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Publication Date
2024-01-25

DOI
10.1109/mems58180.2024.10439353

2024 IEEE 37th International Conference on Micro Electro Mechanical Systems (MEMS) | 979-8-3503-5792-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/MEMS58180.2024.10439353

CONTINUOUS VOLUMETRIC INDOOR TEMPERATURE MONITORING VIA PMUTS

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ABSTRACT

This work presents a continuous volumetric indoor air temperature measurement scheme using PMUTs (piezoelectric micromachined ultrasonic transducers). Advancements as compared to state-of-art works include: (1) “volumetric” temperature monitoring instead traditional “pointwise” temperature information; (2) accurate temperature readings spanning an operational distance of 5 m as validated by a commercial thermometer for 3 days; and (3) capable of detecting global average temperature and local temperature events by installing networked/grid PMUT pairs. This innovative sensing technique could be applicable for the precision control of future building/living environments.

KEYWORDS

MEMS, PMUT, temperature sensing, ultrasound

INTRODUCTION

Efficient indoor temperature monitoring is vital for the control of energy consumption in industrial, research, and building environments. In 2022, the energy consumption by the U.S. residential and commercial sectors accounted for about 29% of the total U.S. end-use energy [1], of which HVAC system contribute 40-60% [2] for the comfort of indoor environments [3]. This prompts the development of sustainable energy-efficient solutions [4] such as data-driven methods of enhanced fault detection and diagnosis in the temperature control for improved energy efficiency, indoor air quality, and occupant comfort [5]. Traditional thermocouples have limited “pointwise” knowledge as shown in **Figure 1** as they rely on achieving thermal equilibrium with the medium at a single location. Here, a volumetric temperature measurement scheme is presented.

Previously, the time of flight (ToF) of acoustic waves have been utilized to measure temperature, such as in tissues during therapy [6] or in materials being processed at high temperatures [7]. Distributed bulk ultrasonic sensor arrays have been used to reconstruct a 3D temperature field [8], to measure both temperature and humidity in a 30 cm-wide controlled chamber by the ToF and attenuation of ultrasonic waves, respectively [9], and to evaluate liquid temperature [10]. On the other hand, PMUTs have been used to estimate the surface temperature of a wall [11]. A scheme of sensor placement to cover a room has been proposed using thermal cameras [12]. This setup is complicated as it requires mutual calibration, sensor placement planning, and 3D thermal surface modeling.

PMUT (piezoelectric micromachined ultrasonic transducer) emerges as a promising solution, overcoming the drawbacks of traditional sensors. Consisting of a thin piezoelectric membrane on a substrate, PMUTs can generate and detect ultrasonic waves through electrical and mechanical stimulations [13]. Their small size and low power consumption make them suitable for a range of applications, from medical imaging [14], underwater networks [15], range finding [16], to non-destructive testing [17].

This work introduces a novel approach to monitor the indoor temperature continuously and volumetrically by characterizing the speed of ultrasonic waves from PMUTs over a 5-meter path. This method represents a significant advancement over traditional techniques, offering a comprehensive and dynamic assessment of temperature across extended areas.

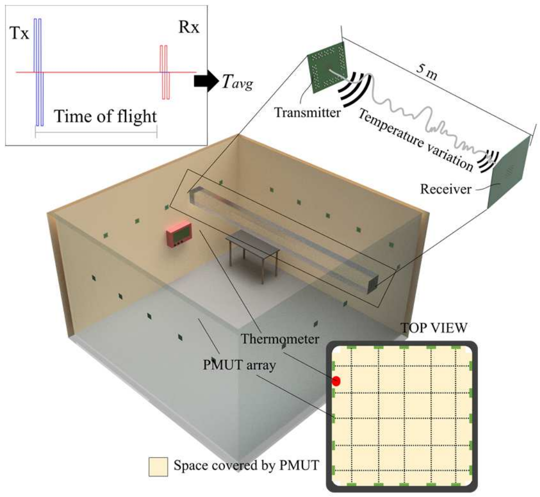

Figure 1: Illustration of the PMUT thermometer setup.

HARDWARE DESIGN

The speed of sound is correlated with the temperature of the medium, and therefore the air temperature can be estimated based on the speed of the ultrasound wave that travels through it. Generally, the hotter the air is, the faster the sound travels, and the speed of sound can be calculated by sending a pulse through air and measuring the time it takes to reach the other side [9].

The prototype system employs two PMUT units based on lithium niobate (LN) as the transmitter to ensure enough output acoustic pressure and one unit as the receiver. Both the transmitter and receiver PMUT units are identical with roughly 38 kHz resonance frequency, and they are part of a 4x4 package array respectively as shown in **Figure 2**. The extra PMUT units are planned for transmission/reception beam-forming schemes for future networked/grid operations. They were deployed in a laboratory/office complex as shown in **Figure 3**. To prevent unwanted reflections from surfaces such as the floor or desks, or disturbances from walking personnel, the setup is raised to 1.9 m of height by a pair of poles and specially designed

PMUT holders. The receiver is placed 5 m away from the transmitter. This distance is fixed and verified by laser distance meter for later speed of sound calculation.

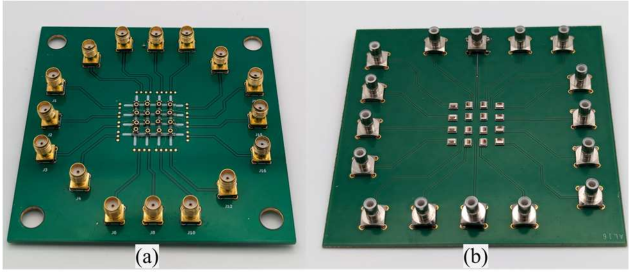

Figure 2: (a) The transmitter PMUT array with two active elements. (b) The receiver PMUT array with one active element.

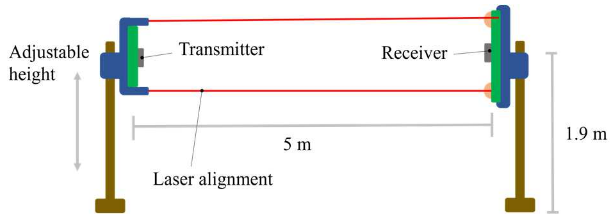

Figure 3: Hardware schematics.

Individual parts for the setup can be found in **Figure 4.** The poles are designed to resemble an I-beam, allowing the sleeves to slide up or down on the pole with better stability. The sleeves have a spring-loaded lever for a self-locking mechanism so that the height of the PMUTs will be fixed after the initial setup. The holders, customized respectively for the transmitter and receiver, are connected to the sleeves with inserts. The holder for the transmitter also has four slots to insert 5-mW laser pointers for the alignment with each of them pointing directly at the four corners of the receiver holder. This sophisticated quad-laser alignment setup is constructed to ensure accurate positioning between the PMUT pair.

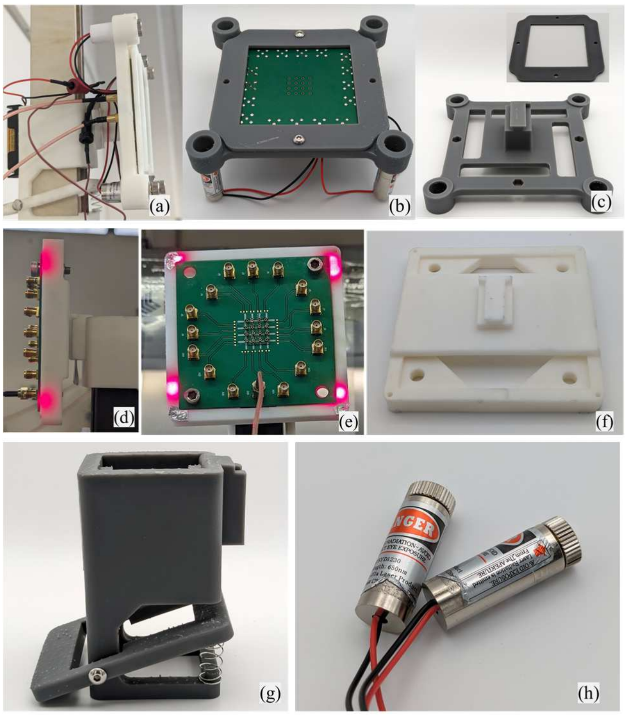

Figure 4: (a) Side view of the transmitter setup. (b) The transmitter PMUT and holder with quad-laser setup. (c) The back of the transmitter holder and the PMUT cover. (d) Side view of the receiver setup during laser alignment. (e) The receiver and the holder during the laser alignment. (f) The back of the receiver holder with an insert for the sleeve. (g) The sleeve with a self-locking mechanism. (h) The 5-mW laser pointers used for alignments.

The circuit diagram for the system can be found in **Figure 5**. The transmitter is excited by pulse signals from an arbitrary waveform generator, and the receiver has its output terminals connected to a charge amplifier before going through a low pass filter to an oscilloscope.

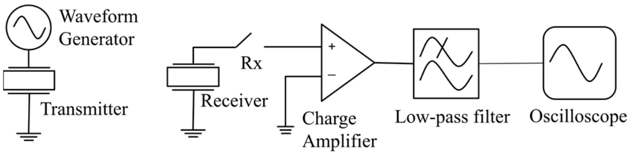

Figure 5: The circuit diagram for the system.

EXPERIMENTAL RESULTS

The acoustic amplitude versus frequency for a PMUT unit and signal strength versus distance plots between the PMUT pair are characterized in **Figure 6**.

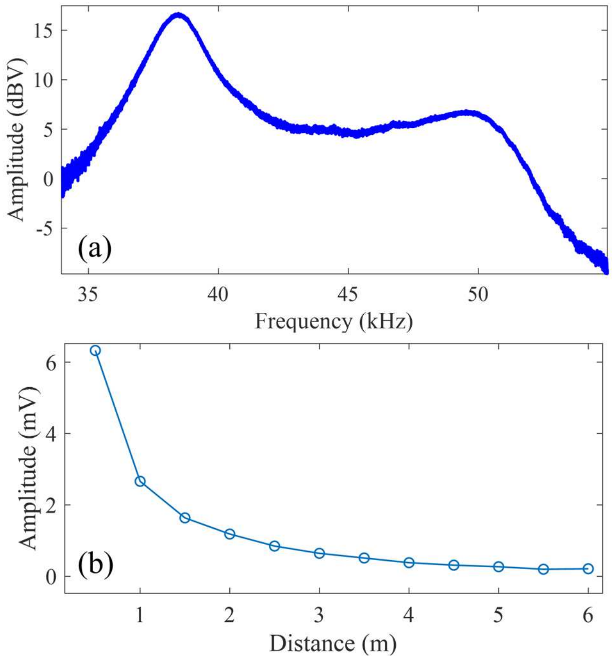

Figure 6: (a) The acoustic amplitude versus frequency for a PMUT unit and the (b) signal strength versus distance for the transmitter.

Before each measurement, the setup had to be fine-tuned to establish a working order. First, the position and orientation of the PMUTs were verified using a laser distance meter and the quad-laser alignment system. This would guarantee the ultrasound travels in a straight line directly to the receiver. Second, the distance between the PMUT units was confirmed by a laser distance meter. The last step is to drive the transmitter with pulse signals and observe the received signal to check whether the ToF falls within a reasonable timeframe. Once the setup is complete, PMUTs can perform continuous measurements for days.

For temperature tests, the transmitter PMUT was actuated using a square wave at its resonance frequency, 38 kHz, with an amplitude of 6 Vpp and a 3V offset. The unipolar transmission wave packet consists of a series of 6 square waves, succeeded by 2 waves with a 180-degree phase shift. These inverted waves are used to minimize the ring-down effect of the transmitter PMUTs [18]. After each excitation, the signals were then zeroed for 20 ms to allow the sound wave to travel across to the receiver. The setup was placed in our laboratory/office complex to measure the temperature continuously for 3 days, capturing 32 pairs of transmitter and receiver signal every 30 min for 72 h, during which the maximum temperature swing was more than 6°C. Alongside the PMUT setup was a SHT-31 smart gadget from Sensirion AG to measure the humidity and temperature with an accuracy of ±0.2% RH and ±0.3°C respectively. It logged the readings every 1 s. This sensor is placed in the middle of transmitter and the receiver but slightly lower than their heights to avoid blocking the sound waves.

Signal Processing

After the three-day trial, the average signals over every 32-wave log went through 5 signal processing steps shown in **Figure 7**.

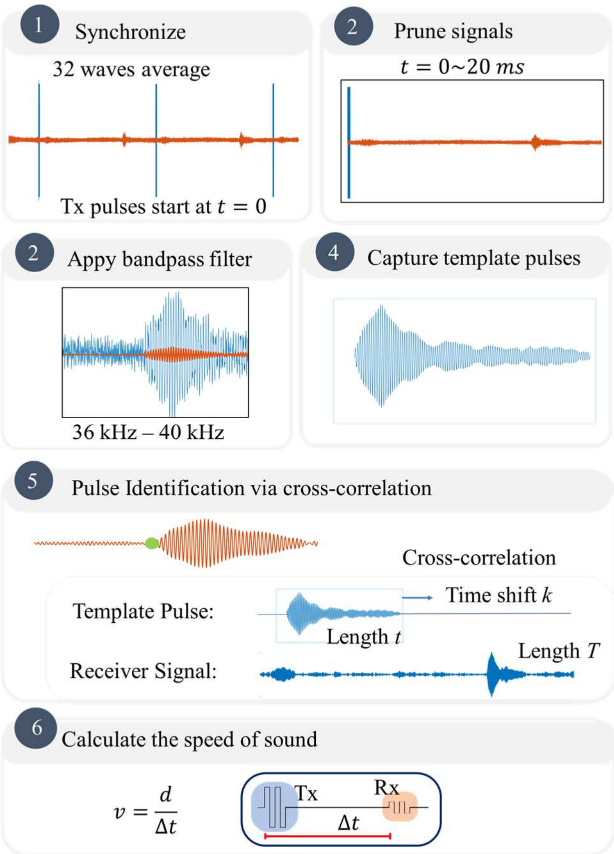

Figure 7: The six steps in signal processing.

First, both transmission and reception signals were synchronized and pruned to have only one pair of transmission and reception signals. Second, the start of the received signal is pinpointed by performing cross-correlation with a template reference pulse capture manually from a randomly chosen data point. The reference pulse will remain effective provided that the sampling frequency is consistent throughout all measurements. When cross-correlation is evaluated on a signal with a length, T, the algorithm slides the template waveform with a length, t, across the signal from a time shift, k, padding zeros to the rest of the $T - t$ time steps to make them the same length. There is a correlation index associated with each k, and the shift with the largest correlation index indicates a match with the template, which is deemed as the start of the signal. The signal has automatic triggers on the transmission pulse, and therefore with the knowledge of the start of the received signal, the ToF can be calculated.

From the distance and ToF, the ultrasonic wave's sound speed can be computed, and the speeds of sound are evaluated together with the measurements from SHT-31 temperature sensor. The relationship exhibits excellent linearity as shown in **Figure 8**, which an R^2 of more than 0.98, which indicates that speeds of sound can be used for temperature estimations.

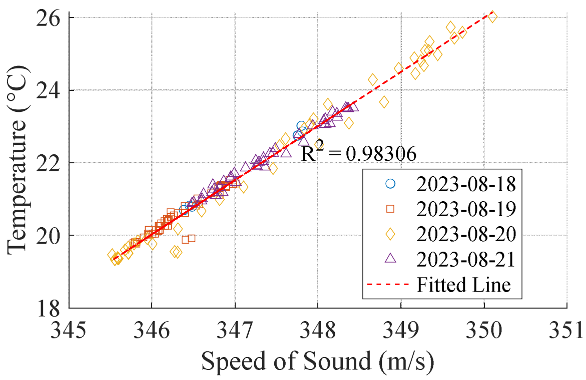

Figure 8: The temperature versus the speed of sound and the fitted line used for temperature estimations.

It is found that PMUT estimations consistently register within a ±0.5°C range with respect to the readings of a commercial thermometer as shown in **Figure 9**. On rare occasions, deviations are observed and attributed to local events such as room occupancy. What is worth noting is that not only did PMUT measurements demonstrate great accuracy, but its readings also lead the commercial thermometer whenever there is a drastic temperature change. These changes happen early in the morning and later in the evening when the presence/absence of sunlight heats up/cools down the lab space. This demonstrates the unique advantages of this PMUT thermometer setup, as it measures the average temperature volumetrically and thus can be more sensitive to a general change. It also does not require a thermal equilibrium to be reached, leading to faster results. A commercial thermometer, on the other hand, is slower and limited to pointwise measurements. If placed at a local cold/hot spot, commercial thermometers can give misleading readings that are not representative of the overall temperature in a room.

CONCLUSIONS

This study introduces a novel approach to indoor temperature monitoring using PMUTs (piezoelectric micromachined ultrasonic transducers). The key advancements include the ability to provide continuous volumetric temperature measurements over an extended operational distance, accurate temperature readings validated against a commercial thermometer, and the potential for detecting both global average temperature and local temperature events through networked/grid PMUT pairs. This innovative sensing technique holds significant promise for precision control of future building and living environments, offering benefits in HVAC optimization, energy management, and occupancy-driven temperature control. The method's ability to capture detailed and accurate indoor temperature mappings contributes to the goal of creating more energy-efficient and comfortable living and working spaces.

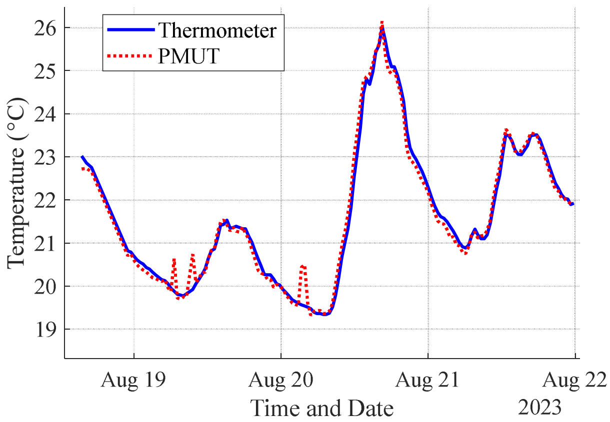

Figure 9: Temperature variations over 3 days in a room as measured using PMUTs (estimated Temperature) and a commercial thermometer (actual Temperature).

ACKNOWLEDGEMENTS

This work was supported in part by BSAC (Berkeley Sensor and Actuator Center, an NSF/Industry/University collaboration center).

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