AUTO-POSITIONING AND HAPTIC STIMULATIONS VIA A 35 MM SQUARE PMUT ARRAY

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ABSTRACT

This work reports an engineered platform for the non-contact haptic stimulation on human skins by means of an array of piezoelectric micromachined ultrasonic transducer (pMUT) via the beamforming scheme. Compared to the state-of-art reports, three distinctive achievements have been demonstrated: (1) individual single pMUT unit based on lithium niobate (LN) with measured high SPL (sound pressure level) of 133 dB at 2 mm away; (2) a beamforming scheme simulated and experimentally proved to generate ~2.3x higher pressure near the focal point; and (3) the combination of auto-positioning and haptic stimulations on volunteers with the smallest reported physical device size to achieve haptic sensations. As such, this work could have practical applications in the broad areas to stimulate haptic sensations, such as AR (Augmented Reality), VR (Virtual Reality), and robotics.

KEYWORDS

Haptic Sensation, LN pMUT, Beamforming, Ultrasound

INTRODUCTION

Haptic feedback is an important tool for the human-machine interfaces in areas such as mobile phones, entertainment devices, … etc. [1] By applying force or displacement signals to human's mechanoreceptors, haptic sensation can effectively deliver information and bring different experiences in addition to the conventional visual and auditory ways currently used in the AR & VR systems. Recently, high intensity acoustic actuation has attracted attentions due to several key advantages. First, the acoustic actuation provides a non-contact way for haptic sensation, which does not require physical contact and can avoid hygiene issues. Second, the acoustic actuation can achieve high spatial resolutions when compared to other methods based on mechanical contacts [2] to enable more localized sensation patterns and provide various excitation features.

Several prior reports have demonstrated the feasibility of acoustic haptic sensations utilizing bulk piezoelectric transducers with a very large form-factor and high power-consumption [3,4]. Recent works have proposed the use of small-size and large array of piezoelectric micromachined ultrasonic transducers (pMUT) [5,6] with potential benefits in terms of size and ease of integration with other consumer electronics. However, the low piezoelectric coefficient of AlN used in the prior works produces low acoustic energy utilization efficiency to generate limited output pressure and vague sensation even with a large area of 256 mm^2.

Here, we report a pMUT array with an area of only 35 mm^2 by using lithium niobate (LN) as the piezoelectric

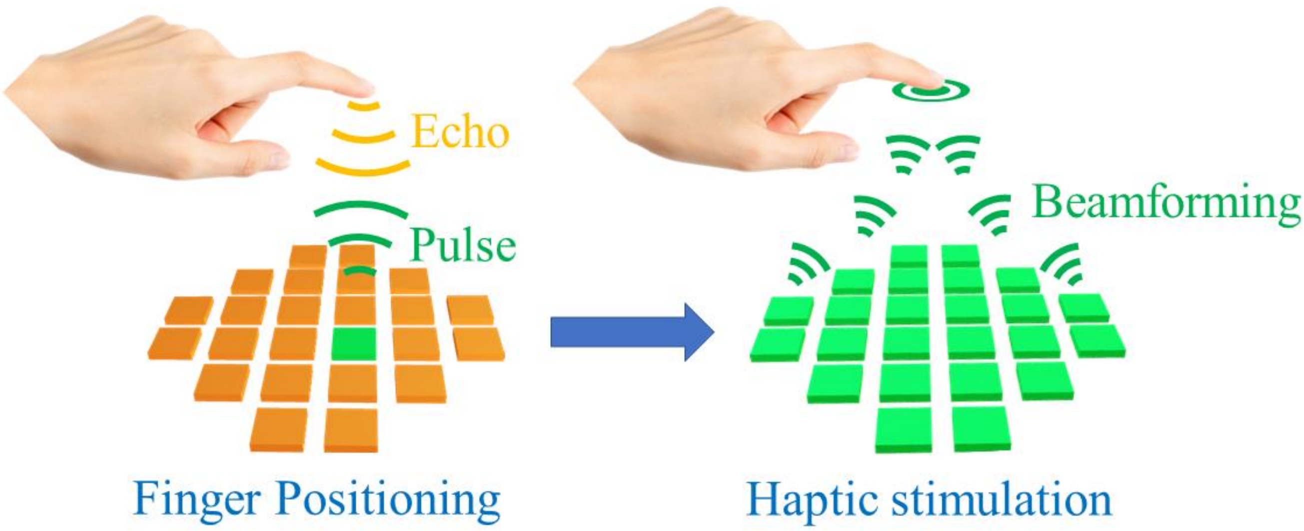

Figure 1: Illustration of the two-step haptic stimulation system. The array can locate the finger first, and generate haptic sensation with the beamforming scheme. In the finger position detection step, a transmitting pMUT unit shown as the green color emits a pulse signal, which is reflected by the surface of the finger. The echo signal can be received by the receiving units which are shown in the orange color. The position information can be analyzed with the obtained time-of-flight (ToF) information. Next, all pMUT devices are actuated with the beamforming scheme, to stimulate haptic sensations on the surface of the finger.

material. The single pMUT unit shows a high sound pressure level (SPL) of 133 dB at a distance of 2 mm benefiting from the better material property of LN due to the combination of piezoelectric coefficients (i.e., d_{31} and d_{11}) [7]. In addition, the pMUT array platform can detect the target and conduct beamforming based on the location to better utilize acoustic energy. As such, a high SPL of 156 dB has been achieved 2 mm away and haptic sensations have been experiences by volunteers at different heights. To the best of our knowledge, this is the smallest reported physical size to achieve haptic sensation.

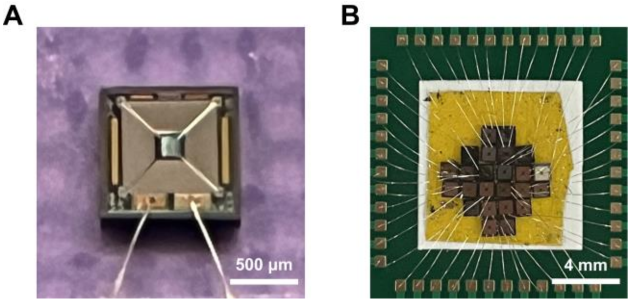

*Figure 2: **A**) The optical image of a single pMUT element. The size of the pMUT device has a rectangular shape with the size of 1.1 mm by 1.2 mm. **B**) The optical image of the 24-element array. The pMUT elements are placed on a PCB board, and the center-to-center distance between adjacent elements is 1.2 mm. The total area of the array is ~35 mm^2 and each element is connected to two different electrodes with aluminum wires.*

METHOD

The two-step haptic stimulation system is illustrated in **Fig. 1**, including the finger position sensing part and the haptic stimulation part. In the finger position sensing step, a transmitting pMUT emits a pulse wave, which is reflected by the finger to form an echo wave. The time-of-flight (ToF) information is extracted from the receiving pMUTs to analyze the location of the finger. This is accomplished by comparing the receiving signals without and with the finger. The haptic stimulation step is followed by exciting pMUT elements in the array with different phases for the resulting beamforming at the finger position. As such, the acoustic power is concentrated on the surface of the finger to stimulate haptic sensations. The excitation frequency of the acoustic wave is modulated to 200 Hz by pulse width modulation (PWM), for the optimal sensation results for mechanoreceptors in the skin [8]. The duty cycle in the PWM is set as 50%, which means the signal will be on for 2.5 ms and off for 2.5 ms in a cycle of 5 ms. Although the vibration frequency of the pMUT is still at 50.64 kHz, the modulated signal shows the behavior of a low frequency excitation of 200 Hz.

The optical photo of a single pMUT device used in this work is shown in **Fig. 2A**. The LN-based pMUT device has a rectangular shape with the size of 1.1 mm by 1.2 mm. AC signal can be applied to the two separate terminals to generate the desired ultrasound outputs. 24 identical pMUT devices are assembled as shown in **Fig. 2B** as the prototype. The pitch size between adjacent elements is 1.2 mm and the whole array has a total area of 35 mm^2. Each device has

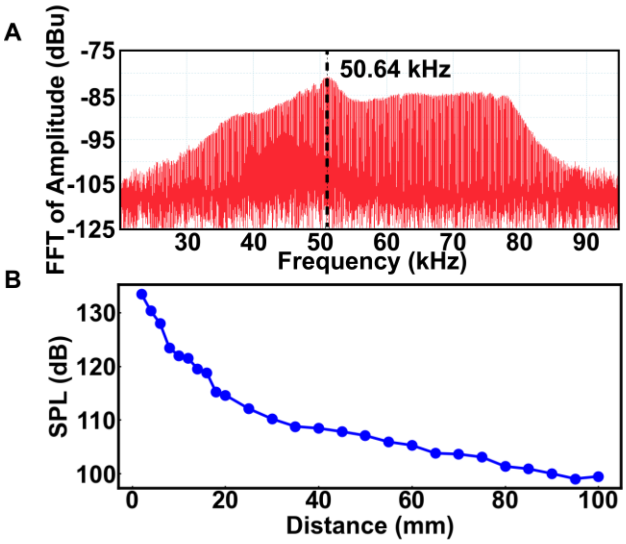

*Figure 3: **A**) Fast Fourier transform (FFT) of the measured output pressure from one device in air. The resonance frequency is observed at 50.64 kHz, which leads to the strongest pressure output. **B**) Measured sound pressure level (SPL) vs. distance curve at 50.64 kHz from one device. The SPL reduces from 133 dB at 2 mm to 100 dB at 10 cm.*

two aluminum bonding wires to electrodes on the PCB board and different signals can be applied on different pMUT devices to enable independent control.

RESULTS AND DISCUSSION

Characterization of a single pMUT

The characterization results of a single pMUT device are shown in **Fig. 3**. The resonance frequency is determined by applying a chirp signal with varying frequencies on the pMUT and measuring the pressure output at certain point by the microphone (Bruel & Kjaer 4136). The applied chirp signal plays the role of a frequency sweeping signal, containing equally strong components from different frequencies (20 kHz ~ 95 kHz). Therefore, the output sound wave generated by the pMUT can show frequency-varying patterns. The FFT of the amplitude obtained by the microphone is shown in **Fig. 3A**, from which the resonance

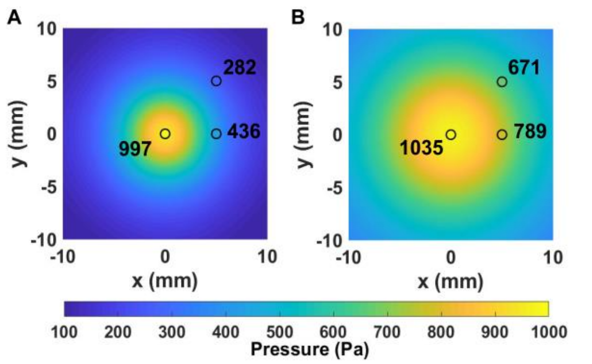

*Figure 4: Experimental and simulation results of pressure in a plane 5 mm above the array system: **A**) without and **B**) with beamforming. The circle symbols are experimental results at the three-dimensional Cartesian coordinates of (0 mm, 0 mm, 5 mm), (5 mm, 0 mm, 5 mm) and (5 mm, 5 mm, 5 mm), respectively.*

frequency is observed at 50.64 kHz. **Fig. 3B** shows results of the SPL of a single pMUT driven at resonance with respect to distance. The SPL declines monotonically with the distance, due to the spreading and attenuation [9]. At 2 mm above the surface, the SPL can reach ~133 dB, which is strong considering the area of a single unit is 1.32 mm^2.

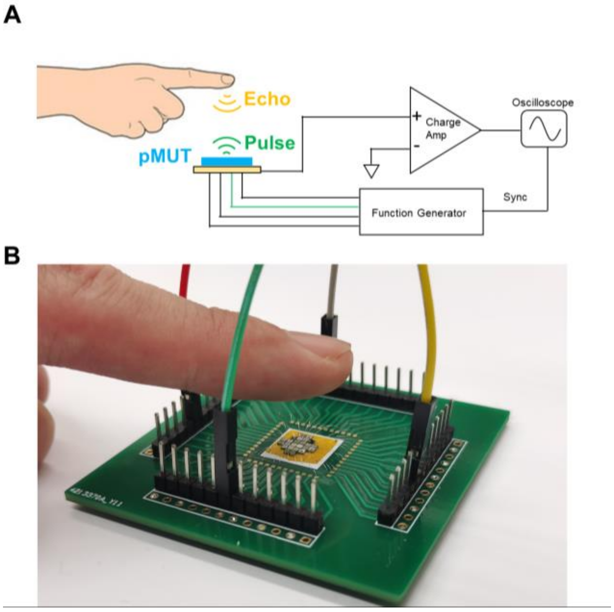

*Figure 5: **A**) The experimental setup for the finger position sensing test. The pulse signal emitted by the transmitting pMUT unit is reflected by the finger, and the echo signal is received by receiving pMUTs. The receiving signal is amplified by the charge amplifier first and collected by the oscilloscope for analysis. **B**) The optical photo showing the setup. The position of the finger can be located by the pulse-echo scheme. The beamforming scheme is utilized afterwards to stimulate haptic sensations by controlling the pMUT elements independently.*

Beamforming results

Low acoustic energy utilization is an important reason that a large array is needed for high pressure outputs. Here, we utilize the beamforming technique to concentrate the acoustic power by applying individual pMUT devices with input signals at the same frequency but different phase angles in the array to significantly increase the SPL at the focal point. The improvement on the 24-element array can be observed in **Fig 4**, showing the difference in the pressure output at 5 mm above the surface. The simulation results of the pressure output generated by the array without and with beamforming scheme together with several experimental measurements are shown in **Fig 4A** and **Fig 4B**, respectively. At each position in the plane, the pressure shown in **Fig 4B** represents the maximum pressure output obtained with the beamforming technique. Obviously, the beamforming technique strengthens the pressure output, especially in the region far from the center. Because at the location far from the center, the distance from this point to different pMUT elements can be different, which also leads to totally different phases of sound waves. When two sound waves have phase difference close to 180°, they can counteract with each other and generate negligible pressure output. At the three-dimensional Cartesian coordinates of (0 mm, 0 mm, 5 mm), (5 mm, 0 mm, 5 mm) and (5 mm, 5 mm, 5 mm), the measured pressure output increases by 4%, 81% and 138%, from 997 Pa, 436 Pa and 282 Pa to 1035 Pa, 789 Pa and 671 Pa, respectively.

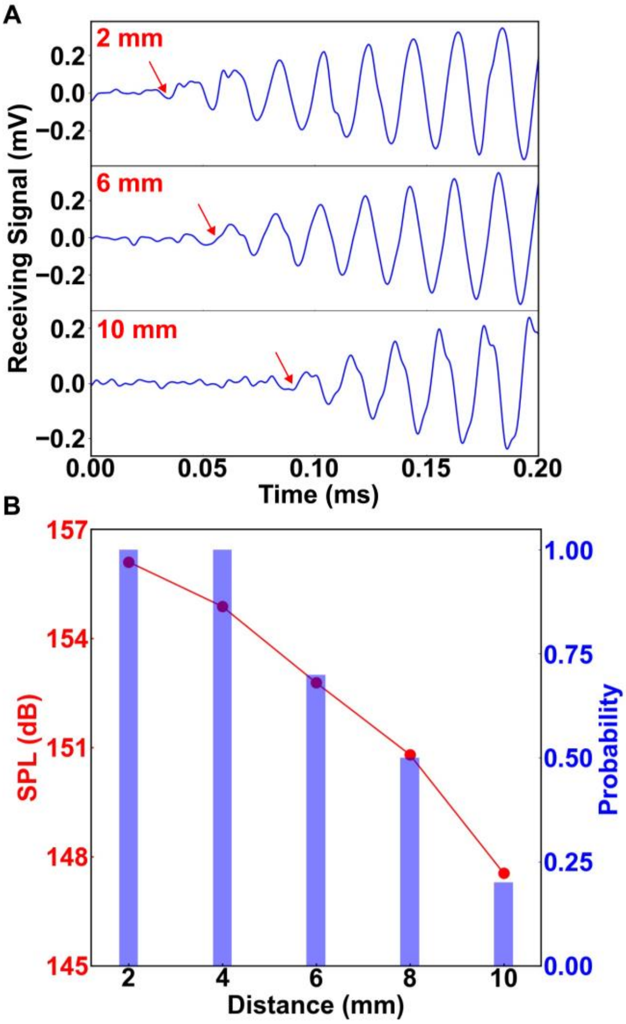

*Figure 6: **A**) Time-of-flight results at three distances of 2, 6 and 10 mm above the system. The beginning point of the echo signal indicates the distance of the finger. **B**) Measured SPL (red color dots) and human sensation probability results (blue color histogram) at 5 different distances of 2, 4, 6, 8, and 10 mm. The SPL reduces from 156 dB at 2 mm to 147 dB at 10 mm. All 10 volunteers report the haptic sensation 4 mm or closer to the system and two volunteers still have the sensation at 10 mm away.*

Experimental setup

The experimental setup diagram of the finger-position sensing experiment is illustrated in **Fig. 5A**. The transmitting and receiving pMUTs are assembled in the same board. When the target finger moves close to the system, the pulse signal sent by the transmitting pMUT unit will produce an echo signal from the surface of the finger to be received by each receiving pMUT unit due to different acoustic impedance. A charge amplifier is utilized to amplify the receiving signal before it is collected by the oscilloscope. The finger position is then analyzed and calculated from the receiving signal based on the Time-of-Flight (ToF). **Figure 5B** shows an optical image of the experimental setup. The 24-element array is fixed on a PCB board and each pMUT unit can be controlled independently with pre-defined phase angle by applying different input signals. Once the position of the finger is detected, pMUT units can be driven correspondingly to concentrate the acoustic power on the surface of the finger to generate strong haptic sensations.

Volunteer test results

The functionality of the two-step haptic stimulation system is demonstrated by volunteer tests with a total of 10 volunteers. They are asked to put their fingers at different locations, and the echo results at different distances of 2 mm, 6 mm and 10 mm are shown in **Fig. 6A**. The beginning point of the echo signal indicates the distance of the finger, which can be calculated based on the ToF. The echo signals can be clearly recognized so that the finger position can be precisely measured. This is accomplished by subtracting the background noises from the raw echo signal. When there is no finger over the array, the signal collected is defined as the background noises, including environmental noises such as wires and the terminals which may interfere the pulse-echo scheme. When the finger is present, echoes from these noise sources are still present and they will appear in the raw echo signals. By subtracting these noises, the signals representing the finger can be clearly presented. After identifying the finger position, the array is driven to stimulate haptic sensations by beamforming on the surface of the finger. The phase angles for different pMUT devices can be calculated with given finger positions and assigned separately to different elements. The haptic sensation at different distances from 2 mm to 10 mm are recorded and shown in **Fig. 6B**. An increased human sensation is observed as the finger is moving closer to the system as all volunteers report haptic stimulations 4 mm or closer to the system. Even at 10 mm away, two volunteers report clear sensations. The SPL at different distances by the beamforming scheme is also measured in **Fig. 6B**, reducing from 156 dB at 2 mm to 147 dB at 10 mm.

CONCLUSION

This paper demonstrates a two-step haptic stimulation system for both auto-positioning and haptic stimulation via a 24-element pMUT array. In the finger position sensing step, the pulse signal emitted by the transmitting pMUT can be reflected by the surface of the finger. The echo signal received by the receiving pMUTs is analyzed and the ToF information is used to determine the finger position. In the haptic stimulation step, the beamforming scheme is utilized to concentrate the acoustic power on the surface of the finger for haptic stimulations. With the beamforming scheme, the pressure output is significantly increased by up to ~138% at some points to make it possible to generate strong haptic sensations with a small array of only 35 mm^2. The SPL versus distance curve of the array is measured by a microphone, and the SPL reduces from 156 dB at 2 mm to 147 dB at 10 mm. All 10 volunteers report strong haptic sensations 4 mm or closer to the system, and two of them can still feel the sensations at 10 mm away. This proves the functionality of our proposed two-step haptic stimulation system, which can fine potential applications in mid-air haptic stimulations such as AR/VR.

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