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 of touch sensing; 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 tool with scalable ultrasonic MEMS hardware and intelligent software for touch sensing-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 the intent (force magnitude) recognition. Furthermore, there is no "actuator" stimulation function as these ultrasound transducers fail to produce high acoustic pressure for haptic stimulations. By generating haptic sensations, devices can communicate with a user other than traditional auditory or visual pathways (*e.g.*, cellphone vibration to indicate an incoming call), which is termed, "the sense of touch"—from the mechanical stimulus of mechanoreceptors within the skin [3,4]. While distinct receptors are present at different skin-depths and in different locations around the human body, the most convenient ones to stimulate via acoustic pressure are the Pacinian corpuscles within glabrous (hairless) skin and sensitive to gentle stimulus at frequencies ranging from 100-400 Hz [5]. 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 [6,7]. This work advances state-of-art by using a PMUT array with *in-situ* fabricated lenses for: (1) touch and force magnitude sensing 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 communications. Pulse-echo, a time-of-flight-based method, performed by transmitting an ultrasonic pulse and recording the time it takes to receive a return echo back to the transducer, has enabled a variety of mid-air gesture-detecting functionalities [8,9]. By utilizing phased delays of an array of transducers to perform acoustic beam steering, mid-air haptic sensation has been generated with acoustic pressure previously [10]. In this work, the human-machine interface system is based on direct contact and a small form-factor instead of airborne gesture recognitions and haptics.

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 paths of the

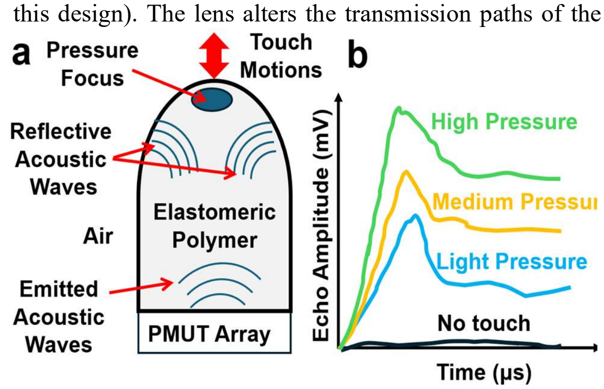

Figure 1: An ultrasonic human-machine interface (HMI) button with in-situ molded acoustic lenses designed to: (a) maximize acoustic pressure at the lens tip for haptic sensation, and (b) provide different levels of pressure-sensitive echoes from the interface.

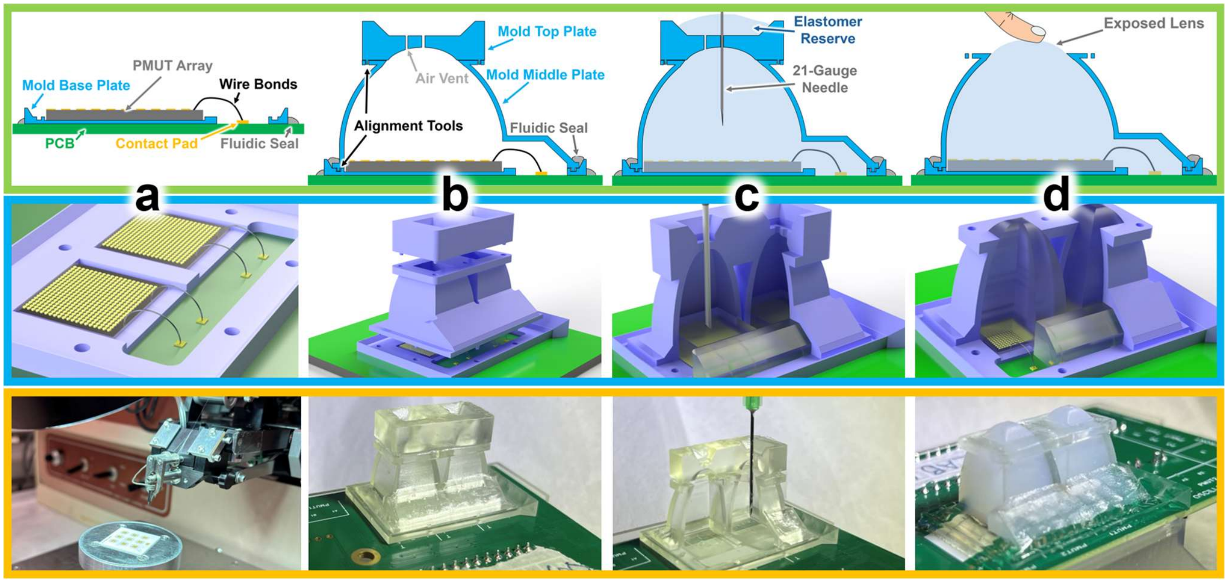

Figure 2: Manufacturing process, with illustration (top), renderings (middle) and photographs (bottom) of each step: (a) placement of the base plate and PMUTs and wire-bonding of the PMUTs to the custom PCB, (b) assembly of the middle and top plate of the lens mold with epoxy to fluidically-seal interfaces,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

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 compresses the button tip with different forces, lens curvature and boundary conditions change to result in (1) increased echo magnitudes, (2) shorter time-of-flight durations, and (3) specific echo magnitude versus time patterns due to various lens deformations 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 bimorph actuation, using lithium niobate 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 has several transmit/receive (T/R) switches, a microcontroller, contact pads, and supporting hardware to enable the pulse-echo detection function (**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 in K-Wave (MATLAB MathWorks, Natick, MA), were used to determine the 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 cubic-shape, an arc-shape, and an ellipsoid lens (**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 could 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 the PMUT placement (**Fig. 2a**). Slots on the top face of the base plate ensured the proper placement of PMUTs. Liquid epoxy was used to fluidically seal the baseplate to the PCB and prevent the leakage of liquid elastomer. Following the wire-bonding process, the middle and top plate were placed with additional alignment holes (**Fig. 2b**). Epoxy was again used to fluidically seal the middle plate to the base plate, while a tape was used to

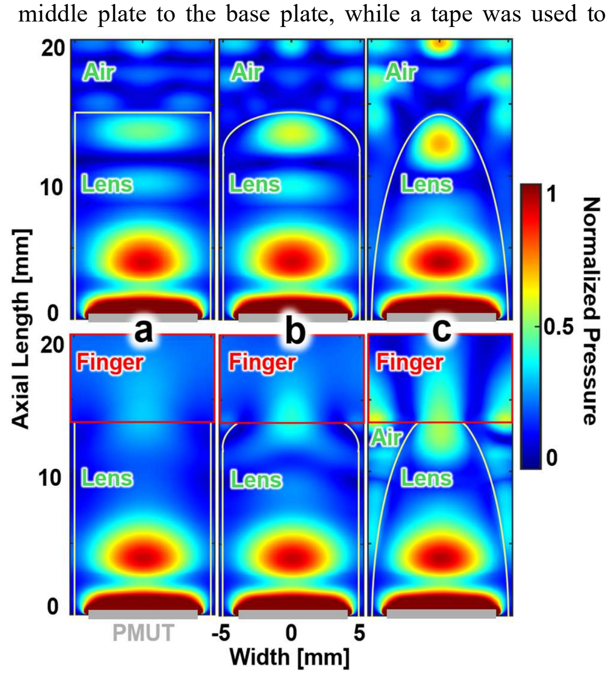

Figure 3: Simulated pressure fields using MATLAB's K-Wave for (a) a cubic-shape lens, (b) an arc-shape lens, and (c) an ellipsoid lens. Simulations with: (top) original lens, and (bottom) compressed lens with downward deformation of 1mm. Results indicate >3 kPa into the finger, sufficient for haptic sensation.

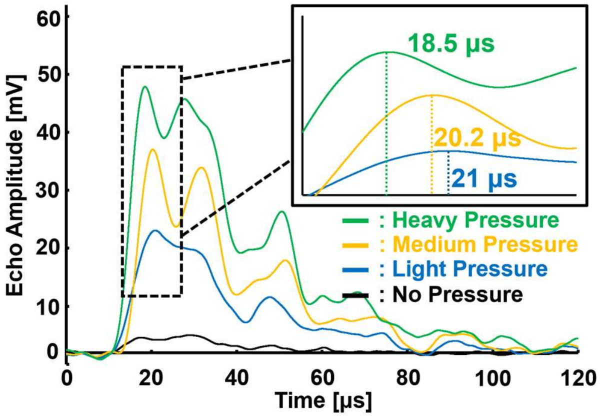

Figure 4: Echo for different applied pressure levels. Echo magnitude corresponds to the amount of acoustic pressure reflected to the transducer array. Echo peaks represent interface distance, with a stronger pressure resulting in a closer interface.

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 the curing process to prevent the creation of air-bubbles. After 24 hours, the top plate was removed with the 2 mm-high cured elastomer lens (**Fig. 2d**).

Output Pressure Readings

Acoustic pressure tests 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:

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

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 measurements with reflections from the tip of the acoustic lens were conducted for deformations corresponding to user interactions. A single 100 kHz pulse was transmitted at 50 ms intervals by the microcontroller. The PMUT switched between transmitting and receiving (between the waveform generator and oscilloscope). As the acoustic echo deforms the PMUT diaphragm, a voltage is generated and fed into the PicoScope (Pico Technology, UK). A low-pass filter with a 100 kHz cutoff and mean-subtraction was used to remove DC bias, and 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 interaction patterns. A hybrid convolutional neural network (CNN) and long short-term memory (LSTM) recurrent neural network were 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 with 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 the gesture detection, four classifications were created based on using the aforementioned CNN scheme.

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 [7,11,12]. Human trials will be performed to evaluate haptic sensations after the approval from the institutional review board (IRB). As the ultrasonic carrier frequency of 100 kHz is too high for human sensation, a pulse width modulation (PWM) scheme will be employed to generate stimulation at frequencies within the 100-400 Hz range to activate the Pacinian corpuscle.

Force Detection

Experimental results show echoes from the interface increase significantly in magnitude and the time-of-flight decreases as predicted when the button is compressed (**Fig. 4**). The change in echo magnitude represents a stronger reflection as the button tip deforms downward for a shorter distance for the ultrasonic wave transmissions and reduced attenuations. The shorter time-of-flight is expected as the interface gets closer to the transducer when a higher pressure is applied. These and other characteristic changes enabled the linear regression model to quantify the applied

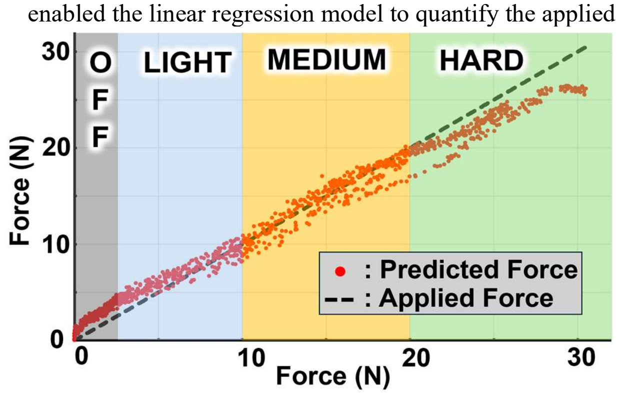

Figure 5: Applied vs predicted force determined via a hybrid convolutional neural network (CNN) and a long short-term memory (LSTM) neural network linear regression model in MATLAB. RMS error of ~1.5N, <5% of active range.

force with a root mean squared (RMS) error of ~1.5N, < 5% within the active pressure sensing range. The regression model maintained consistent results across multiple testing sessions, demonstrating robustness to variations in testing conditions.

Gesture Identification

An additional layer for 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 detects the simple recognition of whether a button was pressed. 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 focusing pressure waves and serving as an interface for the pulse echo measurements. The high-pressure focal point at the lens tip appeared to have sufficient acoustic pressure for haptic applications, while the ML algorithm successfully performed 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 [13].

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REFERENCES

[1] "Sentons ISA Inc," https://www.sentons.com/.

[2] "Ultrasense," https://ultrasensesys.com/.

[3] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces," *IEEE Trans Haptics*, vol. 13, no. 3, pp. 450–470, Jul. 2020, doi: 10.1109/TOH.2020.2990712.

[4] D. Deflorio, M. Di Luca, and A. M. Wing, "Skin and Mechanoreceptor Contribution to Tactile Input for Perception: A Review of Simulation Models," Jun. 02, 2022, *Frontiers Media S.A.* doi: 10.3389/fnhum.2022.862344.

[5] A. Handler and D. D. Ginty, "The mechanosensory neurons of touch and their mechanisms of activation," *Nat Rev Neurosci*, vol. 22, no. 9, pp. 521–537, Sep. 2021, doi: 10.1038/s41583-021-00489-x.

[6] M. Billen, E. M. Ferrer, M. S. Pandian, X. Rottenberg, and V. Rochus, "Mid-Air Haptic Feedback Enabled by Aluminum Nitride PMUTs," in *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 247–250. doi: 10.1109/MEMS51670.2022.9699528.

[7] W. Yue *et al.*, "Auto-Positioning and Haptic Stimulations via A 35 mm Square Pmut Array," in *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, Institute of Electrical and Electronics Engineers Inc., 2023, pp. 941–944. doi: 10.1109/MEMS49605.2023.10052452.

[8] D. Lv *et al.*, "Noncontact Human-Machine Interaction for Air-Writing Based on Piezoelectric Micromachined Ultrasonic Transducers," *IEEE Trans Instrum Meas*, vol. 74, 2025, doi: 10.1109/TIM.2024.3509540.

[9] Y. Liu, Y. Fan, Z. Wu, J. Yao, and Z. Long, "Ultrasound-Based 3-D Gesture Recognition: Signal Optimization, Trajectory, and Feature Classification," *IEEE Trans Instrum Meas*, vol. 72, 2023, doi: 10.1109/TIM.2023.3235438.

[10] S. Pala, Z. Shao, Y. Peng, and L. Lin, "Ultrasond-Induced Haptic Sensations Via PMUTS," in *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, Institute of Electrical and Electronics Engineers Inc., Jan. 2021, pp. 911–914. doi: 10.1109/MEMS51782.2021.9375455.

[11] W. Frier, A. Abdouni, D. Pittera, O. Georgiou, and R. Malkin, "Simulating Airborne Ultrasound Vibrations in Human Skin for Haptic Applications," *IEEE Access*, vol. 10, pp. 15443–15456, 2022, doi: 10.1109/ACCESS.2022.3147725.

[12] Fan Xia, Yande Peng, Wei Yue, Mingze Luo, Megan Teng, Chun-Ming Chen, Sedat Pala, Xiaoyang Yu, Yuanzheng Ma, Megha Acharya, Ryuichi Arakawa, Lane Martin, and Liwei Lin, "High sound pressure piezoelectric micromachined ultrasonic transducers using sputtered potassium sodium niobate," Microsystems & Nanoengineering (Nature Publishing Group), Vol. 10, 205, 2024

[13] N. Lukhanin *et al.*, "Biological Bone Age Assessment Via pMUTs," in *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, Institute of Electrical and Electronics Engineers Inc., 2025, pp. 1007–1010. doi: 10.1109/MEMS61431.2025.10917856.

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