Tactile Displays Realized Using MEMS Actuator Arrays

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Project Staff

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1 Introduction

The purpose of this project is to develop new tactile interfaces that capitalize on advances in MicroElectroMechanical Systems (MEMS) technology to create high-bandwidth displays for stimulating the user's tactile sense. Such devices may also receive manual or other types of pressure/contact input. We envision two major classes of applications: (1) Tactile interfaces mounted on machines could indicate the state of the machine--such as the remaining charge in a battery--or it might respond to the operator's touch in subtle ways not possible with conventional controls, (2) Tactile interfaces attached to the human body--for example, through a glove or wrist band--could be used with wearable computers or communication devices for both input and output.

The project is a collaboration between the MIT Touch Lab at RLE and Prof. Kaigham J. Gabriel at the MEMS Laboratory at Carnegie Mellon University (CMU). To date, the work at MIT has consisted of experimental studies of biomechanics and tactile perception. This work is intended to guide the design of tactile interfaces and it will also advance the science of human haptics. The group at CMU is developing the MEMS stimulators and sensors that will be incorporated in future prototype interfaces. Following are summaries of the work accomplished in each task area.

2 Characterization of Human Skin and Tissue Impedance

The goal of this part of the project is to measure and characterize the mechanical impedance of human skin at various body sites. This involves *in vivo* measurements of the force response to mechanical displacement of the skin. The measurements are made using the Skin Dynamics Test Apparatus (SDTA) that we have developed. The SDTA uses an Aurora Scientific Inc. Dual-Mode Lever Arm System that is controlled by a PC via an A/D card. The apparatus continuously samples both the position and the resulting force on a 0.5 mm diameter probe as it is first pressed against the skin and then displaced sinusoidally about the mean pre-indentation depth. The resulting biomechanical data will be used to determine parameters in previously developed skin models.

Most of our effort up to this point has been devoted to setting-up the apparatus and establishing the experimental procedures. This includes writing the software to run the experiments and to analyze the data, mechanical construction, tuning, and calibration of the stimulator using a Laser Doppler Vibrometer.

Preliminary data for 3 human subjects has been obtained for the finger pad at frequencies ranging from 1 Hz to 400 Hz, amplitudes ranging from 50 microns to 150 microns, and mean pre-indentation depths of 200 and 300 microns.

3 Perceptual Resolution Measurements

The goal of this part of the project is to determine the limits of perceptual resolution for various kinds of vibratory tactile stimulation at various body sites. The measurements are made using apparatus that is similar to that used for the skin biomechanics experiments (i.e., the SDTA). The Tactile Perception Test Apparatus (TPTA) will ultimately include two Aurora-Scientific-based tactile stimulators and it will incorporate a 5-axis micro-positioning assembly (x, y, z, theta, and stimulator separation). Under computer control, the motorized micro-positioning assembly will be able to continuously adjust the position of the two stimulators over the course of hundreds of successive experimental trials.

At this point, the apparatus is still under construction although all of the major components have been purchased. The hardware design and the development of the software to run the apparatus have taken longer than anticipated. As an interim measure, we have used the SDTA to make some one-point threshold measurements on the finger pad. This was done in order to help develop our experimental procedures, to verify the acceptability of the Aurora-Scientific-based tactile stimulators for perception experiments, and to obtain some preliminary data.

Detection threshold measurements were obtained on the right index finger of four adult subjects at eight frequencies in the range of 2 to 256 Hz. Thresholds were estimated using a two-interval forced-choice adaptive-level procedure with trial-by-trial correct-answer feedback. Each run began with the stimulus level set well above threshold. Presentation level was changed following two correct responses (resulting in a decrease in stimulus level) or one incorrect response (resulting in an increase in stimulus level). The step size was set initially to 4 dB but was changed to 2 dB after the first reversal. A run was terminated after 8 reversals in level and the threshold for that run was calculated by averaging across the levels of the final 6 reversals. The two observation intervals were 500 msec in duration and were separated by 200 msec. Visual cueing of the observation intervals was provided on a computer terminal. The tactual stimulus was presented in one of the two observation intervals, selected at random on each trial. Data were collected in 8-run blocks with random ordering of the 8 frequencies within each block. Five blocks of data were collected on each of the four subjects, leading to five threshold estimates at each of the 8 frequencies (2, 4, 8, 16, 32, 64, 128, and 256 Hz).

Reliable threshold estimates were obtained in the range of 2-64 Hz; however, threshold measurements at 128 and 256 Hz were limited by both the resolution of the system and the level of the electrical noise. Thus, we will summarize only the measurements in the range of 2-64 Hz. Mean nominal thresholds and standard deviations across the five subjects (in dB re 1 micron peak) were:

	2 Hz	4 Hz	8 Hz	16 Hz	32 Hz	64 Hz
Mean	29.7	21.5	19.8	15.3	9.6	6.2
Std. Dev.	2.6	1.0	0.6	1.2	3.1	4.9

Subject means and inter-subject variability at these frequencies are consistent with other measurements reported in the literature. During each observation interval, values of stimulus amplitude as a function of time were sampled and stored. Using these sampled values, a calculation was made of the “actual” presentation level on each trial. When these “actual” values were used to calculate thresholds, they were found to be in excellent agreement with the thresholds from “nominal” stimulus levels (i.e., within 0.1 dB at five of the six frequencies).

4 Development of MEMS Tactile Stimulators and Sensors

The goal of this part of the project is to develop the MEMS stimulators and sensors that may be incorporated into tactile interfaces. Initial work has focused on the development of a single stimulator or actuator that consists of two gas- or fluid-filled chambers as shown in Figure 1. The chambers are covered and sealed by a common membrane such that when the membrane covering the outer chamber is displaced by electrostatic force, the membrane covering the inner chamber is also displaced (a greater distance) by the movement of the fluid. Two design approaches have been explored: (1) Surface Micro-machined and (2) CMOS Fabricated.

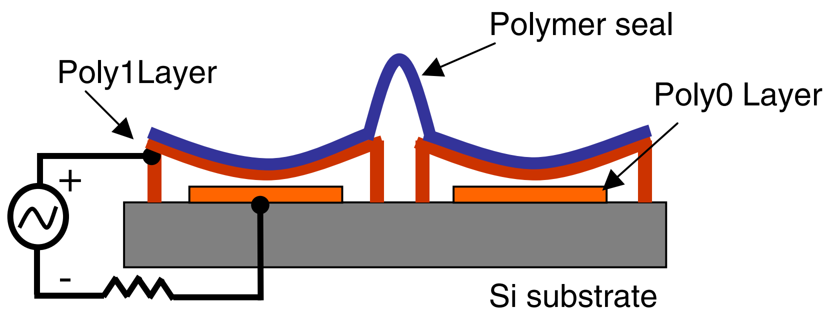


Figure 1. Surface Micro-machined Actuator with Polysilicon Membrane.

The past year has yielded progress in the MEMS tactile actuator project in simulation, fabrication, and experimental testing. Along with the development and analysis of the surface micro-machined actuators, improved CMOS fabricated versions with greater deflection potential were designed and fabricated. Initial testing of the CMOS fabricated actuators is currently underway. Various sealing techniques have been explored in other membrane related research in the CMU MEMS group with promising results applicable to the tactile project.

A meshed based aluminum membrane (Figure 2) is currently under investigation in research to produce a variable deflection surface for acoustic MEMS. This concept was adopted for the design of a CMOS fabricated tactile actuator. The mesh provides the following advantages when implemented in the CMOS process:

- Provides more compliant spring constant than uniform aluminum plate.
- Creates etch channels to silicon substrate for isotropic release.
- Supplies frame to support polymer seal.
- Lessens the effect of curl after release due to minimal continuous beam lengths.

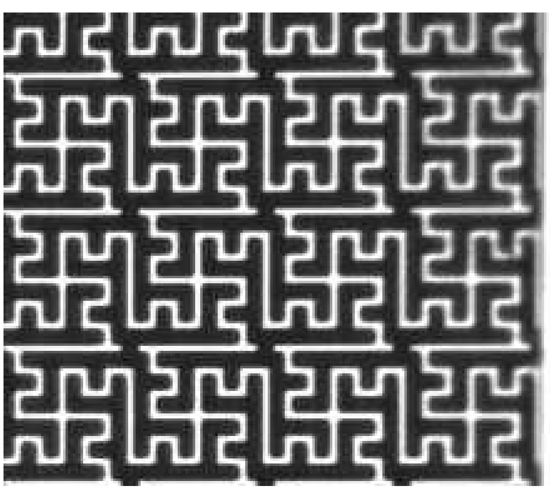


Figure 2: Mesh Based Aluminum Membrane

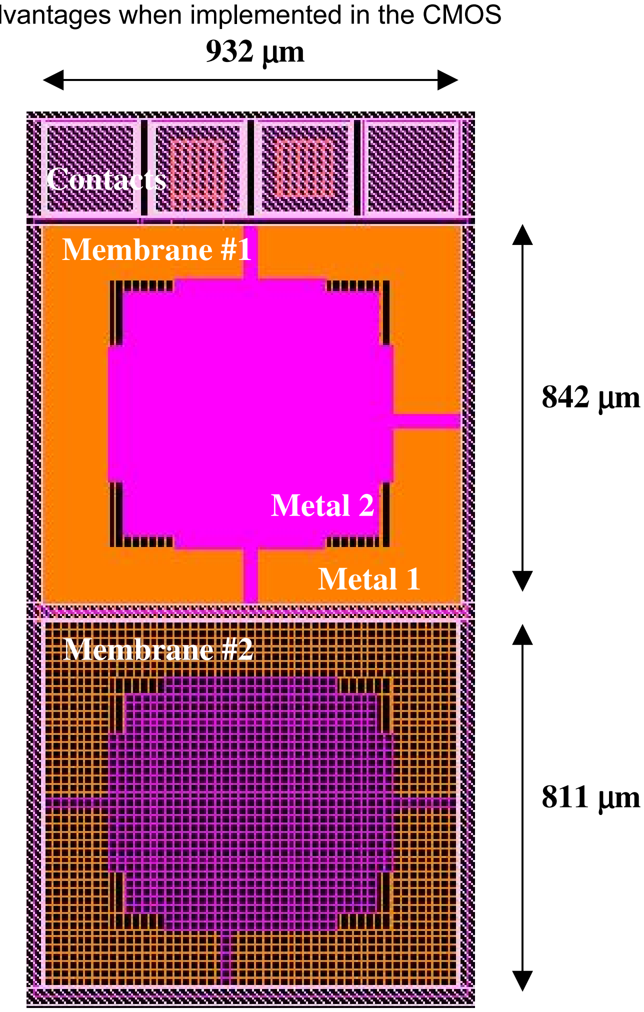
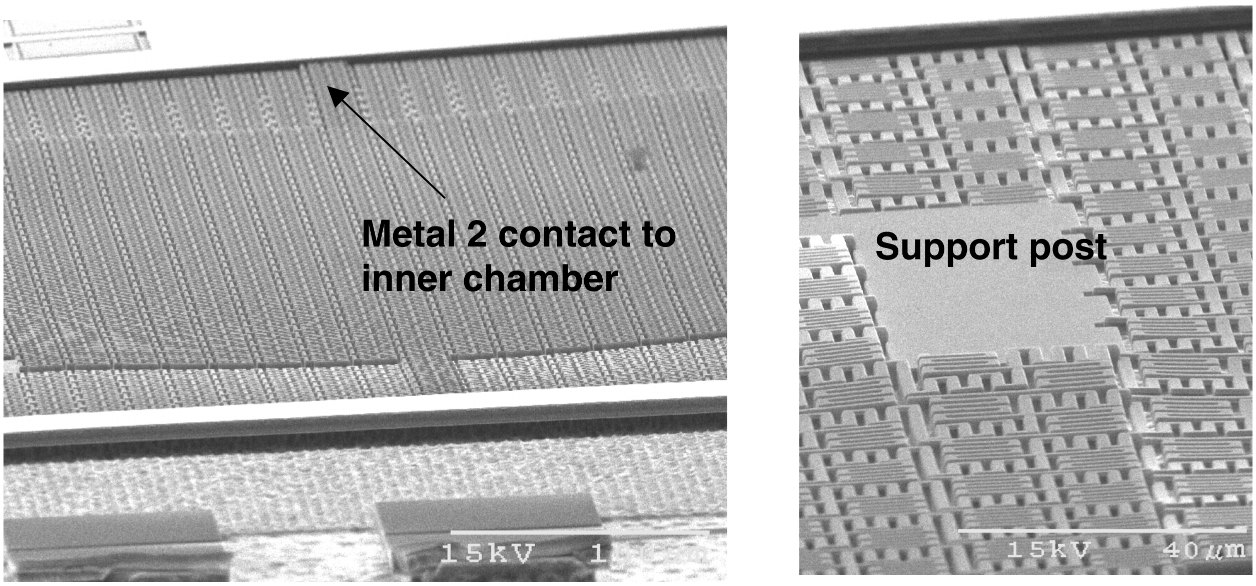


Figure 3: CMOS Tactile Actuator Layout

The Cadence layout for two CMOS fabricated actuators is presented in Figure 3. Each actuator was designed with two aluminum layers for the inner and outer chambers of the mesh-patterned membrane. The two regions are electrically isolated by an oxide layer, which raises the inner chamber metal layer above the outer region. This provides the ability to actuate the pneumatic compression with the outer chamber while measuring the change in capacitance with the inner Metal 2 layer. Posts at the corners of the inner chambers provide support and isolation from compression region. Two mesh patterns at roughly 0.7 inner/outer membrane width ratio were designed to quantify deflection, etch rate through the mesh, and membrane stiffness.

The chips were fabricated and released through a XeF2 isotropic etch. Current testing reveals a 4 m outer chamber deflection at 25 V for Membrane #1 and 40 V for Membrane #2. Released photos of the



Figures 4, 5: SEM views of Released CMOS Tactile

actuators are presented in Figures 4 and 5.
The resonant frequency for a 2 mm x 2 mm membrane was estimated using the MEMCAD finite element-modeling package. This was accomplished by modeling the inner and outer sections of the CMOS actuators separately, assuming the interface between the sections will serve as a fixed boundary. Although the actual geometry of the actuator surface could not be modeled, the composite membrane resonant frequency is assumed to fall between the results for an aluminum plate and polymer coating. The results are presented in Table 1.

Membrane	Material	# of Elements	Thickness (m)	Length x Width (mm)	Resonant Frequency (kHz)
Inner	Aluminum	384	2.8	1.4 x 1.4	120
Outer	Aluminum	522	2.0	2.0 x 2.0 (minus inner membrane)	17.0
Inner	Polyimide	384	1.0	1.4 x 1.4	19.0
Outer	Polyimide	522	1.0	2.0 x 2.0 (minus inner membrane)	1.40

The 2nd generation of surface micro-machined actuators were released and characterized:

- Design modifications intended to remove the electrical shorting in the 1st generation actuators have been successful. The dimple ridge under the upper plate, which contacts the nitride surface under maximum compression, successfully prevents capacitor plate contact.
- Depending on capacitor area for each design, required voltage for compression lies between 40-60 V.

A number of sealing options have been experimented on the surface micro-machined actuators as well as CMOS meshed aluminum surfaces. The following candidates have been tested on the 2nd generation MUMPS actuators:

- *Dupont Kapton KJ*: Thermoplast polyamide coating has shown to immobilize the microstructures after application. KJ requires high pressure and temperature, which capsizes the microstructures.
- *Dupont Clysar*: Initial characterization of heat-shrink polyamide currently underway.
- *Pyralin Polyimide*: Applied by spin coater. Adheres to polysilicon structures fully but marginally to the nitride surface. Testing currently underway to form sealed bubble above nitride surface.

The following progress has been made with sealing onto the CMOS aluminum surfaces:

- *Parylene C*: Polyimide was deposited onto similar meshed surface to form acoustic membrane. A uniform seal successfully formed among the beams (Figure 6), but rendered a stiff composite membrane.
- *Pyralin Polyimide*: Testing currently underway on spin coated Pyralin membranes. Initial observations include the stretching of the compliant mesh surface due to centrifugal force and a difficulty in maintaining uniform thickness.

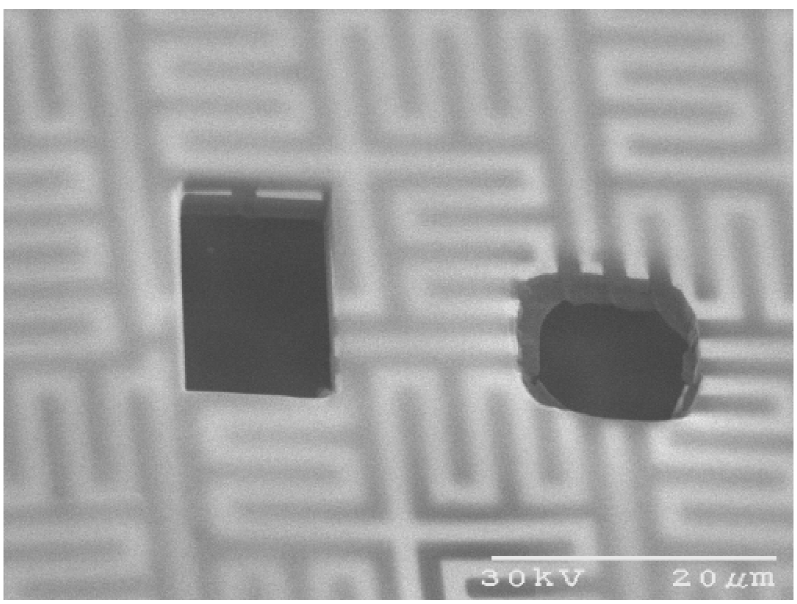


Figure 6: Parylene C coating on aluminum mesh. Focused ion beam used to cut holes for uniformity analysis.

Future research efforts will focus on characterizing the released CMOS actuators, testing the performance of the polyamide coated actuator, verifying simulation results, and optimizing the CMOS actuator design based on experimental results.