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DRONE-MOUNTED LOW-FREQUENCY PMUTS FOR > 6-METER RANGEFINDER IN AIR

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ABSTRACT

This paper reports a low-frequency piezoelectric micromachined ultrasonic transducer (pMUT) with a small attenuation coefficient to realize the long-distance range finding applications in air. Pulse-detection measurements of one pair of pMUT devices show a >6-meter traveling distance in air under a 37.32 kHz driving frequency. As an example, two pMUT chips are mounted on two drones as the transceiver and receiver, respectively. Measurements of the separation distance are conducted based on the time-of-flight (ToF) principle with up to 32 fps (frames per second) for real-time detections. This demo of drone-mounted pMUT system illustrates the advantages of pMUT in terms of compactness and low power consumption for applications in drones including obstacle avoidance, inter collision prevention, aerial coordination, and acoustic-based vision.

KEYWORDS

MEMS, pMUT, rangefinder, ultrasound, drone-mounted devices.

INTRODUCTION

Range finding is an important sensing technology in which sensors can detect the location of other devices or objects around the neighborhood areas [1]. Recent development in micromachining technologies have illustrated the new possibilities in range finding schemes using piezoelectric micromachined ultrasonic transducer (pMUT) for reduced size and power consumption when compared with those of bulk acoustic transducers, radars, and LIDAR for mobile drone and robotics applications [2]. Furthermore, pMUTs are also attractive in short-range navigation, obstacle avoidance, and robotic coordination applications in the uncertain or unknown environment [3,4], as compared with optical cameras and infrared transducer which requires clear optical paths [5].

Most current pMUT-based range finding systems have relatively short sensing distances. For example, a prior report shows a pMUT rangefinder reaches 4.8-meter in the traveling distance by using a 4×4 array [6] or >2-meter in traveling distance by using a single pMUT [7] due to the low coupling efficiency in air transmissions. Several approaches have been proposed to increase the sensing distance. In the area of the emission of ultrasound waves, the attenuation efficiency is related to the ultrasound frequency and the working frequency of pMUTs should be low to decrease the signal attenuation effect in air and there are several pMUT devices with relatively low operation frequencies in the 30-40 kHz range [8,9,10]. In the area of piezoelectric material property, the piezoelectric constant (e_{31}) and electromechanical coupling coefficient (k_t^2) [11] should be high for high emission efficiency, while the dielectric constant (ε_{33}) should be low for high receiving sensitivity [12]. In terms of the structural characteristics, a large bandwidth is expected, which usually results in better coupling and efficient energy transfer.

Here, an air-coupled and wide bandwidth rangefinder is demonstrated based on the low- frequency lithium niobate (LN) pMUT (**Figure 1**). The rangefinder consists of two pMUTs as the transceiver and receiver, respectively, with a relatively low resonant frequency at 37 kHz. The system design enables a maximum of 6.4 m detection range in air. With the assistance of signal processing, the rangefinder can realize real-time distance detection up to 32 frames per second. Two mini drones (unfolded size with propellers of 245 mm × 289 mm × 55 mm and max speed in no wind condition of 4 m/s) are loaded with two pMUTs to demonstrate the range finding application. Experimental results show > 6-meter for the pMUT-based rangefinder with small form factor and low power consumption mounted on drones.

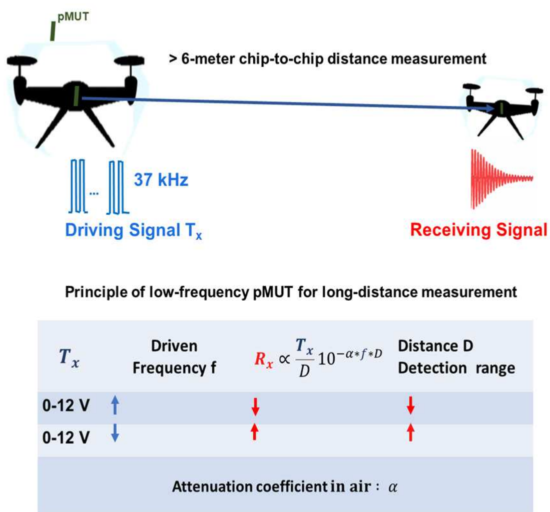

Figure 1: The low-frequency pMUT device for long-distance ultrasound transmissions in air for drone-mounted rangefinder applications. Inset table shows the influence of frequency for the detection range.

DESIGN

In this work, lithium niobate is used as the piezoelectric layer in the pMUT to enable a large electromechanical coupling coefficient, k_t^2, as compared to those of traditional piezoelectrical materials such as AlN, PZT and AlScN [13].

A packaged prototype device is shown in **Figure 2a** with a size of 7 mm ×10 mm × 1.0 mm. The two pins are used for input voltage signals. A well-designed acoustic hole (1 mm in diameter) is used to optimize the acoustic path (AP) for better wave propagations. **Figure 2b** shows the cross-section view of the packaged device. The pMUT is mound at the PCB board and aligned with the acoustic port. In the rangefinder application, two pMUTs are used as the transmitting and receiving unit in two drones and the time of flight (ToF) scheme is used as the sensing principle.

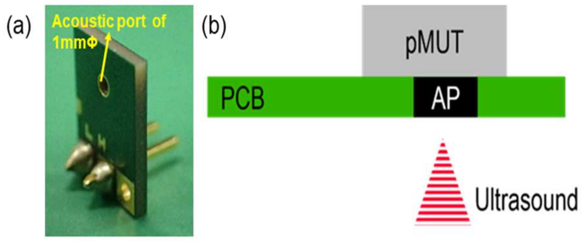

Figure 2: (a) The lithium niobate based pMUT device with package. Size: 7 mm ×10 mm, thickness: 1.0 mm. (b) Cross-section schematic of the device.

DEVICE CHARACTERATIONS

The transceiver function is characterized under the ambient environment by applying chirp signals with sweeping frequencies between 20-100 kHz and 12 V_{pp} in amplitude. The sound pressure is characterized by a microphone (Type 4138, Brüel & Kjær Type 4138-L-006). The received signal is analyzed with FFT as shown in **Fig. 3a** and results are shown in **Fig. 3b**. Two resonance peaks are identified at 37.32 kHz with a bandwidth of 2.53 kHz, and at 49.35 kHz with a bandwidth of 5.42 kHz. The broadened bandwidth ensures the efficient acoustic energy transfer between the pMUT and the medium. In this work, the working frequency is chosen at 37.32 kHz for high acoustic pressure outputs.

The measured sound pressure level (SPL) with respect to distance from 2 mm to over 1,100 mm is plotted in **Figure 3c**. At 2 mm, a high SPL of over 133 dB is obtained. The low operation frequency result in low attenuation lost such that the SPL remains over 70 dB at 1 m away. Analytically, the sound pressure reduces as the distance increases from the attenuation model [14]:

$$p_x \propto \frac{1}{D} 10^{-\alpha D}$$

where p_x is the sound pressure of a specific point in space; D is the distance, and α is the frequency-related attenuation coefficient. The relationship of sound pressure level (SPL) and distance is described in the following formula:

$$SPL \propto -\alpha D - m * log_{10}(D) + n$$

Where m and n are constants. The measurement results correspond well with the theoretical model as the blue curve in **Figure 3c**.

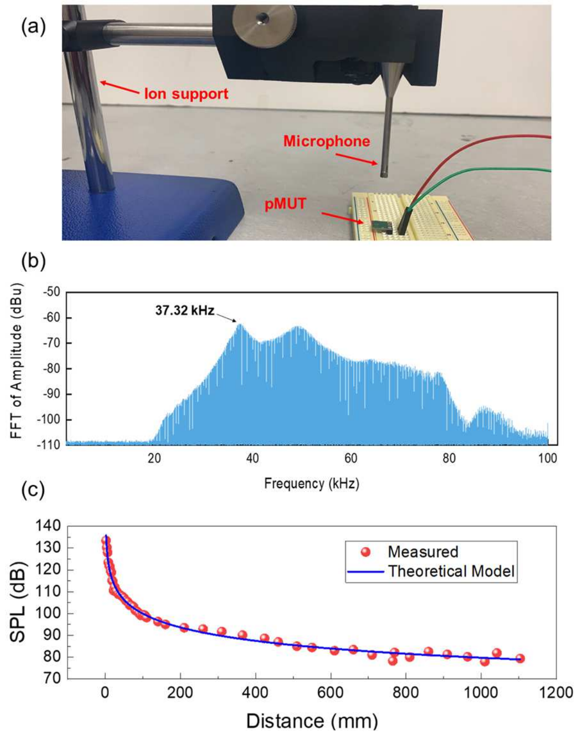

Figure 3: (a) The experimental setup for the PMUT Transceiver characterizations in air. (b) Fast Fourier transform (FFT) of the measured output pressure of a pMUT device in air. (c) Measured results and theoretical model of sound pressure level (SPL) vs. distance at 37.32 kHz under 12 V_{pp}.

MEASUREMENT SETUP AND RESULTS

The characteristics of a prototype pMUT rangefinder is evaluated by measuring the receiving signals amplitude with respect to the distance. As is shown in **Figure 4a**, two pMUTs are used as transmitter (T_x) and receiver (R_x), respectively. The transmitter is driven by a 10-cycle 12 V_{pp} 37.32 kHz square waves with 30 ms as the interval. The

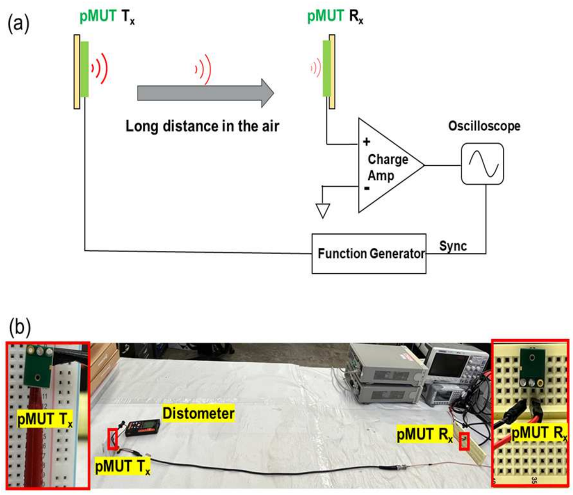

Figure 4: (a) The experimental setup for the distance measurement in air. (b) The optical photo showing the long-distance measurement setup. The insets are the T_x and R_x pMUTs.

receiver is placed at different distances and the receiving signal is collected through the oscilloscope and amplified by a charge amplifier. **Figure 4b** shows the optical photo of the setup with the insets showing the pMUT mounted on two separated breadboards. A laser distometer is used to measure the distance from 0.4 m to over 6 m.

The receiving signals at the pMUT receiver are extracted and plotted in **Figure 5**. **Figure 5.a** shows the example of the measured receiving signal 5.46 m away from the T_x with good signal-to-noise ratio (SNR) of 22.79 dB. The ToF of 15.92 ms matches perfectly with the real distance by using the velocity of sound of 343 m/s.

The receiving signal amplitude with respect to the distance is plotted in **Figure 5b**. It is found that the signal can be detected up to 6.42 m away. Besides, there are no ring down effects due to the cross-talking phenomena of as the transceiver and receiver are separated (different from pulse-echo measuring principle). This means that there are no blind regions in the receiving signals.

The directional properties of the prototype rangefinder are characterized with a setup shown in **Figure 6a.** Under an excitation signal of 37.32 kHZ and 10 V_{pp} square waveform, the receiving voltage amplitude is measured 30 cm away at the same height. The transmitting pMUT is connected to a rotatable column, and the angle of rotation is measured by using the protractor at the bottom. **Figure 6b** shows the results of the normalized sound pressure level from -90 deg to 90 deg. Results show the range of the -6 dB sound pressure region relative to the maximum value is

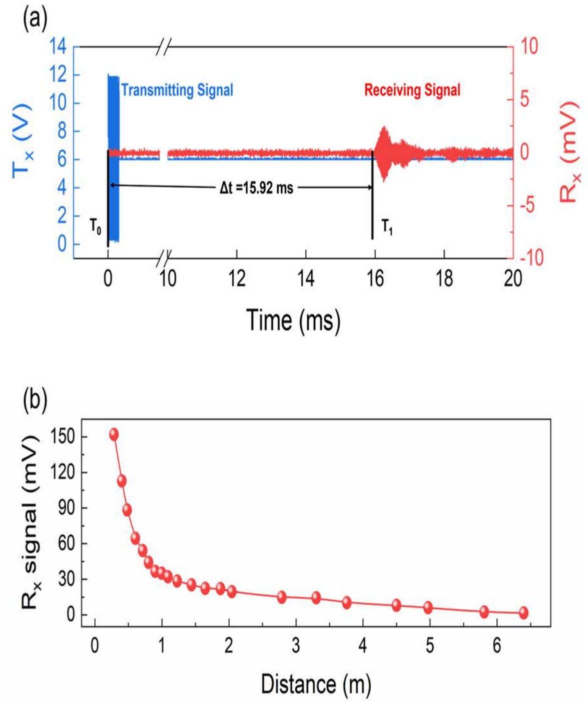

Figure 5: (a) Pulse detection results at a distance of 5.46 m. The transmitting pulse signal has 10 cycles of square waves with 20 ms intervals, and the receiving signal is 15.92 ms after the beginning of transmitting process. (b) Detected signal amplitude with respect to distance from 0.285 m to 6.42 m.

from -30 deg to 30 deg, which implies the rangefinder's field of view is around 60 deg.

One possible application of the rangefinder is for the inter drone collision prevention. In this test, T_x and R_x pMUTs are mounted to the two drones as shown in **Figure 7a.** The small form factor, light weight, and low power consumption of pMUTs enable this possible application for battery-powered drones. Experimentally, the two drones are hovering in air and the rangefinder is working

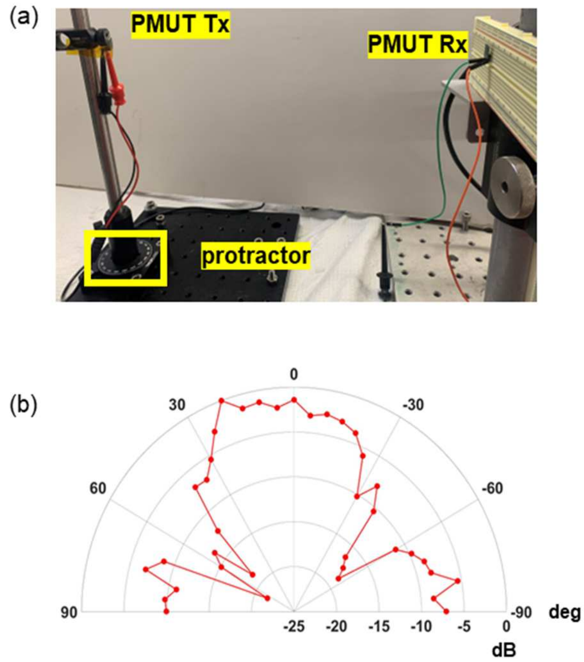

Figure 6: (a) An optical photo showing the experimental setup for the directional property characterization of the pMUT rangefinder. (b) Measured directional characterization results from -90 to 90 deg.

continuously. For the two examples, drones are separated with a distance of 4.38 and 6.05 m (**Fig. 7b**), respectively. The real-time receiving signals are clearly observed from the ToF information. The burst signals applied on the transceiver are continuous periodic signals with the same interval and the calculated distance corresponds well with the actual distance. As such, the distance perception information can be measured continuously which is important as drone-mounted sensing systems for collision prevention or machine vision applications.

CONCLUSION

In this work, a pair of well-packaged pMUTs are utilized for rangefinder applications based on the LN piezoelectric thin film and the application example to drones is demonstrated. The transceiver device is operated at 37.32 kHz while the sound pressure level at 2 mm is 133 dB. The low working frequency enables the low attenuation losses in air and long detecting range with measurements of over 6.4 m Two drone-mounted pMUTs are used as a demo to show the long-distance detection capability of pMUTs in the rangefinder application. The periodical burst signals with 0-12 V_{pp} are applied to the transmitter with a cycle of 30 ms, and the rangefinder system can operate at the 32-fps refresh rate. The pMUT rangefinder system has many advantages, including low power consumption with very small amount of computation power based on the ToF method, independent of lighting conditions, and small factor. The preliminary experiential results in this work also show the long-range detection potential of the pMUT rangefinder for flying drones.

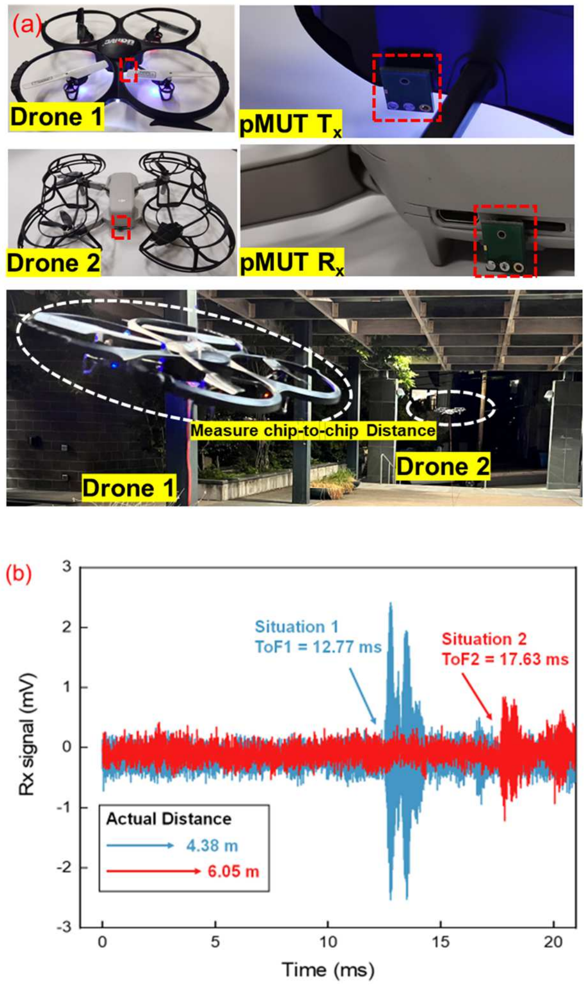

Figure 7: (a) Experimental setup of drone-mounted pMUTs for chip-to-chip distance measurement in real-time. (b) Time-of-flight results of two examples for the distances of two drones of 4.38 m and 6.05 m measured from the pMUT receiver.

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REFERENCES

[1] Przybyla, Richard J., et al. "3D ultrasonic rangefinder on a chip." IEEE Journal of Solid-State Circuits 50.1 (2014): 320-334.
[2] Joontaek J, et al. "Flexible soi-based piezoelectric micromachined ultrasound transducer (PMUT) arrays." Journal of Micromechanics and Microengineering 27.11 (2017): 113001.
[3] Zhou, Xin, et al. "Swarm of micro flying robots in the wild." Science Robotics 7.66 (2022): eabm5954.
[4] Richard J., et al. IEEE Sensors Journal, "In-Air Rangefinding with an AlN Piezoelectric Micromachined Ultrasound Transducer," Vol. 11 (2011): 2690-2697.
[5] Wu, Han, et al. "An ultrasound ASIC with universal energy recycling for> 7-m all-weather metamorphic robotic vision." IEEE Journal of Solid-State Circuits 57.10 (2022): 3036-3047.
[6] Shao, Zhichun, et al. "Bimorph Pinned Piezoelectric Micromachined Ultrasonic Transducers for Space Imaging Applications." Journal of Microelectromechanical Systems 30.4 (2021): 650-658.
[7] Shao, Zhichun, et al. "3D ultrasonic object detections with> 1 meter range." 2021 IEEE 34th International Conference on Micro Electro Mechanical Systems (MEMS). IEEE, 2021.
[8] Luo, Guo-Lun, et al. "Airborne piezoelectric micromachined ultrasonic transducers for long-range detection." Journal of Microelectromechanical Systems 30.1 (2020): 81-89.
[9] Simeoni, et al. "Long-range ultrasound wake-up receiver with a piezoelectric nanoscale ultrasound transducer (pNUT)." 2020 IEEE 33rd International Conference on Micro Electro Mechanical Systems (MEMS). IEEE, 2020.
[10] Simeoni, et al "A 100 nm thick, 32 kHz X-cut lithium niobate piezoelectric nanoscale ultrasound transducer for airborne ultrasound communication." Journal of Microelectromechanical Systems 30.3 (2021): 337-339.
[11] Pop, et al. "Laterally vibrating lithium niobate MEMS resonators with 30% electromechanical coupling coefficient."2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS). IEEE, 2017.
[12] Smyth, et al. "Experiment and simulation validated analytical equivalent circuit model for piezoelectric micromachined ultrasonic transducers." IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 62.4 (2015): 744-765.
[13] Pop, et al. "Lithium Niobate Piezoelectric Micromachined Ultrasonic Transducers for high data-rate intrabody communication." Nature communications 13.1 (2022): 1-12.
[14] Przybyla, Richard J., et al. "In-air range finding with an Aln piezoelectric micromachined ultrasound transducer." IEEE Sensors Journal 11.11 (2011): 2690-2697.

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