silicon and oxide layer. As the top or bottom layer is heated, the chevron beam on that layer expands. The heated chevron beam moves forward and bends out-of-plane by a small amount at first, then by a rapidly increasing amount as more current is applied. For now, we choose to model this out-of-plane bending displacement by using a model which treats the shallow angle chevron beam as a straight beam which is grounded on both ends. As the beam strains thermally, the beam bends out-of-plane, the length of the beam increases and the out-of-plane curvature changes. The curved beam equations [3] shown in Fig. 4A and the dimensions of the chevron beam actuator were used to generate the stiffness graph in Fig. 4B.

\[
\delta_{H_A} = \frac{R^3}{EI} \left( A_{HH} H_A^2 + A_{HM} \frac{M_A}{R} - LP_H \right)
\]

A: Curved beam displacement

Figure 4B shows the out-of-plane stiffness of a curved beam as a function of the curvature. A decrease in stiffness is observed as the curvature increases. As the out-of-plane included angle approaches 0.4 degree, a decrease in the stiffness is observed. Regions I and II are defined to the left and right of the 0.4 degree angle. Initially, the in-plane stiffness of the actuator is smaller than the out-of-plane stiffness. This is required to ensure that the displacement of the chevron beams will be confined to in-plane directions. However, the out-of-plane stiffness is a function of the out-of-plane curvature. Should the out-of-plane stiffness decrease below a specific stiffness value (at the border between Regions I and II), the actuator will find it is easier to deform out of plane than in-plane. At this point, an actuator which is told to move in plane will actually move out of plane.

5 Experimental results

Testing of the tri-layer chevron beam actuator was performed with the white light interferometer for motion in three major axes $\theta_x$, $\theta_y$, and $\theta_z$. Figure 5A and 5B show the input current versus actuator tip displacement in $\theta_x$ and $\theta_z$ axes. Both plots can be divided in two regions as in Figure 4B. In Region I, the displacement outputs vary from 0 to 3µm where, as the input current increases, the displacement increases
at slightly more than linear. This result corresponds to Region I in Figure 4B. Likewise, Region II in Figure 5 corresponds to Region II in Fig. 4B.

![Graph](Image)

**Figure 5:** The plots of $\theta_x$ and $z$ error motion which occur as chevron beam stiffness changes

The buckling beam model accurately predicts the error transition point between Region I and Region II and the amount of error at this transition, yet fails to predict the correct behavior of the actuator within Region II. We are presently examining how to make the transition in the curve more pronounced so that we might use these actuators as binary actuators.

## 6 References


