AN ACOUSTIC TOUCH-MOTION BUTTON WITH HAPTIC FUNCTION VIA AN *IN-SITU* FABRICATED ELASTOMERIC LENS ATOP PMUTS

Novelty / Progress Claims

Here we present an integrated manufacturing process and implementation of a variable acoustic touch motion button with haptic function via *in-situ* fabricated elastomeric lens atop piezoelectric micromachined ultrasonic transducers (PMUTs). Three distinctive features have been achieved as compared to the state-of-art: (1) direct integration of an elastomeric lens with an acoustic pressure focus point of larger than 3000 Pa for enhanced haptic feedback sensation; (2) pressure-sensitive recognitions with variable levels for touch motions; and (3) ML (machine learning)-based regression with adaptive bidirectional interface for high sensing accuracy. As such, this work represents a new class of human-machine interface with scalable ultrasonic MEMS hardware and intelligent software for touch-sensation applications in hand-held device buttons, including cell phones.

Background / State of the Art

Highly accurate, multi-mode ultrasonic sensing buttons have attracted attention in the advancement of human-machine interfaces by replacing traditional bulky "on-off" mechanical buttons [1,2]. However, these systems often require other strain sensors to detect motions such as force for intent recognition. Furthermore, there is no "actuator" function for these ultrasound transducers to produce high acoustic pressure for haptic stimulations. This work advances state-of-art by using a PMUT array with *in-situ* fabricated lenses for: (1) both touch and force sensing for variable levels of touch-motions, (2) haptic feedback actuation, and (3) ML (machine learning)-based user intent recognition.

Description of the New Method or System

Figure 1 illustrates the schematic of the system, where a PMUT array is placed at the bottom with an *in-situ* fabricated elastomeric lens atop to redirect the ultrasonic waves with a focus point (underneath the tip of the lens in this design). The lens alters the transmission of traditional ultrasonic waves as the air-polymer boundary serves close to a total reflecting surface to redirect the pressure waves with a designated focus point under the lens tip. As a finger touches the tip with different forces, the lens deforms to results in (1) increased echo magnitudes, (2) shorter time-of-flight durations, and (3) specific echo magnitude versus time patterns due to the various deformation of the lens for ML-based pattern recognitions. **Figure 2** shows the (a) PMUT array and its (b) cross-sectional construction. **Figure 3** shows the *in-situ* lens fabrication process. The PMUT array is wire-bonded to a custom PCB (**Fig. 3a**), and a three-part acoustic lens mold is assembled on top (**Fig. 3b**). A liquid elastomer, BBDINO 20A Clear, is injected and allowed to cure (**Fig. 3c**) and the top mold is removed (**Fig. 3d**).

Experimental Results

The prototype utilizes a 9.5×9.5 mm^2 PMUT array with 19x19 transducers and bimorphic actuation as shown in **Fig. 2a** [3] with a fabricated system in **Fig. 2b**. T/R switches are controlled by a Teensy 4.1 for transmitting/receiving 100 kHz pulses for touch sensing and transmitting the 200 Hz square wave for haptics. Simulations performed in MATLAB's K-wave show that the ellipsoid lens creates a pressure focus at the interface, either the lens is gently touched or compressed by 1 mm in **Figure 4**. Microphone readings taken just beyond the interface indicate that >3,000 Pa would be delivered into the user's finger, surpassing pressures demonstrated to create haptic sensation [4]. The echoes from the interface increase significantly in magnitude and time-of-flight decreases as predicted when the interface is compressed (**Figure 5**). Using a commercial force sensor, a linear regression model is prepared using MATLAB's machine learning toolbox to interpret force via the received echo magnitude with 1000 data points and their interpreted vs actual force is plotted in **Figure 6** with an RMS error less than 5% of the operating range. A classification ML algorithm is used to identify four different gestures based on the order in which interfaces are compressed with 100% accuracy.

Word Count: 600

[1] UltraSense Systems, https://ultrasensesys.com/
[2] Sentons USA Inc., https://www.sentons.com/
[3] Y. Peng *et al.*, MEMS, 2024
[4] F. Xia *et al.*, Transducers, 2023

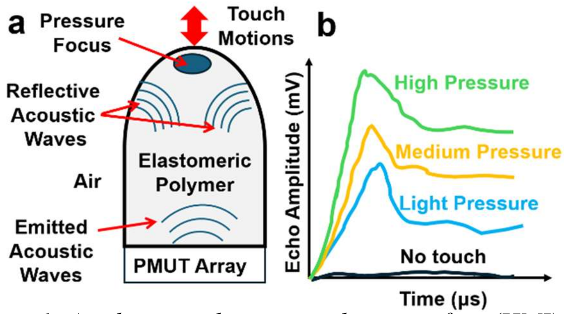

*Figure 1: An ultrasonic human-machine interface (HMI) with in-situ molded acoustic lenses designed to both **(a)** maximize acoustic pressure at the lens tip for haptic sensation and **(b)** provide pressure-sensitive interface reflections.*

Figure 2: Due to copyright reasons, it is not allowed to display this figure before its official publication.

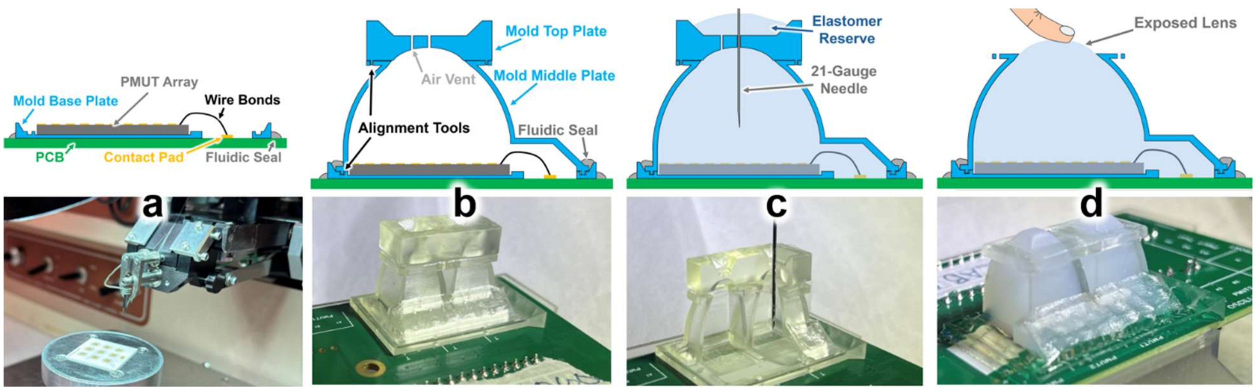

*Figure 3: Manufacturing process, with illustration (top) and photographs (bottom) of each step: **(a)** wire-bonding, **(b)** assembly of lens mold, **(c)** injection of liquid elastomer, and **(d)** exposing cured elastomer lens tip.*

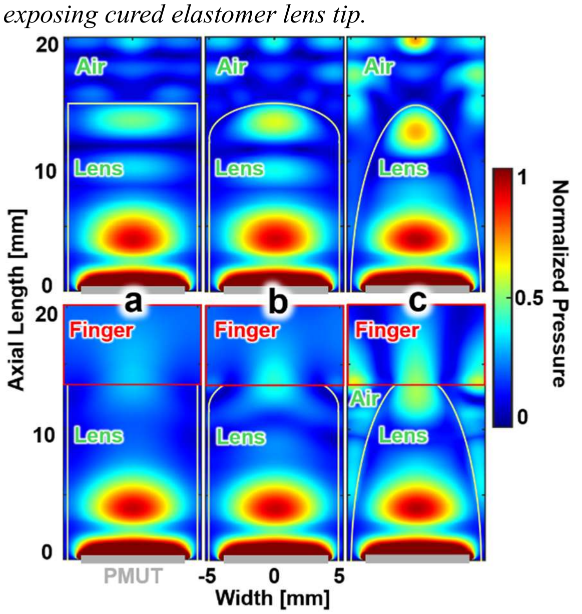

Figure 4: Simulated pressure fields using MATLAB's K-Wave for (a) a cubic lens, (b) a spherical lens, and (c) our ellipsoid lens. Simulations run with (top) an unmodified lens and (bottom) with the lens compressed 1mm. Microphone readings indicate >3 kPa transferred into a finger, sufficient for haptic sensation.

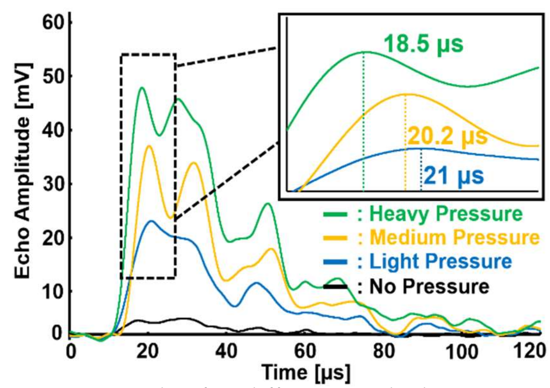

Figure 5: Echo for different applied pressure levels. Echo peaks represent interface distance, with a stronger pressure resulting in a closer interface.

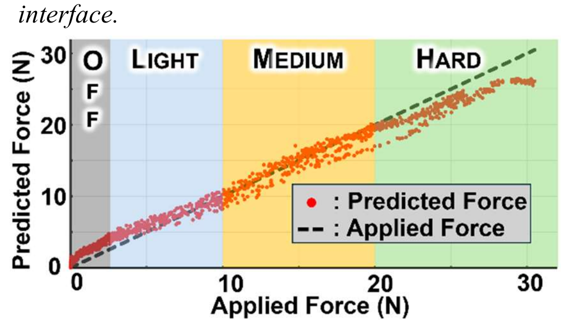

Figure 6: Applied vs predicted force determined via linear regression ML model in MATLAB. RMS error of ~1.5N, <5% of active range.