Design, Fabrication, and Characterization of a Microgripper Device

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ABSTRACT

In this work, we present the development process of SU-8 polymer based microgrippers applied to novel parallel displacement geometry and assembly techniques. Finite element based simulations were utilized to determine the geometry dimensions, and to verify its operation. Two actuation techniques, mechanical, and piezoelectric are implemented, and characterized. The fabrication process requires a single mask, and it is described along with the assembly process required to implement the actuator-microgripper system. Experimental results are presented for both actuation techniques, along with failure analysis. The microgrippers are designed to manipulate microstructures in the range of 5 to 50µm.

Keywords

SU-8, micromanipulation, polymer microgripper, piezoelectric.

1. INTRODUCTION

Throughout the development of the Microelectromechanical Systems (MEMs) field, there has been an increasing interest in developing a system that would allow the manipulation of small structures in the µm range, namely microgrippers [2, 5, 6]. A variety of these systems have been developed by different researchers, with the most common application being single cell manipulation [2, 5], however, other applications such as microassembly of 3-D MEMS structures have attracted significant interest [4]. However, a very common issue with the utilization of microgrippers has been their assembly; namely the fact that once the microgripper device is fabricated it needs to be connected (electrically and mechanically) to a micromanipulator which often leads to significantly larger devices [4-6]. A very popular material utilized for the implementation of microgrippers has been SU-8, a negative tone, epoxy based high aspect ratio photoresist suitable for MEMS implementation [3].

In this work, a novel design for mechanical microgrippers and related assembly structure are presented, which are implemented by means of a simple photolithographic process, and a novel compact assembly technique suitable for purely mechanical or electrical piezo-actuation. This external actuation approach is possible due to the "fishbone" structure which controls the gripping arms; to the best of our knowledge, this is a unique design, and a first of its kind for micro-electro-mechanical-system (MEMS) devices. The microgrippers presented in this work are implemented with gripping elements widths ranging from $10\mu m$ up to $100\mu m$. It should be mentioned that the somehow large overall dimensions of these microgrippers increase the feasibility of a macroassembly technique of the gripper-micromanipulator system, while the small gripping elements allow the manipulation of structures in the micrometer range.

2. DESIGN

The microgrippers are designed to manipulate structures in the range of 5 to $50\mu m$ in diameter, given that different gripping arms widths are suitable for manipulation of different microstructure sizes. These microgrippers are designed so that a single controlled displacement is necessary for both gripping arms to open and close. Two actuation approaches were implemented, first a purely mechanical by means of a micrometer actuator, and secondly by means of a piezoelectric actuator.





2.1 Mechanical Actuation

The principle of actuation for the presented microgrippers is based on a controlled push and pull displacement of center of the fishbone structure located between the gripping arms, namely the backbone; Figure 1 presents a diagram of the microgripper with the terminology followed in this work. When the backbone of the fishbone structure is pushed forward, the spines experience compressive forces and therefore force the gripping elements to open. In a similar manner, when the spine is pulled, the spines experience tensile stresses, consequently pulling the gripping elements together closing the gripper. The fact that the gripping elements are pushed/pulled apart by four identical pairs of spines that receive the same exact displacement turns to be highly beneficial to the performance of the microgripper because the gripping facets remain parallel at all times, being this a very attractive feature of this unique design. It should be mentioned that this feature allows the manipulation of different microstructure sizes within a wide range, while at all times the gripping facets remain parallel. In order to obtain a controlled motion, the backbone is attached to an actuator by means of a 100 μ m diameter shaft bonded with UV curable glue. As explained previously, the opening and closing of the gripping elements; for this the microgripper legs are bonded to the outside wall of a hollow cylinder. The shaft passes through the inside of the cylinder, having one end bonded to the backbone and the other end bonded to the micrometer actuator mechanically fixed in space with the cylindrical support.

2.2 Piezo-electric Actuation

The previous actuation technique requires turning of a micrometer actuator, which provides an accuracy of approximately 1 µm, however the vibrations introduced by turning the actuator could reduce the precision with which the microgrippers operate. In a case where more accuracy is required, piezo-electric actuation is more suitable, furthermore a higher degree of automation is enabled since it only requires an electric signal to operate. The system arrangement is the same, except that in this case the backbone displacement is induced by the expansion of the piezoelectric actuator. Another advantage of this second actuation approach is that the system can be implemented in a more compact manner due to the smaller dimension of the piezoactuator compared to the micrometer screw. It should be mentioned that the micrometer screw provides an easy method of actuation since it provides the possibility of pushing and pulling therefore allowing the microgripper to increase or decrease its initial gap. The piezo-electric actuator is limited to only pushing; this issue can be addressed by assembling the microgripper in a normally closed arrangement, placing the shaft under tension before fixing the actuator in place, in a way that when no voltage is applied, the microgripper is completely closed, and as voltage is applied, the microgripper starts to open.

2.3 Mathematical Model of Actuation

For the two different actuation methods that cause a mechanical displacement of the backbone, the dimension of the microgripper gap (G) is given by:

$$G = g_0 + 2 \cdot \Delta g \tag{1}$$

Where: Δg : variation in the microgripper opening gap per arm

g_0 : initial gap separation

At the same time Δg can be expressed in terms of the length of a spine, and the angle it makes with the backbone as:

$$\Delta g = \sqrt{L^2 \cdot \sin^2(\theta_0) - (\Delta s)^2 + 2 \cdot L \cdot \cos(\theta_0) \cdot \Delta s} - L \cdot \sin(\theta_0) \quad (2)$$

Where Δs : displacement induced by the shaft on the backbone

L: length of a spine

 θ_0 : starting angle between spines and backbone

Figure 2 shows the relation between the gap and the displacement induced by the shaft, which is controlled by the actuator of choice; this is for a fixed spine length $L = 354 \mu m$, implemented in this work. Theoretically, the maximum displacement is achieved when the angle between the spine and the backbone becomes 90 degrees, which corresponds to $\Delta s = L \cos(\theta_0)$; the curves presented in Figure 2 are plotted all the way to this maximum displacement value, where a maximum theoretical gap is observed. From this it can be observed that the rate of change of the gap approaches zero as Δs approaches $L \cos(\theta_0)$. Consequently, if a higher degree of control is required on the gap dimension, the microgripper could be fabricated with the spines at a higher than 45 degree angle, however this would reduce the opening range of the gripper. Furthermore, if a larger gap range is required, the microgripper could be fabricated at a lower than 45 degrees, but as expected, this would reduce the level of control over the gap. The microgrippers presented in this work were fabricated with the spines at 45 degrees as a good compromise for the range and control using the piezo-electric actuator.



Figure 2. Theoretical gap range vs. shaft displacement dependence on initial spine angle θ_{θ} . Curves are plotted up to the max theoretical value

3. SIMULATION

The performance of the device depends on several design parameters and material properties. To explore the structural and layout parameters and determine the best design we carried out 3D mechanical simulations. We addressed the non-planarity of the motion due to unintentional off-plane actuation, and the minimum spine dimensions that would allow pushing the gripping elements open. For instance, if they would be too narrow, instead of opening the gripper they would only buckle.

The device was simulated using COMSOL Multiphysics, a finite element simulations suite. The model simulated took into consideration physical properties of SU-8 such as Young's modulus E = 4.02 GPa, Poisson coefficient v = 0.22, and density $\rho = 1190$ kg/m³ [7]. The mesh generated for the finite element simulation is presented in Figure 3.



Figure 3. Mesh generated by COMSOL Multiphysics, utilized for finite element based simulation

The simulation of the model predicted the device behavior accurately for backbone displacements from -8 μ m (at which the microgripper closes) to 40 μ m, beyond which instability problems were observed; the convergence of the model needs to be improved to analyze this regime, which will be carried out in the future. From simulations it was determined that 20 μ m width bones are strong enough to push apart even the 100 μ m width gripping arms. Figure 4 shows the microgripper in it's a) completely closed position after an 8 μ m backbone pull and b) opened to ~85 μ m after a 40 μ m backbone push, which is consistent with Figure 2; in Figure 4, the lower limit of the color scale (blue) represents no displacement while top (red) represents maximum displacement. From these simulations it was clearly observed that the gripping facets remain parallel at all times.

Even though the structure could be simulated in 2D, it was necessary to perform 3D simulations to analyze the effect of a non-planar actuation. This was studied by adding a component to the displacement vector perpendicular to the actuation plane, applied to the backbone. It was observed that the effect of this out-of-plane actuation is not critical. This is due to the extra spines attaching the backbone to gripper arms which restrain the out-of-plane motion; the backbone is displaced a very small percentage of the of the microgripper total length.

The fine element simulation technique is highly dependent on the meshing minimum element size, which becomes smaller as more detailed simulation are required, causing the computational power required to increase as well. In a later section, it is mentioned that inducing a large backbone displacement results in mechanical failure, or fracture. Most of the time the device breaks at the V junctions due to the propagation of micro cracks present at these junctions. This phenomenon has not been simulated yet due to the high computational power required for the extremely small mesh needed for simulating a microcrack within a relatively large device. However, the microcrack theory is verified by SEM images presented in Figure 5 where the crack initiation is visible; this issue will be discussed in more detail in the following section.



Figure 4. 3D Simulated microgripper actuation where lower limit of scale (blue) represents no displacement while top (red) represents maximum displacement. (a) Completely closed after 8µm backbone pull, (b) opened to ~80µm after a 40µm backbone push



Figure 5. Microcrack present at the V junctions. Under extensive actuation, device failure (fracture) is originated at these points due to crack propagation

4. SYSTEM IMPLEMENTATION

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In this section, the microfabrication process will be described, followed by the assembly process. Finally, the implementation of the microgripper-micrometer actuator, and the microgripperpiezoelectric actuator systems is presented.

4.1 Microfabrication

The device was completely designed and fabricated at FIU's Motorola Nanofabrication Research Facility (MNRF), a class 100/10000 cleanroom facility located in the College of Engineering and Computing [1].

4.1.1 Mask Design

One of the advantages of this device is the ability to completely pattern the device using a single mask (see Figure 6). The mask is comprised of large frames that support the microgrippers so that once released they can be located and manipulated easily. The pattern in the mask was prepared to allow a fast complete release; for this purpose the main frame that supports the microgrippers contains an array of 50 µm x 50 µm orifices with a pitch of 150 µm leading to approximately 10% hole coverage. Nonuniform etch of the underlying layers lead to microgrippers being released much before the main frame. The current mask included microgrippers of 10, 20, 30, 40, 50, and 100 µm, two of each. Each microgripper is attached to the main frame by means of thin stubs, which are strong enough to maintain each microgripper in place during the fabrication process, but weak enough to break away from the main frame once the microgripper has been bonded to the actuation part of the system. The mask was designed with a dark field and included a frame for alignment to the chip edges for improved uniformity. The mask was fabricated using FIU's new uPG101 table top maskless lithography system from Heidelberg.



Figure 6. Single mask utilized for microgrippers fabrication. The mask produces 12 microgrippers of 10, 20, 30, 40, 50, and $100 \mu m$, two of each

4.1.2 Photolithography

The fabrication of the device uses standard contact photolithographic processes at wavelengths shorter than 435 nm which are needed to expose the SU-8. This is relevant as our uPG101 is not able to directly expose the SU-8 layer. The fabrication starts with a silicon substrate with 2 μ m of silicon dioxide (Figure 7,1). The substrate is spin-coated at 2000 RPM with SU-8 25 to a thickness of 30 μ m, pre-baked for 13 min at 95 C and exposed with I line illumination, followed by post-exposure-bake (PEB) at 95 C for 16 min and developed (Figure 7,2 - 4). An exposure matrix was carried out to optimize the lithography conditions. The exposure energy density for these conditions was 250 mJ/cm².



Figure 7. Fabrication process steps: 1: Silicon substrate with 2µm of SiO₂, 2: SU-8 Spin-coat, 3: UV exposure, 4: Develop, 5: Complete structure release in HF

4.1.3 Release

Subsequent to the SU-8 layer patterning and inspection, the complete structure is released by immersing the substrate in buffered hydrofluoric acid for approximately 10 minutes (figure 7,5). The previously described perforated mask enables an uniform silicon dioxide release etch. Once the structure is released, the SU-8 devices come afloat on the acid surface, making it possible to pick them up manually. Each structure is then rinsed in deionized water and placed in an absorbent tissue; such drying technique is required in this case since blow drying would be destructive. Note that the devices do not float in water as the density of SU8 is higher than both water and isopropanol. At this point the microgrippers are ready for assembly (see Figure 8). In the previous section, the reason for the most common failure mechanism was briefly discussed, that is, the microcrack sometimes present at the V junctions. It was verified that this microcracks are not present before the complete release of the structure, however they are present sometimes after the release process. It is suspected that at the point that the floating structures are removed from the hydrofluoric acid, immersed in DI water and then removed from it, the physical interaction between the two liquids, because of their surface tension, causes the microgripper structures to experience forces that could originate these microcracks (see Figure 5).



Figure 8. (a) SEM micrograph of released main frame containing microgrippers of different arm widths. (b) Detail of 30 μm arm width microgripper supported by 4 stubs

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4.2 Assembly

In order to complete the micrometer actuator-microgripper assembly, the main frame is placed in an XYZ stage. While the shaft (already attached to the micrometer actuator), with its tip previously coated with UV glue, is visually aligned to the backbone of a microgripper of the desired size under a stereoscopic microscope. Once the desired alignment is achieved, the backbone is brought in contact with the shaft and UV cured, producing a strong bond. In a similar manner, the microgripper arms are bonded to the end of the hollow cylinder (see Figure 9a). At this point the microgripper is ready to be detached from the main frame. A slight pull on the mainframe is enough to break the supporting stubs, completing the assembly process (see Figure 9b). The result is a microgripper attached to a support large enough to be easily manipulated.

The assembly of the piezoelectric actuator/microgripper system requires the positioning of the actuator in a precise location, for this, a micrometer screw is attached to the piezoelectric actuator, which is fixed in place once the desired position is obtained (the micrometer screw is then detached). Figure 10 shows the assembled system mounted onto a microscopy glass slide for ease of use in a high resolution optical microscope.



Figure 9. Microgripper assembly (a) bonding completed, (b) microgripper detached from main frame.



Figure 10. Piezoelectric actuator/microgripper assembled system. The arrow points to the microgripper

5. EXPERIMENTAL RESULTS

In this section, the results of testing the two different kinds of actuation implemented are presented. The results presented for the purely mechanical actuation correspond to a 50 μ m arm microgripper, and the results presented for the piezoelectric actuation correspond to the testing of a 100 μ m arm microgripper.

5.1 Mechanical actuation

After the completion of the assembly process, the microgripper was tested by turning the micrometer actuator knob to achieve different opening gaps. The system was monitored using an Olympus MX40F optical microscope and a COHU 2222-1320 CCD camera. Figure 11 shows optical graphs of the micrometer opened to desired gap dimensions. These were achieved manually actuating a micrometer screw. The target gaps were (a) 0 μ m, (b) 5 μ m, (c) 10 μ m, (d) 20 μ m, (e) 30 μ m, and (f) 40 μ m. The measured values are within the resolution of the measuring system, except for the closed value of zero microns, which was not achieved. This is believed to be due to the non-verticality of the facets of the gripper. This result translates to a non verticality of 2 degrees (positive profile), which is consistent with the SEM measurements.



Figure 11. Microgripper (50μm)actuated mechanically with a micrometer screw showing different levels of actuation.
(a) 2.4μm, (b) 5μm, (c) 10μm, (d) 20μm, (e) 30μm, and (f) 40μm

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In order to study the fracture mechanism of the device, the gripper was further actuated still showing a stable behavior at 130 μ m gap opening, however when actuated up to 140 μ m fracture occurred at the V joints as expected (see Figure 12). It is evident that if the operation of the device is limited to openings below 100 μ m, the lifespan of the device is significantly longer than if the device would be operated in the 100-130 μ m range. As mentioned earlier, failure analysis will be carried out by simulation and experiment. This will enable us to design suitable microgrippers that have the widest gap opening range, best control in size, and highest reliability.



Figure 12. Microgripper (50μm) actuated mechanically with a micrometer screw. (a) Actuated to ~130 μm (b) Device failure when attempted to open to 140 μm, fractures occurred

5.2 Piezoelectric actuation testing

We used an AE0505D18 15 μ m piezoelectric device from Thorlabs, and for the actuation of the piezoelectric actuator/microgripper a General Photonics PZD001 piezocontroller. The system was tested utilizing the same optical microscope and CCD camera, and Gap openings were measured as the driving voltage was varied from 0 to 120 volts in steps of 10 volts. This was followed by measuring the gap as the voltage was decreased to 0 volts also in steps of 10 volts of approximately 10 s duration. Figure 13 shows the resulting gap versus actuation voltage plot for the ramp-up and ramp-down of the voltage across the piezo.



Figure 13. Measured microgripper gap (100µm arm) for different voltages. Voltage was increased in steps of 10 volts from 0 to 120 volts and then lowered back to 0volts as indicated by the arrows. A 5 min wait brings the gap down to the starting value.

Ideally, the gap vs. voltage curve should be retraced as the voltage is reduced back to zero, and therefore returning the gap to its original size. However, as the voltage is lowered to 0 volts, the curve takes a different direction, showing hysteresis. Hysteresis is commonly seen in piezoelectric actuators and is due to internal stresses stored inside the piezoelectric actuator which prevent the system to respond immediately. The SU-8 polymer was also observed to present permanent deformation if subject to extreme mechanical deformations. It was also observed that when lowering the voltage to zero, after 5 min the gap value would return to the corresponding initial value.

6. CONCLUSION

We have demonstrated a new design of a MEMS fishbone actuator, and novel assembly method. Its mathematical modeling, including the 3D mechanical simulation of performance, were investigated in this particular implementation. We have developed a polymer microgripper device that is externally actuated leading to controlled operation with sub-micron resolution. The device has a simple fabrication process flow, which was developed and implemented completely at the Motorola Nanofabrication Research Facility, including the photomask fabrication, photolithography, and release steps. The system implementation was accomplished through a manual assembly process as a proof of concept of the feasibility of a microgripper of this kind; however, a completely automated assembly process is easily conceived requiring accuracy better than 5 μ m.

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