

# HIGH SENSITIVITY, HIGH DENSITY MICRO-HYDRAULIC FORCE SENSOR ARRAY UTILIZING STEREO-LITHOGRAPHY FABRICATION TECHNIQUE

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## ABSTRACT

We introduce a micro-hydraulic force sensor with the ability to maintain high sensitivity at reduced footprint size to realize an array of force sensors with capability resembling human fingertip touch sensing. This sensor utilizes a micro-hydraulic structure as an enhanced sensing mechanism along with a tactile interface fabricated with a low cost, fast prototyping stereo-lithography apparatus. The sensor is capable of delivering high average sensitivity of 87 fF/mN (maximum observed: 260 fF/mN), a minimum detectable capacitance change of 80 aF at quiescence and a spatial resolution of 1 mm. It is sensitive enough to detect the fall of a 38.5 nL water droplet. The sensor full-scale force range with a 2- $\mu$ m thick parylene membrane is 15 mN. With an array using 15  $\mu$ m thick parylene, the full-scale range can be expanded to 180 mN.

## INTRODUCTION

Highly sensitive, highly dense force sensors are required for robotic tactile interface applications designed to mimic the capabilities of the human fingertip. Previous work has used various structures and mechanisms to achieve this goal. However, in these conventional sensors sensitivity is traded off with either density or dynamic range (Table 1). We have plotted force sensitivity vs. force range in Figure 1 for various published force sensors. Sensors closer to the top right corner have better performance.

Table 1: Summary of previously published force sensors

Ref.	Transduction method	Sensitivity	density (cells/cm <sup>2</sup> )	Range (mN)
[1]	capacitive	27 fF/mN	400	10
[2]	CMOS- cap.	122 fF/mN	1600	0.517
[3]	capacitive	6 fF/mN	52.9	40
[4]	capacitive	6 fF/mN	25	10
[5]	resistive	2%/mN	28.6	600
[6]	capacitive	35 fF/mN	95	25
[7]	cap. $\mu$ -hyd	5 fF/mN	4	-
this work	cap. $\mu$ -hyd	260 fF/mN	100	10

Micro-hydraulic structures can be utilized for high performance sensing and actuation. They can be functionalized with the addition of application-specific appendages. We have previously integrated a hair-like appendage to a micro-hydraulic system to create an air flow sensor with high accuracy without sacrificing dynamic range [8]. The sensor presented in this work also makes use of an electrostatic micro-hydraulic system to deliver high sensitivity over large dynamic range while maintaining reasonably small footprint size. Additionally, we successfully fabricated micro-hydraulic arrays with a

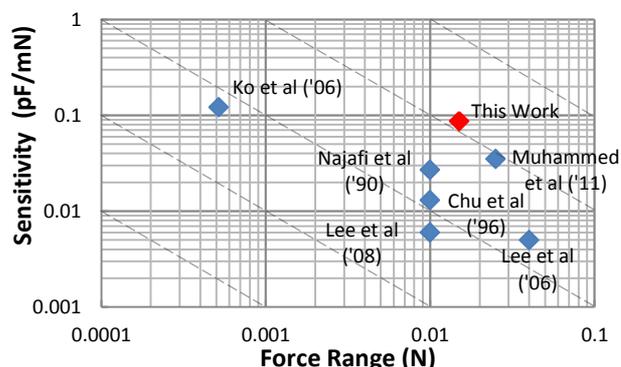


Figure 1: Force sensitivity vs. force range.

minimum pitch size of 1 mm, comparable to the spatial resolution to that of the human fingertip [9].

The appendage specific to this force sensor application (described in detail in the next section) can be fabricated using a low cost stereo-lithography apparatus (SLA) [10]. The SLA machine we used is Viper SI2 (3D Systems, Inc.), which operates based on laser-assisted polymerization of Accura S10 polymer. The SLA is capable of creating a dense array. The SLA technique can have resolution as high as 16  $\mu$ m. Based on our characterization, the smallest structures that can be reliably made include 100  $\mu$ m walls and 300  $\mu$ m diameter holes. The SLA was chosen over other conventional fabrication methods for a few reasons. First, its resolution fits the dimensions needed for the purposes of this device. While here the device density is limited by the hydraulic fabrication method, the SLA allows for density up to 100 units/cm<sup>2</sup>. Second, it is a very low cost method of fabrication for millimeter-sized parts in comparison to conventional micro-fabrication techniques. Finally, the fabrication of complex three-dimensional (3-D) structures is simplified by SLA. Some of the 3-D structures with intertwined patterns are not even feasible to make using conventional micro-machining methods.

## DESIGN

### Structure

The force sensor consists of a plunge, which sits on the top parylene membrane of a micro-hydraulic structure, inside a protective casing (a base and a cap), as schematically depicted in Figure 2. The micro-hydraulic system is made of a cavity formed on a silicon wafer, filled with an incompressible liquid and covered by two flexible membranes on front and back sides of the silicon wafer. Inside the micro-hydraulic chamber, a perforated membrane forms one electrode, and the second electrode is positioned on the flexible membrane to realize a liquid-gap capacitive sensing element [11, 12].

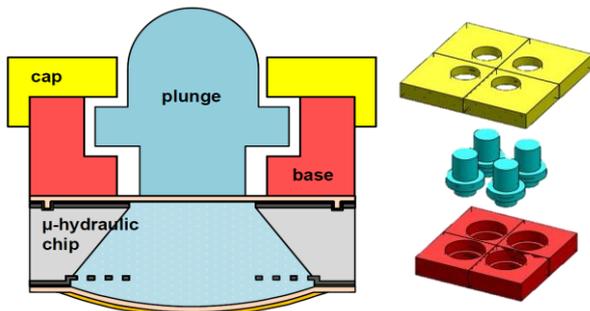


Figure 2: Hydraulic structure [12] along with tactile structure design (left) 3-D layout of tactile parts (right).

A load on the plunge causes deflection in the top membrane and pushes the fluid to the lower membrane, which also deflects. An electrode is deposited on the bottom membrane such that capacitance is measured between this electrode and the conductive perforated membrane inside the bottom part of the micro-hydraulic chamber. The tactile plunge is held in place by the casing, which protects the parylene membrane from deformation or rupture by limiting the vertical motion of the plunge to the allowed range of stress for parylene deflection. Each plunge has an individual isolated cavity, as shown in Figure 2, to eliminate cross talk (discussed in detail later).

### Simulation

We have done multiple simulations to co-optimize the deflection range of the plunge on the top membrane, the contact area between the plunge and the membrane, and the thickness of the parylene membrane. The maximum stress on the membrane should be kept below the parylene yield strength of 59 MPa, while maximizing the force range. To do this, we made a 3-D COMSOL model that consists of a parylene membrane (Young's modulus: 3.75 GPa) and a rigid cylinder, representing the plunge, sitting on top of it. Figure 3 shows the simulation setup and plotted von Mises stress and deflection with 40 mN force applied to the center of the plunge atop a 5- $\mu$ m thick parylene membrane. A point force was used to apply force from 1-10 mN and 10-100mN using parametric sweeps. The radius of the button and thickness of the top membrane were varied from 100  $\mu$ m to 750  $\mu$ m and 2  $\mu$ m to 15  $\mu$ m, respectively, to determine the optimal design.

Based on calculation of von Mises stress in this simulation, we obtained the maximum measurable force and corresponding maximum deflection to keep the stress level below parylene's yield strength (Table 2).

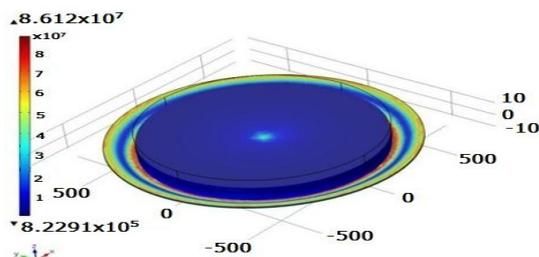


Figure 3: Simulation of parylene membrane stress with plunge deflection on surface, with membrane radius 750  $\mu$ m, plunge radius 600  $\mu$ m, point force from 0.001N to 0.01N, and 0.01N to 0.1N applied on center (40 mN here).

Additionally, we have calculated the membrane deflection and associated capacitance change at 1 mN force applied (Table 2). Based on these results, we decided to use a parylene thickness of 2  $\mu$ m (to obtain high sensitivity) and a plunge contact radius of 600  $\mu$ m. To increase the dynamic range, a thicker parylene may be used without affecting the design parameters for the tactile interface parts (i.e. the plunge and casing).

We did a test-to-failure on a 2- $\mu$ m membrane to experimentally determine the maximum amount of deflection allowed. For a 2- $\mu$ m thick membrane, deformation was found only after 100  $\mu$ m deflection. The difference between this value and the maximum 29  $\mu$ m deflection predicted in Table 2 is most likely due to the initially curved membrane profile. The simulation assumed a flat membrane, however, the membrane is actually curved upward due to the liquid encapsulation method used. Given the larger deflection, it may be possible to obtain a force range 3 $\times$  larger than that listed in Table 2.

Table 2. Simulation results for 600- $\mu$ m button radius on 750- $\mu$ m membrane radius.

Parylene thickness ( $\mu$ m)	15	10	5	2
Max force (mN)	180	100	20	5
Max tolerable deflection ( $\mu$ m)	24	24	20	29
Cap. change at 1mN (fF)	4.26	10.5	55.0	231

## FABRICATION

### Hydraulic Structure

The hydraulic structure was fabricated using bubble-free liquid encapsulation based on conformal parylene deposition on a very low vapor pressure silicone oil (1,3,5-trimethyl-1,1,3,5,5-pentaphenyltrisiloxane) that does not evaporate inside the parylene deposition chamber. This process takes advantages of liquid shaping and patterning by a spin-on hydrophobic layer (Cytop<sup>TM</sup>), i.e. the oil will be contained in Cytop<sup>TM</sup> free areas [11]. The fabrication process steps are shown in Figure 4 and are described in detail in ref. 12.

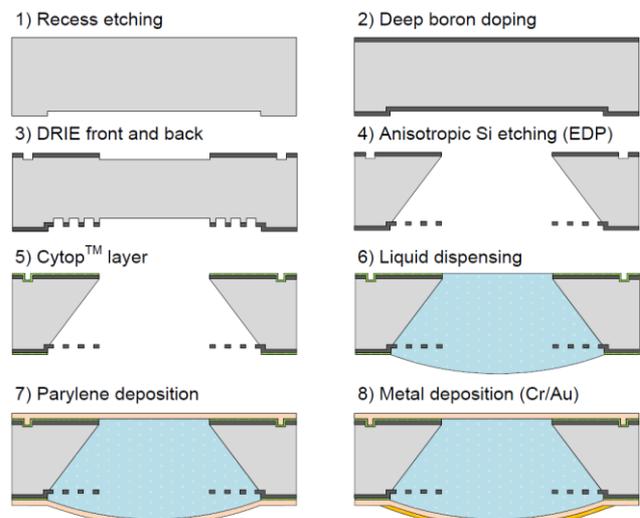


Figure 4: Fabrication process based on direct deposition of parylene over low vapor pressure silicone oil [12].

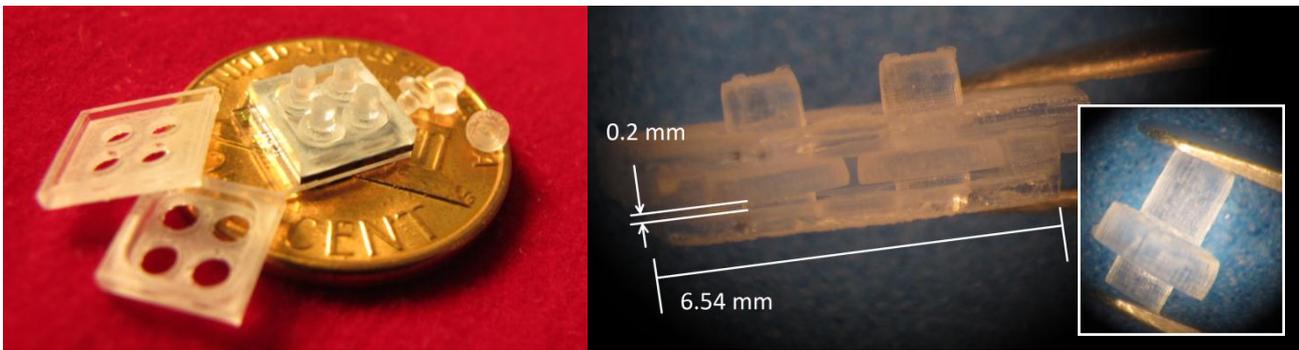


Figure 5: Left: sample device (without cap), casing, and plunges. Right: cross section view of deflection space and plunge.

### Tactile Interface

As mentioned above, we used SLA to fabricate the tactile interface parts that are appended to the micro-hydraulic sensing chip to form the force sensor array. Figure 5 shows the fabricated device and a cross section of tactile interface and assembly. The SLA tool we have used is the Viper S12, which operates based on laser-assisted polymerization of some specific resins. The material used for these parts is Accura S10 polymer.

## EXPERIMENTAL RESULTS

### Force Tests

The device was tested by applying variable loads using milligram-sized weights while the capacitance was measured. The sensor was wire bonded to a PCB designed for interfacing with Analog Devices' AD 7746 capacitance to digital convertor (CDC) chip. The CDC chip is capable of detection of 4 aF capacitance change with maximum base capacitance of 21 pF. We have measured minimum detectable capacitance change of 80 aF at quiescence. Figure 6 shows the capacitance change vs. force for two devices tested. The average measured sensitivity is 87 fF/mN and the maximum is 260 fF/mN. This variation is due to misalignment of the casing with the hydraulic chip, which causes off-center positioning of the plunge and therefore lowers sensitivity.

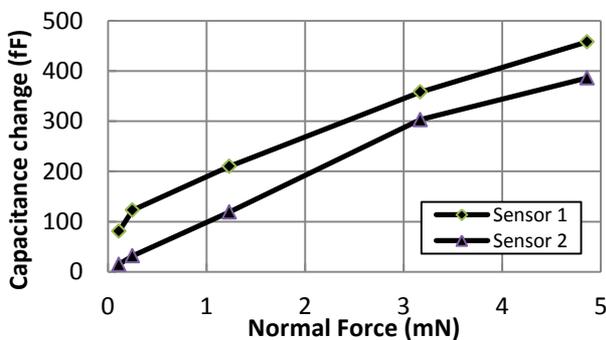


Figure 6: Capacitance vs. force for two tactile sensor samples.

### Cross Talk

In order to measure cross talk, a load is applied to a sensor besides the one being measured, and the change in sensor capacitance is monitored. Figure 7 plots a cross talk measurement for a micro-hydraulic force sensor array with separated plunges. No cross-talk is observed. We also

considered an alternate design where the plunge and casing is replaced by an elastomeric sheet that covers the hydraulic structure. This configuration also provides the needed protection for the membrane. However, we expect that the plunge structure is superior to an elastomeric sheet design due to its abilities to reduce cross talk between sensing cells and to maintain sensitivity. In contrast, a protective elastomeric sheet inherently causes cross talk and reduces sensitivity due to stiffening of the top side micro-hydraulic flexible membrane. To compare the plunge structure to an elastomeric one, a set of hydraulic cells was covered with a 0.85 mm thick sheet of PDMS and tested similarly. The test results suggest that the 0.85mm PDMS sheet demonstrates up to 25% cross talk and a 10 $\times$  decrease in sensitivity.

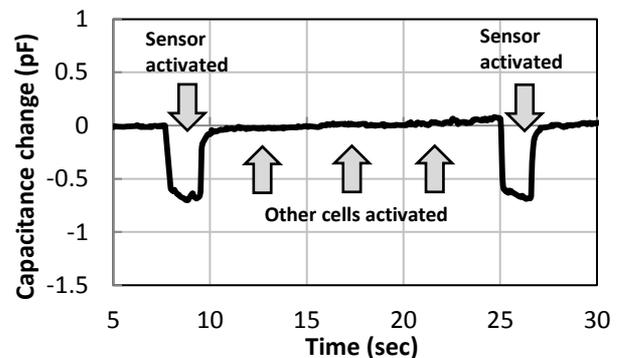


Figure 7: Cross talk demonstration of tactile sensor. No cross talk is observed between cells.

## DISCUSSION

These results open up several possible paths for future research in this field. First of all, this work focused on using rigid plunges. With the SLA technique, we can use rubber plunges/buttons to increase the force range of the sensor, because a softer material can deform to distribute force more evenly on the membrane. This will result in reduced stress level around the contact perimeter at which maximum stress occurs, thus increasing the full-scale force range. Second, different dimensions could be explored. We chose our dimensions to simultaneously achieve a moderate amount of force and sensitivity range; however, different dimensions could be chosen to achieve other performance specifications. For example, a very highly sensitive sensor could be made with limited force range, or a sensor with large dynamic range could have reduced sensitivity. Similarly, various membrane thicknesses

could be tried. Furthermore, pins could be used instead of plunge-like structures, where deflection is limited by the excess height of the pin compared to the casing. Dimensions could also be revised to increase the density of sensing units. As a demonstration of SLA capability for realization of dense arrays, Figure 8 shows an array of  $17 \times 17$  pins made with SLA Viper SI2 and Accura s10 polymer. The array area occupies slightly less than  $1 \text{ cm}^2$ . The array is fabricated on a polymer substrate, shown with and without casing. In the present design, the smallest micro-hydraulic sensing unit occupies an area of about  $0.79 \text{ mm}^2$ , which allows for spatial resolution of about  $1 \text{ mm}^2$ .

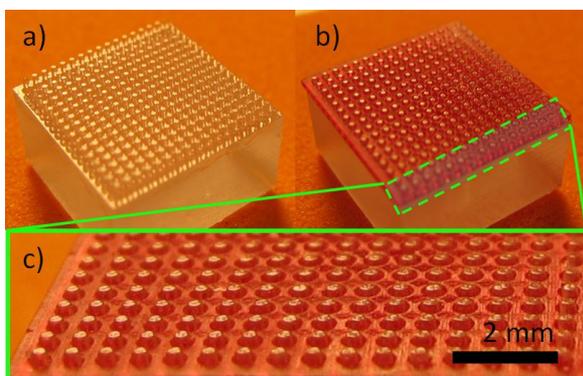


Figure 8: A prototype dense array of pins that can be used to make a skin-like force sensor array: a) pin arrays; b) pin arrays with casing (red translucent part); and c) close view of pins passed through the casing to show the protection mechanism.

## CONCLUSION

Here we successfully created a micro hydraulic force sensor with average sensitivity of  $87 \text{ fF/mN}$  (maximum observed:  $260 \text{ fF/mN}$ ) and potential to minimize pixel size to  $0.79 \text{ mm}^2$ , with a full-scale range of  $10 \text{ mN}$ . The full-scale range can be increased up to  $180 \text{ mN}$  without a change in geometry, but increasing the parylene layer thickness. In addition, we demonstrated the capabilities of SLA to be used for a high-density tactile sensor array at low cost. Moreover, the sensor architecture along with the micro-hydraulic design provides completely isolated pixels for minimized cross talk between adjacent cells. This force sensor shows promise for skin-like sensing applications. Compared to other works, it shows higher sensitivity ( $0.260 \text{ pF/mN}$ ) with a potential spatial resolution of  $1 \text{ mm}$ . Furthermore, this plunge-membrane architecture can be used in actuation applications. For example, the pin can be electrostatically actuated outward; to characterize a surface being probed, or can be used as a miniature piston for air-foil control.

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