A Feasibility Study on Underwater 2D Localization Using PZT pMUTs

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***Abstract*—This work presents, for the first time, underwater 2D localization of a reflector through only two pulse-echo measurements using a trilateration methodology with a pair of lead zirconate titanate (PZT) piezoelectric micromachined ultrasonic transducer (pMUT) arrays. A matched filter method is used to compute the range values for the received signals. Trilateration is employed to determine the absolute location of the reflector via the estimated range values through the use of the geometry of circles. Experimental data are collected using two PZT pMUTs, which exhibit impressive transmit and receive sensitivities, immersed in a FC-70 fluid for the validation of the method with the results highlighting the suitability of the proposed method for underwater 2D acoustic object localization; thus paving the way for the use of pMUTs towards new immersion applications.**

***Index Terms*—pMUT, PZT, matched filter, trilateration, underwater 2D ultrasonic localization**

I. Introduction

Piezoelectric micromachined ultrasonic transducers (pMUTs) have attracted significant attention from the research community and industry due to their advantages. This includes small size, low driving voltage, high fill factor, high transmit (TX) and receive (RX) sensitivities, good impedance matching, and suitability for electronics integration [1], [2]. To date, pMUT devices have been researched for several applications, not limited to: ranging [3], [4], non-destructive testing (NDT) [5], medical imaging [6], [7], fingerprint sensing [8], temperature sensing [9], and vibration monitoring [10].

Underwater acoustic object localization could pave the way towards many new applications including the navigation of autonomous underwater vehicles (AUVs) and serve as $apriori$ information for subsequent targeted imaging (i.e., via beam focusing or steering). Although pMUTs have been used extensively for immersion imaging [6], [7], their use for underwater localization has been very limited to-date. One of the few examples uses a pMUT array for underwater acoustic source localization to estimate the direction of an active source [11]. Unlike [11], this work presents, for the first time, underwater 2D localization of a protruding point on a passive reflector through only two pulse-echo measurements using a trilateration methodology with a pair of PZT pMUTs.

Lead Zirconate Titanate (PZT) pMUTs exhibit very high piezoelectric coefficient resulting in impressive transmit and receive sensitivities, thus making them particularly suitable for imaging applications. This work utilizes these impressive performance characteristics of PZT pMUTs towards underwater 2D object localization. In this paper, for the first time, dual pulse-echo measurements are considered for the localisation of the tip of a reflector immersed in fluid using trilateration. The proposed methodology consisted of a matched filter approach for range estimation with the measured distances used to determine the (x,z) coordinates of the reflector's location in 2D through the geometry of circles. To this end, the use of PZT pMUTs could revolutionize applications involving underwater acoustic localisation for objects-of-interest with very low computational cost.

II. Underwater 2D Acoustic Localization Method

Consider a scenario as depicted in Figure 1 of two sensors (i.e., pMUTs) placed at a fixed known distance from each other along the x axis (z=0) and immersed in a Perspex tank filled with fluid (i.e., FC-70). A reflector is placed at a distance d away from the sensors. Each sensor transmits a pulse and receives the reflected signal in a sequence. The location of the reflector can then be determined by the proposed localisation method as depicted in the block diagram of figure 2.

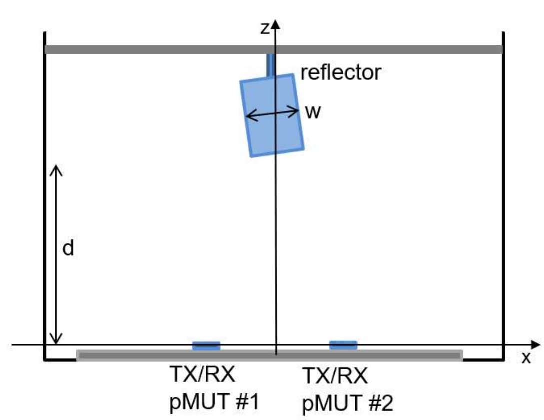

Fig. 1. Proposed scenario for underwater acoustic localzation.

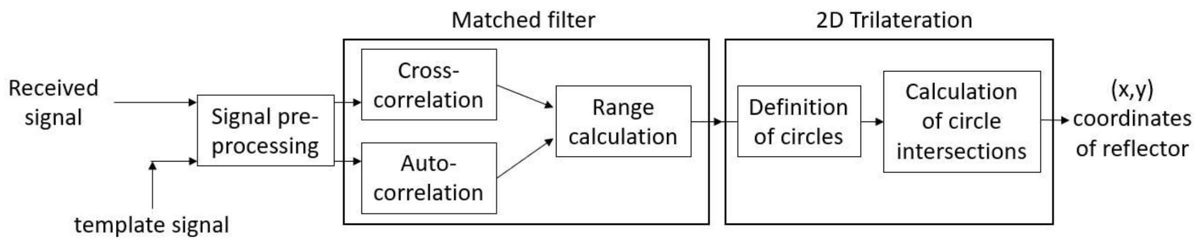

Fig. 2. Block diagram of the proposed algorithm.

The method consists of three processing steps: First, a calibration step is performed, which can eliminate the undesired early-time signal contributions contained in the captured received signals. A measurement without the presence of a reflector is considered and used to subtract out the undesired signal contributions from the measured data with the reflector present. In the second step, the calibrated signals are fed to a matched filter implementation to estimate the range [4] as demonstrated in the block diagram of Fig. 2: The cross-correlation is computed between a received signal $x(t)$ and a template signal $y(t)$. The template signal corresponds to a reference measurement with the reflector being at a known position. The received signal refers to a measurement, where the reflector is at an unknown location. Similarly, the autocorrelation of the template signal $y(t)$ is computed and the range, d, is calculated from the following formula:

$$d = c * \tau_{ToF} = c * (\tau_{cross(max)} - \tau_{auto(max)}) + d_{ref} \quad (1)$$

where $\tau_{cross(max)}$ refers to the time occurrence of the maximum value for the cross-correlation, $\tau_{auto(max)}$ corresponds to the time occurrence of the maximum value of the autocorrelation, and d_{ref} is the known distance between the transducers and the reflector in the reference measurement.

Each range estimate would correspond to the round-trip travel path from the sensor to the reflector's tip and back to the same sensor. By halving the range value, it can be used to define the radius of a circle centered at the position of each sensor, as defined by the following two formulas:

$$(x - x_1)^2 + z^2 = d_1^2 \quad (2)$$

$$(x - x_2)^2 + z^2 = d_2^2 \quad (3)$$

Using eq. (2) and (3), the two intersection points can be computed, from which the one on positive z axis is selected. A visual representation of the trilateration solution is demonstrated in Figure 3 - superimposed to the proposed scenario for underwater acoustic localization. The computed location of the point of interest (in this case, the reflector's tip) is circled in red.

III. PMUT Array and Experimental Setup

Figure 4 shows an optical image of the pMUT die used in this work. The proposed pMUT die design has an aperture of $5mm^2$ within a $3\times3mm^2$ chip and consists of 12×10 membranes (each 170μm wide). The pitch between the membranes

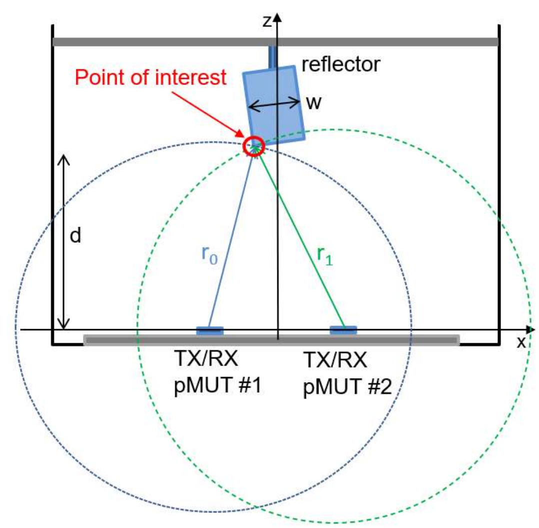

Fig. 3. Visual representation of the trilateration solution.

is 210μm. Each membrane comprises a 2μm-thick sputtered PZT on a 4μm-thick silicon device layer. The device was fabricated at wafer-scale in our 8" line, which is capable of physical vapor deposition (PVD) of high quality PZT.

Every column of membranes within the die is wired so that it forms a channel that can be operated independently with each pMUT chip resulting into six channels that can emit and receive. Both chips are wirebonded to the same custom-designed PCB, encapsulated with epoxy and subsequently mapped to the channels of a Verasonics Vantage 64 ultrasonic research platform (Verasonics Vantage 64 system). The resulting pMUT array consists of 12 channels, from which only two are used to validate this work, one for each die. It is worth noting that at any given time, one of the two channels is transmitting with the same channel receiving the echo signal.

The PCB with the two chips was submerged in a tank filled with Fluorinert FC-70, which is a low-loss liquid with an acoustic impedance, Z (approximately 1.3 MRayls). The two pMUT dies, placed along the z=0 line, are operated in a pulse-echo mode sequentially with the reflector located about a distance, d above them and at a slight angle (experimental setup seen in Fig. 3) to create a protruding point of reflection (marked in red in Fig. 3). A 2-cycle 1.7MHz sinusoidal pulse (13.1V AC) is used for the channel actuation via the

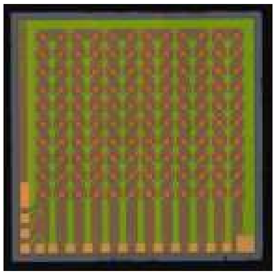

Fig. 4. Optical image of pMUT array die.

Verasonics platform, also used to capture the received signals. Four different locations for the reflector were considered towards the validation of the proposed method with the results summarized in Table I.

IV. Results and Discussion

Figure. 5 depicts the echo signal contributions for pMUTs #1 and #2 considering experimental measurement no. 1. It can be observed from this figure that there is a time delay between the two signals, with the signal from pMUT #1 travelling faster than that from pMUT #2. In addition, the amplitude of the echo signal from pMUT #1 is larger than that of the echo signal from pMUT #2. This would be attributed to the location of the reflector being in the vicinity of pMUT #1. As a result, the echo signal from pMUT #2 would have travelled a longer distance and, thus, would be more attenuated compared to the echo signal from pMUT #1.

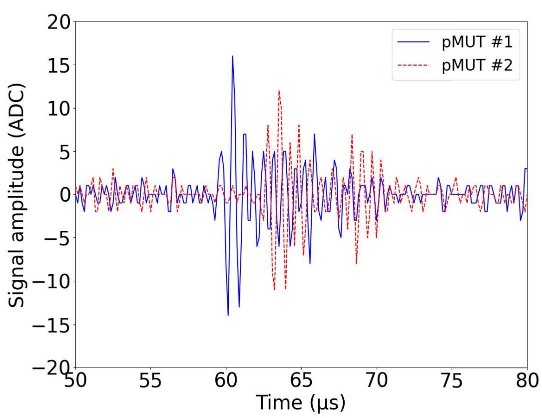

Fig. 5. Comparison of RX (echo) signals from pMUT #1 and #2 for experimental measurement no. 1.

Figure 6 (top figure) depicts the received signal (plotted in blue) for pMUT #1 for experimental measurement no. 1. It can be observed that the calibration step can eliminate the undesired early-time signal contributions very effectively, while leaving the echo signal due to the reflector unchanged and free of distortion. The second and third columns of Table I provide the actual and estimated (x,z) coordinates respectively, whereas the last column calculates the absolute error in millimeters as the Euclidean distance between these values.

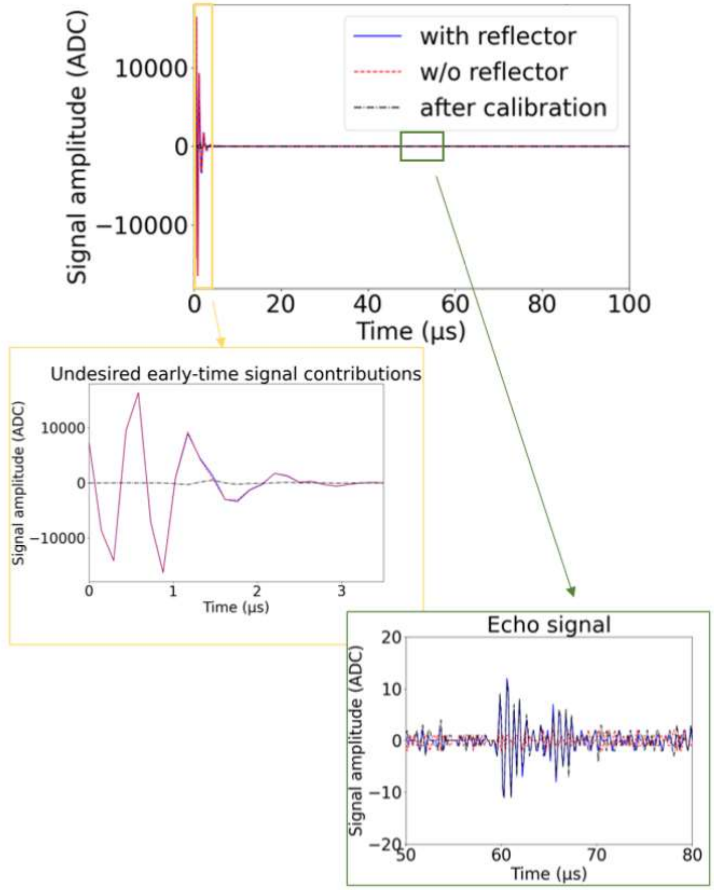

Fig. 6. Effectiveness of the signal calibration step.

TABLE I
True and estimated (x,z) coordinates of the reflector's tip for different reflector positions

Experiment no.	Reflector tip (x,z) coordinates (in mm)		
	True	***Estimated***	***Absolute error***
1	(-3.5, 20)	(-3.47, 20.5)	0.5
2	(-4, 18.5)	(-3.9, 18.3)	0.2
3	(0, 22)	(-0.2, 21.7)	0.36
4	(3.5, 19)	(3.4, 18.85)	0.18

As observed from Table I, the solution of the 2D trilateration problem result in estimated (x,z) coordinates that are excellent approximations of the location of the reflector's tip for every experiment with the absolute error having a mean of approximately 0.3mm and a maximum of 0.5mm. The proposed method not only can accurately measure the location of a reflector in 2D but also has very low computational cost, since it is based on analytical geometry. As a result, it can provide a very fast and reliable estimate of a reflector's position paving the way for the use of pMUTs in applications involving underwater acoustic localisation. Furthermore, only two unique pulse-echo measurements are required for the solution of the trilateration problem in 2D, whereas for its extension in 3D, three unique measurements are needed. Thus, the hardware overhead is also reduced. Finally, this method is evaluated here considering measurements from 2 channels, one for each die, - as opposed to a measurement from a complete die- highlighting the enhanced performance of our PZT pMUT dies.

V. Conclusions

This work successfully demonstrates the use of pMUTs for underwater acoustic localization of reflectors. For the first time, trilateration is used to determine geometrically the (x,z) coordinates of the reflector's position using only a pair of PZT pMUTs in a pulse-echo configuration. The significance of this work is highlighted by the fact that only a column of membranes for each die, rather than all the membranes for each die, is used to solve the trilateration problem and provide highly accuate estimates of the reflector's location. This is a testament to the impressive TX and RX sensitivities of the PZT pMUT arrays fabricated at wafer-scale in our 8" line. This work concludes the suitability of PZT pMUTs for a new generation of applications in immersion such as: the navigation of autonomous underwater vehicles (AUVs) and as a priori information for subsequent targeted imaging (i.e., via beam focusing or steering).

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References

[1] O. Rozen, S. T. Block, X. Mo, W. Bland, P. Hurst, J. M. Tsai, M. Daneman, R. Amirtharajah, and D. A. Horsley, "Monolithic mems-cmos ultrasonic rangefinder based on dual-electrode pmuts," in 2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS). IEEE, 2016, pp. 115–118.

[2] J. Jung, S. Kim, W. Lee, and H. Choi, "Fabrication of a two-dimensional piezoelectric micromachined ultrasonic transducer array using a top-crossover-to-bottom structure and metal bridge connections," Journal of Micromechanics and Microengineering, vol. 23, no. 12, p. 125037, 2013.

[3] R. J. Przybyla, S. E. Shelton, A. Guedes, I. I. Izyumin, M. H. Kline, D. A. Horsley, and B. E. Boser, "In-air rangefinding with an aln piezoelectric micromachined ultrasound transducer," IEEE Sensors Journal, vol. 11, no. 11, pp. 2690–2697, 2011.

[4] M. Sarafianou, D. J. Goh and D. S. Wai Choong, "A Time-of-Flight (ToF) estimation algorithm for ranging using Silicon-On-Nothing pMUTs," 2022 IEEE International Ultrasonics Symposium (IUS), Venice, Italy, 2022, pp. 1-4.

[5] W. Ji, L. Liu, Z. Xing, D. Zhang, Y. Wang, L. Chen, Y. Chen, X. Sun, and Y. Du, "Total-focus ultrasonic imaging of defects in solids using a pzt piezoelectric micromachined ultrasonic transducer array," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 68, no. 4, pp. 1380–1386, 2020.

[6] M. Sarafianou, D. S. W. Choong, D. J. Goh, D. S. -H. Chen and Z. Yao, "A CSM/TFM imaging scheme for Silicon-On-Nothing ScAlN pMUT arrays," 2022 IEEE International Ultrasonics Symposium (IUS), Venice, Italy, 2022, pp. 1-4.

[7] D. E. Dausch, K. H. Gilchrist, J. Carlson, S. D. Hall, J. Castellucci, and O. T. von Ramm, "In vivo real-time 3-d intracardiac echo using pmut arrays," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 61, pp. 1754–1764, 2014.

[8] Y. Lu, H. Tang, S. Fung, Q. Wang, J. Tsai, M. Daneman, B. Boser, and D. Horsley, "Ultrasonic fingerprint sensor using a piezoelectric micromachined ultrasonic transducer array integrated with complementary metal oxide semiconductor electronics," Applied Physics Letters, vol. 106, no. 26, p. 263503, 2015.

[9] Mantalena Sarafianou, et. al, "In-Air Long-Range Environmental Temperature Sensing with a Single Scandium-doped Aluminium Nitride pMUT Array", 22nd International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS) 2023, Kyoto, Japan, 2023, pp. 1-4.

[10] Y. Koh et al., "High Resolution, High Frequency Ultrasonic Ranging in Air with pMUTs," 2021 IEEE International Ultrasonics Symposium (IUS), Xi'an, China, 2021, pp. 1-4.

[11] B. Herrera, F. Pop, C. Cassella and M. Rinaldi, "PMUT-Enabled Underwater Acoustic Source Localization System," 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, UK, 2019, pp. 1103-1106.