A high-force, out-of-plane actuator with a MEMS-enabled microscissor motion amplifier

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Abstract: The design, fabrication, and demonstration of a set of 2 mm², high-force actuators that combine piezoelectric in-plane actuators with MEMS-enabled scissor mechanisms (motion amplifiers) to simultaneously produce high out-of-plane forces and large out-of-plane displacements are presented. The microscissor motion amplifier employs two layers of lithographically-patterned SU-8 microstructure laminated with a thin film of structural polyimide and adhesive to form hinges. Performance is optimized by varying layer thickness and adhesive types. Measured displacements of >3 µm and measured forces of >5 mN are observed, corresponding to a displacement per unit area of 1.6 µm/mm² and a force per unit area of 2.6 mN/mm². Cyanoacrylate adhesive provides superior performance to silicone adhesive, with larger force output. Thicker polyimide hinges provide smaller displacement but greater force than thinner polyimide hinges. These powerful, compact actuators have significant potential for high-force applications like tactile displays and micropumps.

1. Introduction

Providing information to those who are blind or have low vision is critical for enhancing mobility, situational awareness, education, and more. Text-based tactile information delivery can be effective, rapid, and private; examples include Braille and the Optacon [1,2], both of which deliver text through the motion of few centimeter scale piezoelectric bending beam actuators. Conveying graphical information that cannot be expressed as text through tactile stimuli is highly desired, but it is challenging to create actuators that are compact enough to provide high resolution graphical information while still having large force and displacement and being robust enough to be well sensed by users. Existing refreshable tactile graphical display technology includes electroactive polymer (EAP) actuators [3,4], piezoelectric bending beams [5], and other MEMS-enabled actuators [6,7]. EAP actuators are small in size, enabling a few millimeter pitch, but they have large actuation times on the order of seconds. Piezoelectric bending beams must be large enough to achieve the necessary forces, making integration into compact systems a challenge. MEMS devices offer a route to compactness, but engineering MEMS for high force and/or large displacement can be a challenge.
To address these challenges, tactile elements that magnify small in-plane vibrations into the vertical direction using scissor amplifiers were introduced in [8]. Although these tactile actuator elements were at the 30 mm² scale, the ultimate goal of this type of actuator is to achieve high resolution displays (similar to the 1 mm² resolution of human fingerpads) with rapid refreshability and the ability to convey spatial patterns, motions and rhythms for diverse information delivery [8]. The present research employs a new design and process, modeled on that of [9], to reduce the size (area/element) of this technology by 15X relative to [8]. The present tactile elements employ two layers of lithographically-patterned SU-8 microstructure laminated with a thin film of polyimide and adhesives to form hinged microscissor motion amplifiers. The microscissors are integrated with piezoelectric extensional actuators so that the microscissors convert the actuators’ in-plane motions into larger out-of-plane vibrations (figure 1). This approach has potential not only for tactile displays but also for other applications in which high force is desired, such as micropumps.

Figure 1. Schematic diagram of a single actuator for a tactile array. The actuator comprises an in-plane PZT actuator with a laminated, micro-fabricated scissor amplifier to convert small in-plane vibrations into 10X larger out-of-plane vibrations.

2. Design and Fabrication

The microscissor requires both flexible elements (for the hinges) and rigid elements (for the scissor linkages). The flexible elements are made of polyimide film, with a Young’s modulus of about 2 GPa. The polyimide extends along the entire length of the scissor. Because the structure requires bending to be localized in the four hinges as in figure 1, the linkages are made more rigid by the lamination of photolithographically-defined SU-8 elements onto the polyimide film in the regions that are not supposed to bend. After the completed microscissor is mounted on the extensional piezoelectric actuator, contraction and expansion of the actuator bend the hinges so that the center of the scissor rises and falls. The offset, interleaved hinge structure leaves ample clearance for the rigid linkages during bending. Unlike in [8], the present hinge structure shortens the hinge length, maximizing the space available for longer linkages that provide larger vertical displacement.

The rigid elements for the linkages (figure 2) are 200 µm thick, 3 mm long, and 0.67 mm wide, corresponding to a 2 mm² actuator. Both the upper and lower rigid structures are patterned in SU-8 2150 by a single layer photolithography process. The SU-8 is patterned on top of a 15 nm layer of Omnicoat to enable subsequent release from the substrate. A temporary “carrier tape” made of polyimide is adhered to the SU-8 structures, and the Omnicoat is then dissolved to release the SU-8 from the wafer. The carrier tape preserves the relative positions of the SU-8 elements. The upper and lower SU-8 structures are laminated above and below the thin polyimide hinge layer with two layers of adhesive to form the microscissor as shown in figure 3. The carrier tape is then removed. The polyimide hinges are 30 µm long, 670 µm wide, and either 25 µm, 50 µm, or 125 µm thick, depending on the thickness of the polyimide film that is used. Two adhesives are used. The first is a 50 µm thick low-modulus silicone adhesive that comes laminated on both sides of a polyimide tape. The second is an approximately 5 µm thick layer of cyanoacrylate adhesive that is applied manually to the SU-8
parts before they are laminated onto a plain polyimide tape. The thickness of the cyanoacrylate is determined by measuring the thickness of the polyimide/SU-8 composite structure both with and without the adhesive layer; the volume of cyanoacrylate is also well controlled to prevent excess adhesive. The resulting microscissor is shown in figure 4a before the hinges are bent. Two hollow, rectangular SU-8 clamps are microfabricated separately for use in the actuator assembly process.

Figure 2. Optical micrographs of (a) the 200 µm thick SU-8 structures (rigid elements of the actuator) with 30 µm gaps for hinge bending, and (b) the upper and lower hinge structures implemented in SU-8 for a 3 mm x 0.67 mm micro-scissor.

Figure 3. Fabrication process flow of a single actuator for a tactile array. a) Pattern SU-8 on wafer. b) Transfer SU-8 from wafer to polyimide carrier tape. c) Separate upper and lower SU-8 parts. d) Laminate polyimide film, adhesives and both sets of SU-8 parts. e) Peel off the polyimide carrier tape. f) Attach the tactile interface pin. g) Attach the SU-8 clamps (fabricated separately) to the PZT extensional actuator. h) Solder PZT to printed circuit board. i) Adhere scissor to PZT to form actuator.

Figure 4. Optical micrographs of (a) an assembled SU-8 microscissor with total thickness of 430 µm, and (b) an assembled single tactile element with electrical connections.

The two clamps are mechanically registered to the ends of commercially-available, y-poled PZT actuators with dimensions of 3 mm x 0.67 mm x 0.38 mm with cyanoacrylate applied in the gap between clamps and PZT to ensure strong bonding. The scissors are then mounted on the clamps. The overall lengths of the two microscissors are designed to be longer than the length of the PZT actuator. When the microscissor is attached to the PZT, the hinges form a starting (unactuated) angle of 9° between the scissor linkage and the PZT. The clamps serve as an interface between the actuator and the scissor and provide clearance for electrical connections. The center of the actuator is soldered to a
printed circuit board, creating electrical connection and mechanical support. The top of the PZT is grounded via a soldered connection. Because the present actuators are demonstrated for tactile displays, an SU-8 pin is integrated on the scissor’s central element to create the sensing interface. Figure 4b shows a fully-assembled actuator with the scissor mounted on a PZT extensional actuator.

3. Experiments and Results

The individual actuators are mounted on a testing stage under an optical stereomicroscope so that the deformations of the scissor are visible in the microscope’s viewing plane. A square wave bipolar AC voltage with a frequency of 0.5 Hz is output by a function generator, amplified, and applied to the device. The voltage amplitude is increased in 10 V steps from a starting value of 50 V to the maximum value of 170 V. The maximum peak voltage is below the PZT’s maximum allowable voltage and reflects the limits of the test electronics rather than the device. The tip of the actuator moves under the applied voltage, and a microscope camera captures two or three images of the actuator in its maximum and minimum positions for each voltage. The actuator’s displacement is measured by pixel counting in the captured images, in which each pixel is 0.45 µm. Displacement values are recorded for voltage values on which the pixel count increments by a full pixel, avoiding the need for interpolation.

To measure the amplitude of the force that the actuators apply when they vibrate in contact with a rigid surface, the individual actuators are mounted on a second testing stage that is in turn mounted to the grips of a mechanical tester (Instron 5943). The mechanical tester applies a compressive preload of 40 mN to the sensing pin when zero voltage is applied to the actuator. A square wave bipolar voltage with a frequency of 10 Hz is applied to the actuator, and its peak amplitude is increased from 50 V to 170 V in increments of 10 V. The resulting forces are measured by the mechanical tester’s load cell.

Figure 5. Plots of (a) the measured vibrational amplitude and (b) the measured force output by the 2 mm² tactile elements with various adhesives and layer thicknesses vs. applied voltage.

The measured peak-to-peak displacement and the measured force are plotted in figure 5. The solid line represents the displacement predicted analytically for the simplified case of an ideal microscissor with pinned hinges [8]. The dashed lines with markers represent measured data with different thicknesses of polyimide and different adhesives. The results show that the cyanoacrylate provides larger force output than the silicone adhesive does. Increasing the polyimide thickness at a given level of applied voltage typically decreases the displacement while increasing the measured force.

The actuator with a 125 µm thick polyimide hinge adhered by cyanoacrylate adhesive has a maximum displacement of 3.3 µm and a maximum force of 5.3 mN, corresponding to a displacement per unit of actuator area of 1.6 µm/mm² and a force per unit of actuator area of 2.6 mN/mm². This compares favorably with the results of [8], which yielded a displacement and force per unit of actuator area of 0.3 µm/mm² and 1.6 mN/mm², respectively. Its force output also compares favorably with [10-12], which yielded forces per unit of actuator area of 1.1 mN/mm², 0.9 mN/mm², and 0.6 mN/mm², respectively. Furthermore, the actuator’s performance may be optimized for different applications by varying the layer thicknesses.
4. Conclusion
The design, fabrication, and operation of a set of compact tactile actuators that have a 15X smaller footprint than previous generations of actuators [8] but still achieve displacements of \( > 3 \mu m \) and forces of \( > 5 \text{ mN} \) have been demonstrated. The maximum peak voltage of 170 V applied here is below the PZT’s maximum allowable voltage, indicating that the maximum measured displacement and force are lower bounds on the actuator’s performance. The measured performance corresponds to values of force per unit area and displacement per unit area that are 5.3 times and 1.6 times those of [8], respectively. The current actuators’ performance is enabled by the use of a laminated hinge architecture that maximizes the length available for the scissor linkages in a compact area. The performance of the actuators is shown to depend on the details of the microscissor design. Varying the thickness of the polyimide hinge layer provides an effective means of tuning the actuators’ force and displacement, and laminating the layers with a thin layer of cyanoacrylate adhesive instead of a more compliant silicone adhesive optimizes force output at the cost of a slight decrease in displacement. Overall, however, the measured displacements are close to predictions based on an ideal pinned-hinge scissor. Unlike conventional MEMS actuators, which are commonly used for applications like switches and optical devices, these powerful yet compact actuators have significant potential for high-force applications like tactile displays and micropumps.

Acknowledgements
This work was supported by the Samsung Think Tank Team. Microfabrication was performed in the George J. Kostas Nanoscale Technology and Manufacturing Research Center at Northeastern University.

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