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

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ABSTRACT

Ultrasonic smart-button interfaces have emerged as a promising direction for next-generation human-machine interaction, offering compact, highly accurate, and multi-modal sensing. Existing ultrasonic interfaces typically require additional strain sensors for interpreting intent, limiting single-device functionality. Additionally, they lack integrated actuation mechanisms capable of producing the high acoustic pressures required for haptic stimulation. To demonstrate the bidirectional communication ability of ultrasonic interfaces, 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-the-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. This integration provides a unified hardware-software package where the same PMUT platform supports simultaneous sensing, actuation, and data-driven interpretation of user intent. 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 handheld device buttons, including cell phones.

KEYWORDS

Piezoelectric Micromachined Ultrasonic Transducer, Acoustic Lens, Human-Machine Interface, Haptics, Machine Learning

INTRODUCTION

Highly accurate, multi-modal 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. By generating haptic sensation, devices can communicate with a user via means other than the traditional auditory or visual pathways (*e.g.*, cellphone vibration to indicate an incoming call). Utilizing haptic pathways—*i.e.*, the sense of touch—relies on the mechanical stimulus of mechanoreceptors within the skin [3]. While distinct receptors are present at different depths and in different locations around the human body, the most convenient to stimulate via acoustic pressure are the Pacinian corpuscle, present within glabrous (hairless) skin and sensitive to gentle stimulus at frequencies ranging from 100-400 Hz [4]. Using ultrasonic transducers to generate haptic sensation presents three distinct advantages: (1) high spatial resolution enabling control over where haptic sensation is felt, (2) better temporal resolution, allowing actuation at multiple distinct frequencies, and (3) low energy requirements [5], [6]. 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.

CONCEPT

The main functionalities of the device are: (1) detecting and interpreting inputs from the user, and (2) delivering variable tactile sensation outputs to the user to enable bidirectional communication. Pulse-echo, a time-of-flight-based imaging method performed by transmitting an ultrasonic pulse then recording the time it takes for an echo to return to the transducer, has enabled a variety of mid-air gesture-detecting functionalities [7]. Additionally, by utilizing phased arrays of transducers to perform acoustic beam steering, mid-air haptic sensation has been generated with acoustic pressure [8]. However, for a human-machine interface suitable for device integration, a solid contact point and small form-factor is necessary, eliminating the use of a mid-air interface.

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

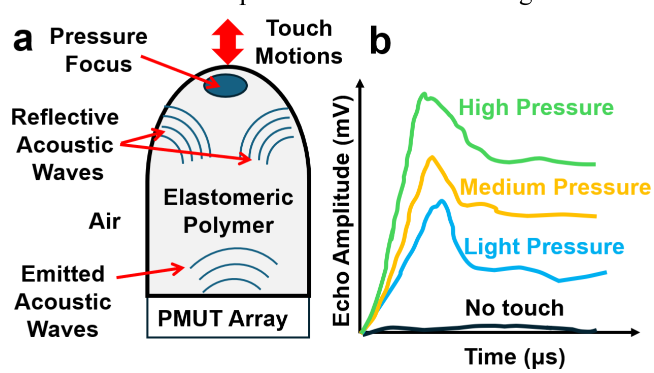

Figure 1: An ultrasonic human-machine interface (HMI) with in-situ molded acoustic lenses designed to both (a) maximize acoustic pressure at the lens tip for haptic sensation and (b) provide pressure-sensitive interface reflections.

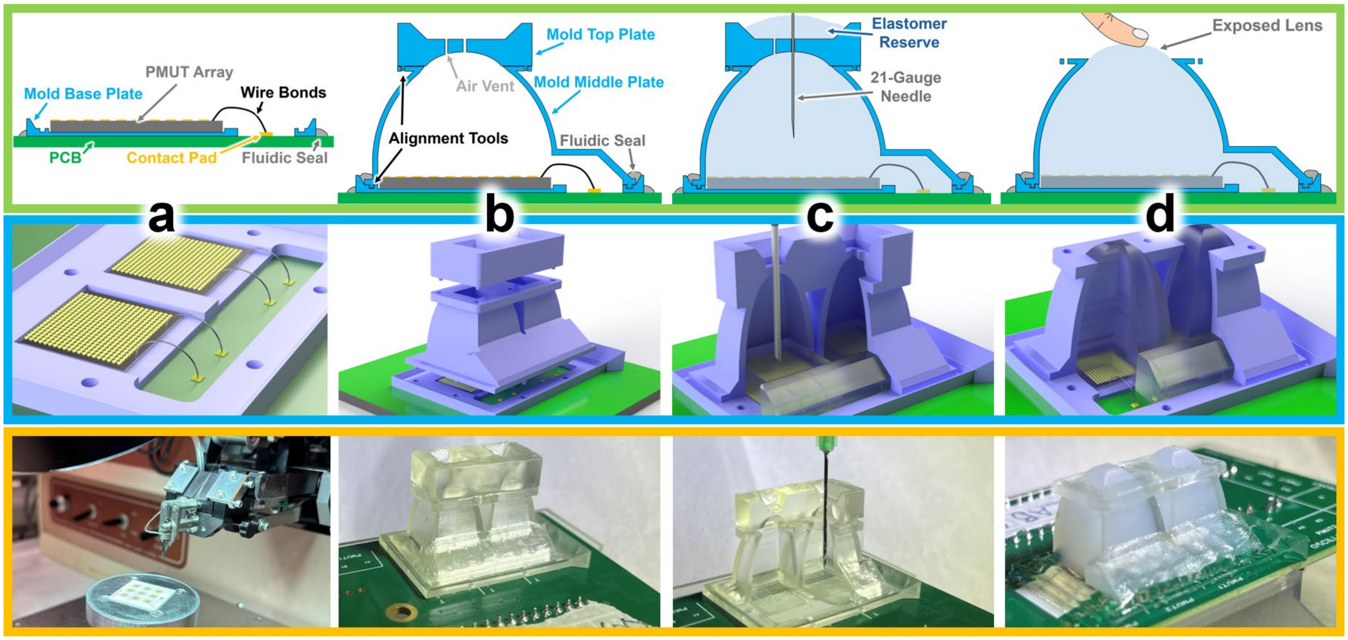

Figure 2: Manufacturing process, with illustration (top), renderings (middle) and photographs (bottom) of each step: (a) placement of the mold base plate and PMUTs and wire-bonding of the PMUTs to the custom PCB, (b) assembly of the middle and top plate of the lens mold with epoxy use to fluidically-seal interfaces, (c) injection of liquid elastomer, ensuring no air bubbles and reservoir to backfill any leaks, and (d) removal of the top plate of the mold to expose cured elastomer lens tip.

point under the lens tip. As a finger compresses the tip with different forces, lens curvature and boundary conditions change, resulting 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.

MATERIALS AND METHODS

PMUT and PCB

The prototype utilizes two single-channel 9.5×9.5 mm^2 PMUT arrays with 19×19 transducers and bimorphic actuation, using lithium niobate (LiN) as the active layer and a platinum top electrode. Manufactured by muRata (Kyoto, Japan), each transducer diaphragm has a circular cross-section and is 368 μm in diameter. The PCB required transmit/receive (T/R) switches, microcontroller compatibility, contact pads for wire-bonding, and other supporting hardware to enable pulse-echo functionality (**Fig. 2**). The PCB was designed in-lab and fabricated by JLCPCB (Shenzhen, China), while a Teensy 4.1 was used as the microcontroller.

Lens Fabrication

Simulations run in K-Wave, a MATLAB (MathWorks, Natick, MA) toolbox, were used to determine lens geometry. With the primary goal of creating a high-pressure focal point at the tip of the acoustic lens to generate haptic sensation, multiple lens designs were considered, including a rectangular control, a hemisphere, and an ellipsoid (**Fig. 3**). The ellipsoidal lens design (**Fig. 3c**) produced the highest pressures both with and without a finger compressing the lens and was chosen as the primary lens design.

Due to the fragile nature of the PMUT diaphragms, acoustic lenses had to be fabricated *in-situ*, as any solid lens placed atop the array would likely destroy the array. To ensure proper lens alignment with the PMUTs, the first component, or the base plate, of the mold was secured to the PCB prior to PMUT placement (**Fig. 2a**). Slots on the top

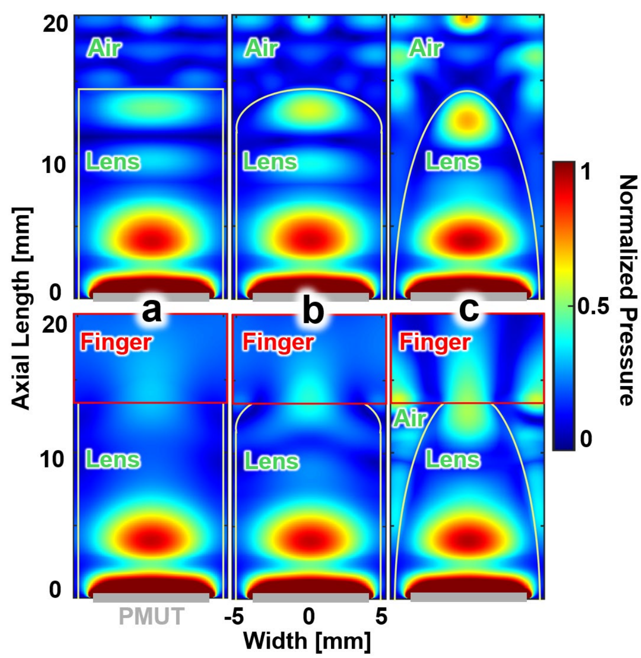

Figure 3: Simulated pressure fields using MATLAB's KWave for (a) a cubic lens, (b) a spherical lens, and (c) our ellipsoid lens. Simulations run with (top) an unmodified lens and (bottom) with the lens compressed 1mm. Microphone readings indicate >3 kPa transferred into a finger, sufficient for haptic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

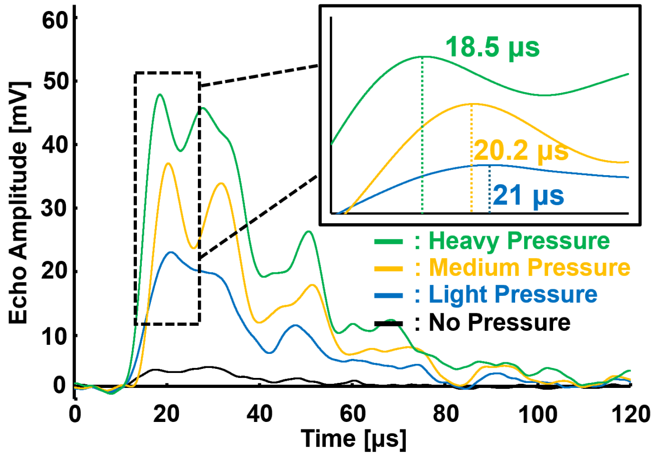

Figure 4: Echo for different applied pressure levels. Echo magnitude corresponds to amount of acoustic pressure reflected back to the transducer array. Echo peaks represent interface distance, with a stronger pressure resulting in a closer interface.

face of the base plate ensured proper spacing of the PMUTs, and liquid epoxy was used to fluidically seal the baseplate to the PCB to prevent leakage of liquid elastomer. Following wire-bonding, the second and third components of the mold, the middle and top plate respectively, were placed with additional alignment holes (**Fig. 2b**). Epoxy was again used to fluidically seal the middle plate to the base plate, while tape was used to temporarily secure the top plate to the middle plate. Silicone elastomer (Platinum 20A, BBDino) was mixed, degassed, and injected into the mold while trapped air was allowed to escape via vents in the top of the mold (**Fig. 2c**). A reserve of liquid resin was piled atop the top plate, ensuring liquid elastomer would fill any gaps created by leaks during curing, preventing the creation of air-bubbles. After 24 hours, the top plate was removed, revealing the top 2 mm of the cured elastomer lens (**Fig. 2d**).

Output Pressure Readings

Acoustic pressures were recorded with a ⅛” field microphone (Type 4138, Brüel & Kjær, Denmark) and amplified with a ½” preamplifier (Type 2669). Output voltages were converted to Pascals via provided calibration curves. As these readings represent the acoustic pressure transferred from the elastomer lens into air, numerical corrections were performed to determine pressure transfer from the acoustic lens into skin:

$$T = \frac{2*Z_2}{Z_1+Z_2} \qquad (1)$$

where T is the transmission of acoustic pressure between materials, and Z_1 and Z_2 are the acoustic impedance of the lens and finger/air respectively.

Gesture Detection and Machine Learning Classifications

Pulse-echo was performed with reflections from the tip of the acoustic lens to monitor for deformations corresponding to user interactions. Single 100 kHz pulses were transmitted at 50 ms intervals, with the microcontroller switching the PMUT connection from the waveform generator to the oscilloscope between pulse transmission and return. As the acoustic pressure of the echo deforms the piezoelectric material of the PMUT, a voltage is generated and fed into the PicoScope (5000 series, Pico Technology, UK) and into MATLAB for further processing. A low-pass filter with a 100 kHz cutoff and mean-subtraction for removing DC bias was performed, then a 20-point moving average was applied for signal smoothing. A z-score normalization was performed to compensate for changing testing conditions while maintaining waveform features.

Two classification algorithms were developed: the first determined the force applied to the lens tip, while the second recognized specific gestures based on the patterns of interaction with the two interfaces. A hybrid convolutional neural network (CNN) and long short-term memory (LSTM) recurrent neural network was used to generate the linear regression model for force detection. The CNN was used to recognize and extract local waveform features using 1D convolutional filters with kernel sizes of 11 and 21, while the LSTM used 64 memory units to track how these extracted features changed over time, enabling recognition of long-term temporal patterns.

A calibrated piezoresistor was used to determine the ground truth of what force was applied to the lens tip when creating the dataset. In total, 16,000 samples were collected of the waveform and their corresponding ground truth, with applied forces ranging from 0~35 N. The dataset was randomly separated into a training and testing subset with a ratio of 4:1. For gesture detection, four classifications were created based on the order each interface was interacted with, using the aforementioned CNN to determine when an interface was compressed.

RESULTS AND DISCUSSION

Haptic Sensation

A maximum reading of 3.55 mV was recorded with the microphone, which corresponds to 4.40 Pa in air. With correction for the transfer of acoustic pressure into air versus into skin using Eqn. 1, the acoustic pressure that would be felt in the finger is 6.8 kPa, well above the threshold necessary for generating haptic sensation [6], [9], [10]. As an

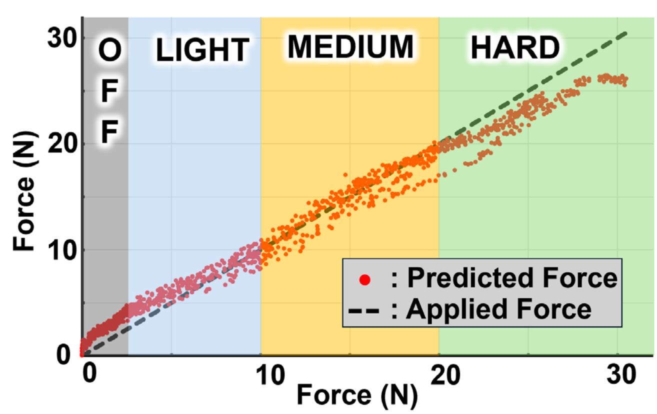

Figure 5: Applied vs predicted force determined via hybrid convolutional neural network (CNN) and long short-term memory (LSTM) neural network linear regression model in MATLAB. RMS error of ~1.5N, <5% of active range.

institutional review board (IRB) clearance has not yet been obtained for this research, human trials cannot be performed to evaluate generated haptic sensation. While the ultrasonic carrier frequency of 100 kHz is too high for human sensation, a pulse width modulation (PWM) scheme can be employed to generate stimulation at frequencies within the 100-400 Hz range necessary to activate the Pacinian corpuscle.

Force Detection

The echoes from the interface increase significantly in magnitude and time-of-flight decreases as predicted when the interface is compressed (**Fig. 4**). The change in echo magnitude represents a more perpendicular interface during tip compression resulting in larger reflections. The shorter time-of-flight is due to the interface getting closer to the transducer array as more pressure is applied. These and other characteristic changes enabled the linear regression model to quantify the applied force with a root mean squared (RMS) error of ~1.5N, < 5% of the active range of the pressure sensing. The regression model maintained consistent results across multiple testing sessions, demonstrating robustness to variations in testing conditions.

Gesture Identification

The additional layer of the ML algorithm was used to identify four typical gestures: (1) pressing the left button for "left," (2) pressing the right button for "right," (3) pressing the left then right button in quick succession for "up," and (4) pressing the right then left button for "down." As the pressure-sensitive monitoring was exceedingly accurate, the four-category classification system requiring simple recognition of whether a button was pressed or not had little room for error; the individual gestures were identified with 100% accuracy, demonstrating the ability to incorporate significantly more complicated classification systems.

CONCLUSIONS

This paper has demonstrated a novel PMUT-based acoustic touch-motion button with integrated haptic feedback via in-situ molded elastomeric lenses. The molding process successfully produced acoustic lenses capable of both focusing pressure waves and serving as an interface for gesture-detecting pulse echo. The high-pressure focal point at the lens tip appears sufficient to generate haptic sensation, while the ML algorithm successfully performed applied force measurements and classified a variety of input gestures.

Future work aims to further reduce the footprint of the device, making it more suitable for incorporation into handheld devices. Using a multichannel PMUT array would facilitate more complex gesture tracking, allowing the detection of movements on all 3 axes with a single transducer array. Additionally, using multiple channels enables the use of phase delay profiles for beam steering, further increasing the pressure at the focal point of the acoustic lens. Finally, as ultrasound is transferred into the finger while in contact with the elastomer interface, echoes reflected off the bone within the finger could serve to verify an intentional button press, helping reduce accidental activation by undesired button compression [11].

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