# PASSIVELY SELF-ALIGNED ASSEMBLY OF COMPACT BARREL HINGES FOR HIGH-PERFORMANCE, OUT-OF-PLANE MEMS ACTUATORS

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## ABSTRACT

A passively self-aligned, assembly-based process for rapidly creating compact, micro-barrel hinges with unconstrained rotation from SU-8 epoxy is presented. The alignment process takes places in two stages: a coarse alignment stage guided by external dowel pins followed by a fine alignment stage driven by the hinges' features themselves. The assembly of pins into housings circumvents the design rules for minimum gap between features of given thickness in SU-8 processing, enabling reduced hinge clearance for minimization of "side play". The present hinges' fabrication and function are demonstrated through the design, implementation, and characterization of a displacement-amplifying, out-of-plane, scissor-based actuator that is driven by an in-plane, piezoelectric extensional actuator. The micro-barrel hinge enabled motion amplifier comprises six functional SU-8 multilayer plates joined by three layers of adhesives. Each functional plate comprises two or three layers of SU-8 fabricated by multiple exposures and a single development step. Displacements of up to 11.5 µm and forces of up to 10.5 mN are measured for the 10 mm$^2$ actuator, corresponding to a displacement and force per unit area of up to 1.15 µm/mm$^2$ and 1.05 mN/mm$^2$ respectively and offering potential solutions for applications like haptic interfaces and micropumps.

## INTRODUCTION

Micro hinges can permit large angular motions in MEMS actuators, but making conventional hinges scalably at the microscale while maintaining good mechanical properties can be difficult. Surface micromachined, pinned hinges are well known [1], but the required investments of time and resources for conventional silicon-based microfabrication are considerable. Flexural hinges comprising laminated stacks of patterned rigid and flexible layers [2,3] offer a rapidly-fabricated, low-cost alternative, but their finite stiffness and spatially-distributed rotation prevent ideal pinned-hinge behavior. To maintain the ideality of pinned hinges while reducing fabrication cost and complexity, pivot hinges were fabricated from patterned, laminated SU-8 plates that define pivots and housings in a common set of mask layers [4]. The resulting minimum nominal clearance of 50 µm separates the pivot from its housing, but the single-layer fabrication introduces significant taper and side play to the hinge's geometry and motion, allowing the pivots to tilt and shift within their housings and limiting ideal hinge function. In contrast, the present pins are defined in separate layers from their housings. The assembly of (sometimes multipart) pins into housings not only minimizes tilt and reduces side play by a factor of >3X compared with [4] but also provides robust, fine-scale self-alignment for straightforward assembly.

The barrel hinge enabled micro motion amplifier is implemented into a haptic actuator where large force and displacement are desired, as shown in Figure 1. The concept of the haptic actuator has been shown and demonstrated via flexural hinges in [5]. When the underlying lead zirconate titanate (PZT) actuator contracts, the micro motion amplifier converts the small horizontal displacement into larger vertical displacement. The amplifier's anchors' recessed design creates end stops that passively align the scissor amplifier to the PZT actuator.

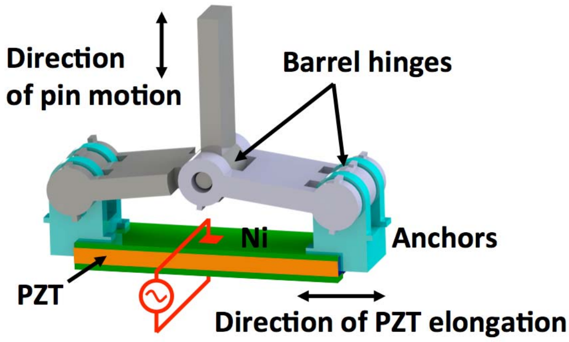


*Figure 1: Schematic diagram of a barrel-hinged micro motion amplifier mounted on a PZT extensional actuator.*

## DESIGN AND FABRICATION

The concept of the haptic actuator is similar to [3-5]. When the PZT is driven by an alternating voltage, its central pin vibrates in a combination of up-and-down and side-to-side motion. The shallow angle of the hinged scissor mechanism ensures that its vertical rise greatly exceeds its horizontal contraction [5]. Compared with the pivot hinges of [4], the barrel hinge offers more ideal pinned-hinge performance, with unconstrained rotation of the hinge pins inside their housings.

Figure 2 shows the fabrication of one of the amplifier's 3-layer SU-8 plates. The plate shown includes two rigid scissor linkages, a haptic interface pin, and parts of the hinges that connect the linkages to each other and to the supports. Three layers of SU-8 are deposited and patterned in sequence over a 15 nm thick Omnicoat™ release layer on a silicon substrate. A single development step removes the unexposed SU-8 from all three layers. Dissolving the Omnicoat™ releases the three-layer plate from the substrate. Figure 3 shows micrographs of two of the amplifier's three multilayer SU-8 plates that define pin and housing elements, functional amplifier elements, and the supporting frames to which the functional elements are connected by removable tethers for ease of alignment.

Three multilayer SU-8 plates together form each half of the amplifier structure (Figure 4a). In the first half, plates a and c define the linkages. The linkages in plates a and c are adhered to each other, retaining the one-part central barrel pin (plate c) in its housing (plate a). The adhesion of plates a and c also captures their two-part outer barrel pins in the outer housings (plate b). The two-part outer pins allow the anchors to rotate without constraint, and the one-part central pin permits motion and rotation of the sensing interface. The two halves (a-c and d-f) are adhered to each other to form the complete device, connecting both the linkage/sensing interface and the anchors that align with the PZT actuator. The thickness of each layer is set to ensure proper mechanical interfaces among the parts. All pins are fabricated from SU-8 50; all structural elements (except for the anchors) are fabricated from SU-8 100; and the anchors are fabricated from SU-8 2150.

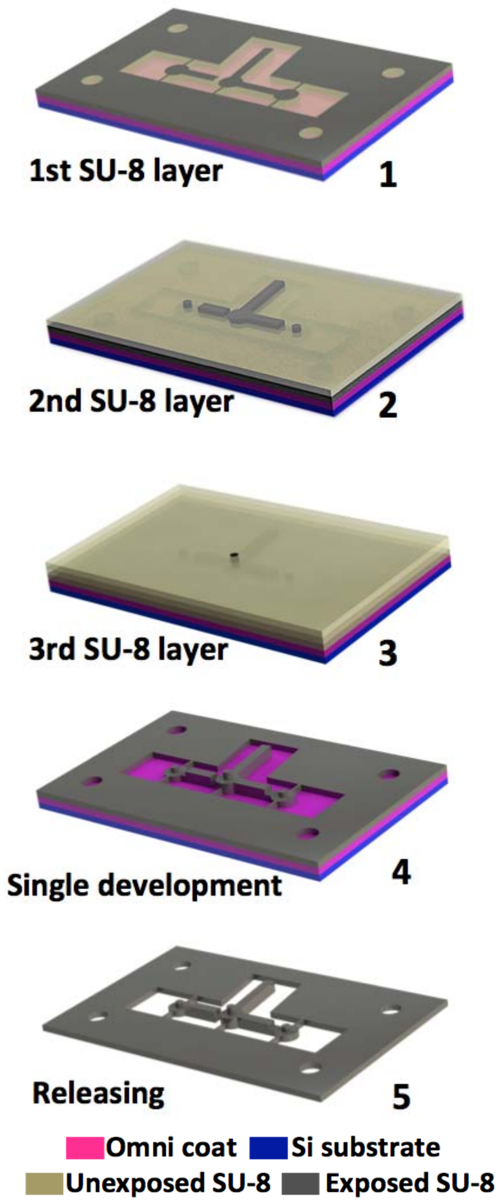


*Figure 2: Illustration of the microfabrication process for a nominal structural layer, showing (1) patterning of the scissor linkages and sensing interface over the release layer; (2) patterning of the linkages, sensing interface, and two-part outer pins; (3) patterning of the one-part central pin; (4) development of the SU-8 multilayer structure; and (5) release of the 3-layer SU-8 plate.*

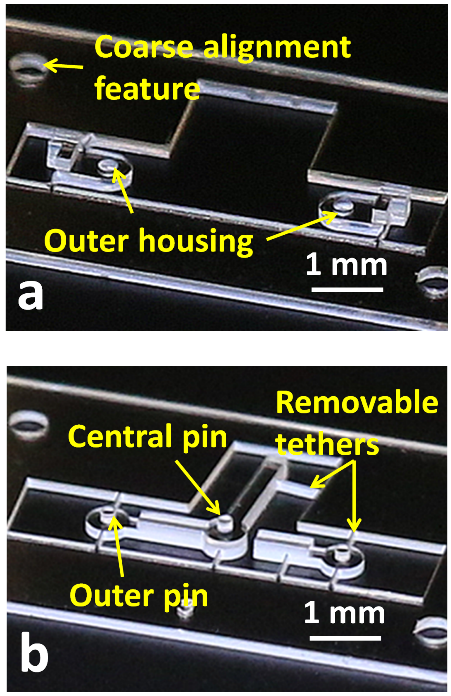


*Figure 3: Micrographs of (a) the 2-layer SU-8 "outer housing" structure on its alignment frame and (b) the 3-layer SU-8 "pins and linkages" structure on its frame.*

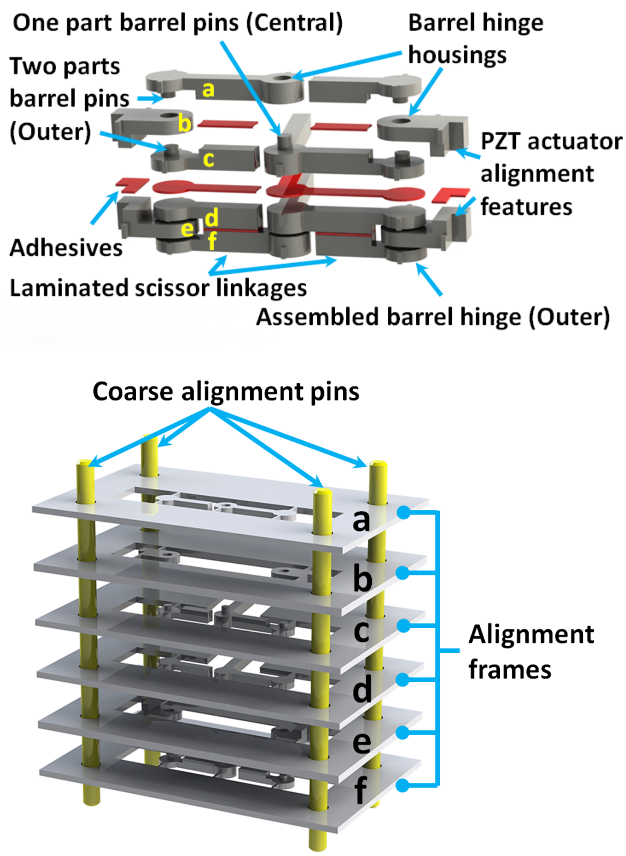


*Figure 4: (above) Exploded view of a micro motion amplifier, in which each functional layer of SU-8 ranges from 100 μm to 300 μm; (below) schematic diagram of the coarse alignment process showing dowel pins aligning the outer alignment frames and the functional features supported in the centers of the frames.*

The supporting frames include four holes through which dowel pins are inserted to provide coarse alignment during assembly (Figure 4b); the barrel hinges provide fine self-alignment via the pin-housing clearance. A thin layer of approximately 5 µm thick cyanoacrylate adhesive is applied as shown in Figure 4a (red) to bond the linkages together, ensuring that the pins remain in their corresponding housings. The two mirror-image sets of three plates each are included to increase stiffness and symmetry. The tethers that connect the scissor to the frame are broken after assembly to release the scissor.

Figure 5a shows the laminated scissor in its initial position; the recessed design of its anchors creates end stops that passively align the scissor onto the PZT actuator. Figures 5b and 5c show how the unlimited rotation of the barrel hinges permits much larger deformation angles than in [4]. Figure 5d shows a completely-assembled actuator with the hinged scissor self-aligned on a PZT extensional actuator.

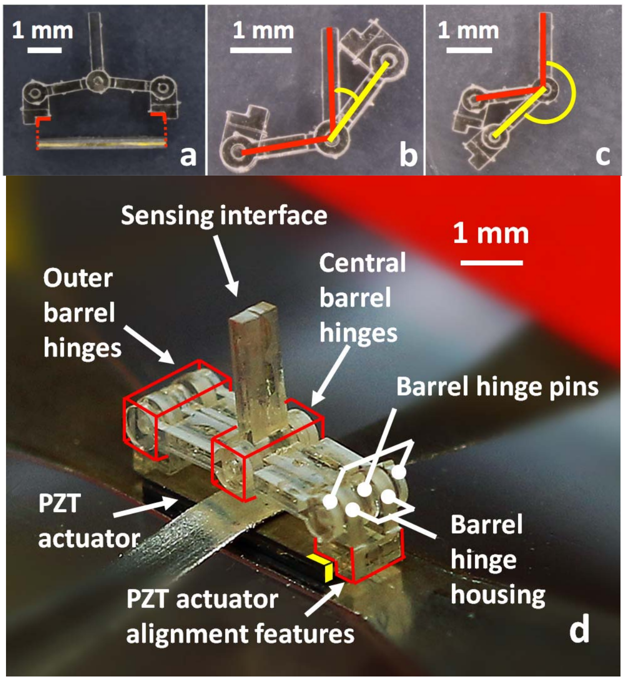


*Figure 5: Photographs of an assembled scissor with three barrel hinges showing (a) alignment of end stops to PZT actuator and (b, c) large rotation angles; (d) photograph of a complete actuator.*

The assembled SU-8 scissors are attached to 5 mm x 2 mm x 0.38 mm (10 mm$^2$ footprint), y-poled PZT actuators to form the final haptic interfaces. Cyanoacrylate adhesive is applied manually to each scissor's recessed anchor points before assembly onto its actuator. The spacing between the anchor attachment points slightly exceeds the length of PZT actuator, creating an initial angle of about 7-8° between the linkages and the PZT after scissor attachment, ensuring predictable motion amplification upon PZT actuation.

The PZT actuators are electrically connected via conductive epoxy to a lengthwise metal strip electrode (below the PZT) and to a perpendicular metal strip electrode (above the PZT) as shown in Figure 5d. Connections are made at the center of the device so that the haptic interface is located above the mechanical neutral point during actuation.

## EXPERIMENTS AND RESULTS

Barrel hinges with as-designed gaps of 15 µm and 50 µm are fabricated. To measure the displacement of the actuator's sensing interface under applied voltage, the assembled actuator is placed so that its direction of motion is parallel to the viewing plane of a stereomicroscope. A voltage amplifier (Falco WMA-02) amplifies the square wave generated by a function generator (BK Precision 4040A) with a frequency of 0.5 Hz; the resulting signal is applied to the PZT actuator. The peak amplitude of the square wave increases in 10 V steps from 50 V to 170 V. The microscope captures the location of the sensing interface in its positive actuated position and in its negative actuated position. For each position, two or three pictures are captured. The displacement of the sensing interface is the difference between the positive and negative positions, measured by pixel counting (1 pixel = 0.5 µm).

The force output of the actuators is measured by an Instron tensile tester (Instron 5943). The actuators are mounted on a stage so that the sensing interface contacts the load cell. A 40 mN preload is applied to the sensing interface when null voltage is applied to mimic a real finger load. Similar to the displacement testing, square wave AC voltages between 50 V and 170 V are applied, increasing in steps of 10 V, but with a frequency of 10 Hz. Force is measured by the load cell of the tensile tester.

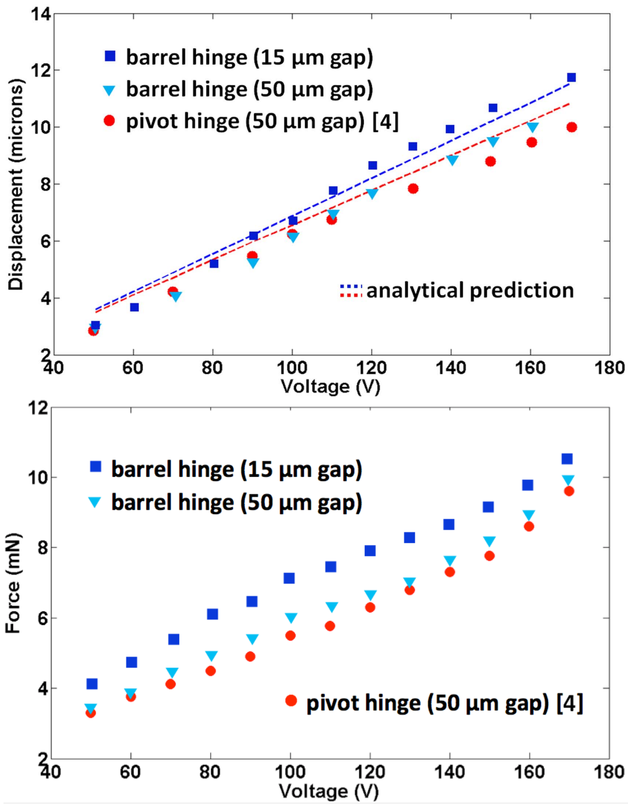


*Figure 6. Plots of the measured displacement (above) and measured force (below) vs. applied voltage.*

Figure 6 plots the measured vibrational amplitude vs. voltage and the measured force vs. voltage for each of the tested devices. The dashed lines represent the displacement predicted analytically for each geometry for the simplified case of an ideal microscissor with ideal, zero-clearance pinned hinges [5]. The blue and red dots represent individual measurements.

The maximum measured displacement of 11.5 μm and the maximum measured force of 10.5 mN for barrel hinged actuators of 15 μm clearance correspond to displacements per unit actuator area of 1.15 μm/mm$^2$ and and forces per unit actuator area of 1.05 mN/mm$^2$. These results exceed the vibrational tactile sensing thresholds for displacement and force of 4 μm and 2 mN reported in [5].

## CONCLUSION

The design, demonstration, and characterization of a two-stage, passively self-aligned, assembly-based process for rapidly creating compact, micro-barrel hinges with unconstrained rotation is shown. The process offers good robustness and rapid speed of development because the final structure's multi-layer architecture is divided among six much simpler microfabricated elements, reducing attrition losses. The advantages of simplified microfabrication could in theory be counteracted by the potential for yield loss during the assembly process. However, the use of a two-stage alignment process (coarse alignment via dowel pins and fine alignment via the hinges themselves) offers robust integration of multiple separate layers into a final, complex, three-dimensional architecture. In addition, the use of an assembly process enables the creation of hinged structures with smaller clearances than would be permitted by the design rules for SU-8 microfabrication of separated, in-plane features of this thickness. Although the integration of diverse microstructures has been demonstrated previously, for example in the context of multifunctional optical, electronic, and MEMS devices [6], the present assembly approach advances the state of the art by leveraging purely low-cost alignment tools to create mechanical structures with full rotation.

The barrel hinges created by this process are demonstrated in the context of a micro-motion amplifier for a haptic actuator. Hinges with two nominal gap clearances of 15 μm and 50 μm are fabricated. Barrel-hinged devices with 50 μm clearance perform similarly to the 50 μm clearance devices of [4]. However, both the measured force and the measured displacement of devices with 15 μm clearance exceed those of 50 μm clearance devices, with up to >18% and >9% increase in displacement and force respectively as compared with [4]. Most significantly, the two-stage passive alignment of the barrel-hinged approach provides rapid, straightforward manufacture of complex, out-of-plane MEMS architectures.


## 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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