High-Accuracy Dry-Bulb Temperature Sensing with Short-Time Fourier Transform (STFT) Using PSON pMUTs

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***Abstract*—This paper presents the methodology for estimating the temperature in moist air, known as dry-bulb temperature, using Piezoelectric over Silicon-On-Nothing (PSON) ScAlN pMUTs based on Short-Time Fourier Transform (STFT). A digital signal processing technique is proposed for the Time-of-Flight (ToF) estimation based on STFT with the estimated ToF value used to compute the ultrasonic speed of sound. Experimental results presented here report a mean accuracy of 95% in the estimated dry-bulb temperature. This is a very positive outcome towards the usage of the proposed signal processing algorithm along with standard PSON pMUTs for sensing temperature in a moist environment.**

***Index Terms*—pMUTs, dry-bulb temperature sensing, ultrasonic time-of-flight estimation, time-frequency analysis (STFT)**

I. Introduction

To-date ultrasound has been used to monitor a number of physical parameters not limited to ranging [1] temperature [2]–[4] and humidity [5], [6]. Specifically enviromental temperature is determined by the speed of sound, which can be measured using an ultrasonic transducer. The speed of sound increases with the presence of water vapour in air (i.e., moist air) with the latter mapping to the relative humidity, albeit introducing a minor increase in the speed of sound [7].

Despite the fact that conventional piezoelectric ceramic transducers have been used for ranging applications [8], their large size and high acoustic impedance deem them unsuitable for portable and small-size ranging solutions [9], [10]. In contrary, micromachined ultrasonic transducers (MUTs) are significantly smaller and have an acoustic impedance being closer to the propagation medium. This is due to their flexural membrane (used for generating and receiving ultrasound waves) which is softer than rigid ceramic [11]. In this work AlN-based pMUTs are used, which are not only lead-free, but they don't require polarisation and are ideal for CMOS integration (i.e., low deposition temperature) [12], [13].

The concept of using ultrasound to measure temperature is not new [14], [15] (whereby conventional bulky ultrasonic transducers were used), however, the use of pMUTs to this end is very recent. One of the few examples has proposed non-contact surface temperature sensing using an AlN pMUT array at 8cm distance [3]. In [16], we proposed a method for short-range (3cm) environmental temperature sensing using two separate opposite-facing pMUT chips in a pitch-catch arrangement. More recently, we succesfully demonstrated, for the first time, long-range (60cm) environmental temperature sensing using a single ScAlN die [17].

In our previous work reported in [3], [16], [17], environmental temperature sensing was achieved via either a pair of dies ([2], [16]) or a single chip ([3], [17]) considering in a dry environment for the testing. In reality, the presence of water vapour in the air is inevitable and as such the consideration of relative humidity in the temperature calculation is needed. In dry air, the temperature value, known as virtual temperature, is higher than the dry-bulb temperature, which corresponds to the true environmental temperature assuming the existence of water vapor in the air. Measuring the dry-bulb temperature with a compact sensing system would be necessary for various applications, where the presence of humidity in the atmosphere is inevitable such as: urban farming (i.e., in land-sparse Singapore with more than 90% relative humidity) and art conservation.

In this paper, for the first time, the measurement of the true (i.e., dry-bulb) temperature using PSON pMUTs is investigated. To estimate the speed of sound in moist air, frequency-time analysis is proposed as opposed to the optimised matched filter approach presented in [2]. Time-frequency analysis has been proposed in the literature for the measurement of the wind speed [18], but to-date it has not been used for environmental temperature sensing. Through the proposed method, the analysis of the time-dependant spectra enables aspects of the signal response to be better understood and the identification of the desired echo to be achieved. This is advantageous over other signal processing methods (i.e., matched filter), since the signals for a wide range of applications, such as temperature sensing, have a time-varying spectral content. Furthermore, the advantage of the proposed setup of the opposing pMUTs placed a known short distance facing each other ensures a more compact sensing system that could be placed in an enclosure.

II. Theoretical Considerations for the Measurement of Dry-Buld Temperature

An ultrasonic wave propagating in dry air will have a speed of sound, c_v, that would be dependant on the temperature present in the propagation medium as determined by the following equation (also reported in [2]):

$$c_v = \sqrt{\frac{\gamma * R * T_v}{M}} \quad (1)$$

where γ refers to the ratio of the gas heat capacity at constant pressure and the gas heat capacity at constant volume, M corresponds to the average molecular weight of gas molecules and R is the specific gas constant of the intervening air medium. The parameter T_v corresponds to the virtual temperature, which is expressed in degrees Kelvin. As discussed in [7], traditional ultrasonic sensors tend to measure the virtual temperature (i.e., the temperature in dry air) as opposed to the true temperature, which could be in the presence of moist air (i.e., the dry-bulb temperature).

The density of air, p, which would correspond to the summation of the density of dry air, p_d and the density of water vapour, p_{wv} can be computed using the equations of state defined in [7] as:

$$p = p_d + p_{wv} = \left[\frac{P}{R_d} + P_{wv}\left(\frac{1}{R_{wv}} + \frac{1}{R_d}\right)\right]\frac{1}{T_d} \quad (2)$$

where P is the atmospheric pressure, R_d refers to the universal gas constant for dry air, P_{wv} corresponds to the atmospheric pressure for water vapor, R_{wv} is the universal gas constant for water vapor and T_d refers to the dry-bulb temperature. In addition, the air density can also be defined as follows:

$$p = \frac{P}{R_d T_v} \quad (3)$$

Using (2) and (3), the relationship between T_v and T_d is defined as:

$$T_d = T_v\left[1 + RHU\frac{P_s(T_d)}{P}\left(\frac{R_d}{R_{wv}} - 1\right)\right] \quad (4)$$

where RHU refers to the relative humidity and $P_s(T_d)$ is the saturated vapor pressure P_s at the dry-bulb temperature T_d, which is estimated using the semi-empirical Antoine equation provided in [7]. It can be observed from equation (4) that the dry-bulb temperature, T_d, which is the true temperature in moist air, can be computed through knowledge of three parameters, namely, the virtual temperature T_v, the atmospheric pressure, P, and the relative humidity, RHU.

III. Speed of sound estimation algorithm using time-frequency analysis

A. Short-Time Frequency Transform

The proposed algorithm is based on the Short-Time Fourier transform (STFT), which is defined as follows:

$$S_t(\omega) = \frac{1}{2\pi}\int e^{-j\omega t'} s(t')h(t'-t)dt' \quad (5)$$

where $s(t')$ refers to the signal, ω is the angular frequency (equal to $2\pi f$) and $h(t'-t)$ corresponds to the window function [19]. Given that the window function can have a number of different shapes (i.e., Hamming, Gaussian, etc), when multipled by the signal $s(t')$ in (5), it can limit the time-frequency analysis within a finite window centered at t. In addition, the size of the window function will determine the resolution in both the time and frequency domains. Through the use of STFT, certain signal characteristics can be determined not limited to the power spectrum analysis and the timings at which certain harmonics are present in the signal.

B. Proposed Signal Processing Algorithm

The proposed signal processing algorithm consists of several distinct steps as shown in the block diagram of Fig. 1. Initially, every acquired signal (example signal is shown in Fig. 1 - signal in yellow box) is normalized to remove the offset (as seen in Fig. 1 - signal in blue box) and then its signal envelope is computed using the Hilbert transform (shown in Fig. 1 - signal in red box). Then the time-frequency analysis is performed on each signal envelope to estimate the time signature corresponding to the echo signal. The spectrogram (i.e., the signal power) would be obtained as per the following equation:

$$P_s(t,\omega) = |S_t(\omega)|^2 \quad (6)$$

Fig. 1 depicts an example spectrogram computed from a received signal at temperature 30^oC. Fig. 2 depicts a visual illustration of the computation of the spectrogram for the reader's assitance. Each signal envelope is divided into segments of equal length, with each segment being short enough to ensure that the frequency content of the signal does not change significantly within a segment. It is worth noting that although the segments may or may not overlap, for the purpose of this work, there was an overalp between the segments. Then each segment is windowed and its spectrum is computed to get the short-time Fourier transform.

The ToF value would correspond to the time instance, at which the maximum power value is obtained for the frequency component of interest. It would be worth noting that by selecting a short window function in the implementation of eq. (5), an optimum temporal resolution would be achieved at the cost of the frequency resolution. The estimated ToF value would subsequently be used to compute the speed of sound assuming knowledge of the distance between the transmit and receive sensors (i.e., which would correspond to the distance travelled by every received signal). Finally, the dry-bulb temperature can be estimated from eq. (4) using the calculated speed of sound and the relative humidity and ambient pressure values measured with reference sensors.

IV. Experimental dry-buld temperature measurement

A. Experimental setup

Fig.3 depicts the experimental setup used for the validation of the proposed algorithm. Specifically, two PSON ScAlN pMUTs dies were used facing each other at a fixed known distance L (equal to 3.75cm) with each die being wire-bonded onto a separate PCB. The pair of PMUTs was placed in a temperature and humidity chamber (Espec SH-242). A 1.2MHz 15-cycle sinusoidal waveform at 10Vpp was generated by

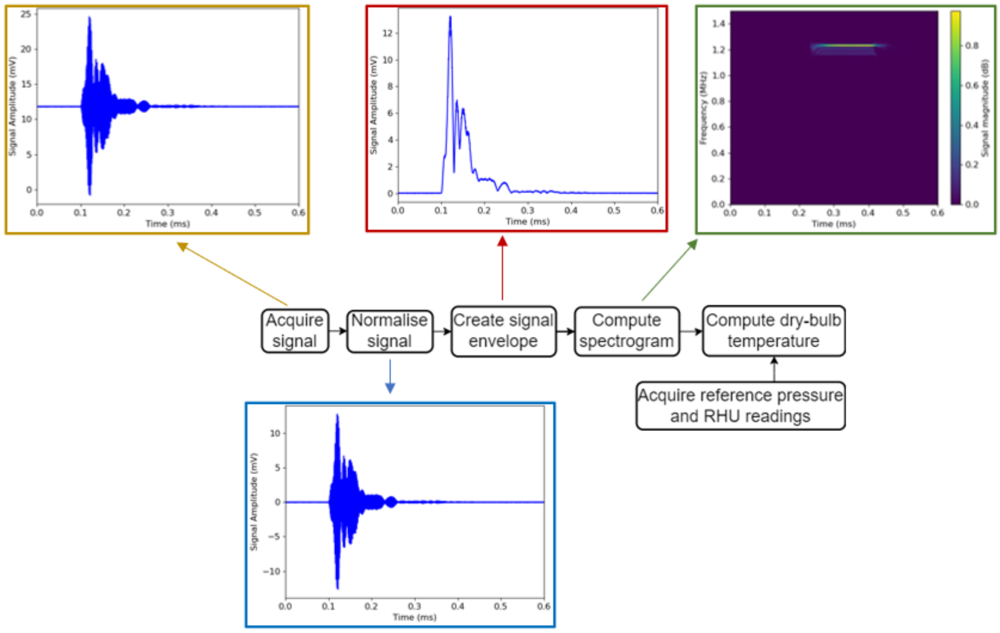

Fig. 1. Environmental dry-bulb temperature sensing - block diagram of signal processing algorithm.

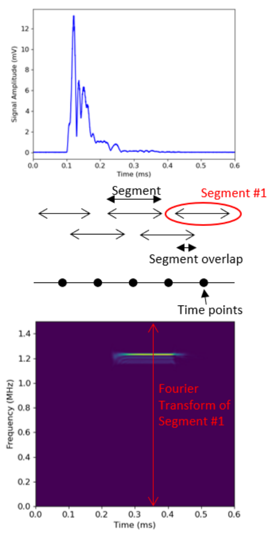

Fig. 2. Spectrogram definition.

a function generator (Keysight 33500B Trueform Waveform Generator) and used to excite the transmitting pMUT die. An oscilloscope (Keysight InfiniiVision DSOX4024A) captured the signals collected at the receiving pMUT device. Measurements of the temperature, relative humidity and ambient pressure were obtained through reference sensors controlled with an Arduino kit. The chamber's temperature was varied from 30 to 60^oC with a step of 5^oC, whereas the relative humidity was set to 40% in order to satisfy the design specifications of the temperature and humidity chamber. The reference temperature readings were used to compare against the estimated temperature values. The dry-bulb temperature was also computed using the matched filter approach proposed in [2] for comparison purposes.

The pMUT devices considered in this work were fabricated using the Piezoelectric over Silicon-On-Nothing (PSON) process. As discussed in [20], [21], the SON process for pMUT microfabrication uses the silicon migration to create a monocrystalline silicon (mono-Si) membrane over a buried cavity on 8-inch Silicon wafers. This results in PSON pMUTs showcasing low-cost, high-yield, and high fill-factor pMUT arrays [20], [21].

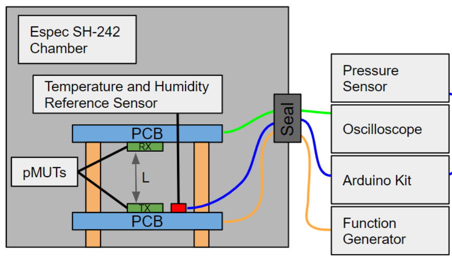

Fig. 3. Experimental setup for environemental dry-bulb temperature sensing.

B. Results and Discussion

Fig. 4 depicts the dry-bulb temperature values estimated with the proposed algorithm and the matched filter approach reported in [2]. The temperature readings from the reference sensor are also plotted for comparison purposes. The proposed algorithm results in dry-bulb temperature estimates with a mean accuracy of 95% outperforming the matched filter approach, which provides dry-bulb temperature estimates with a mean accuracy of 93%.

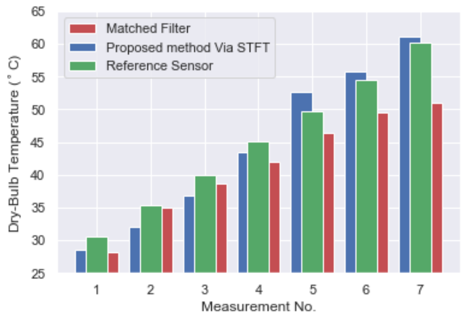

Fig. 4. Actual vs estimated dry-bulb temperatures using the proposed signal processing algorithm and the matched filter approach.

As seen in Fig. 4, the proposed method tends to underestimate the dry-bulb temperature at low temperatures, whereas it overestimates the dry-bulb temperatures at high temperatures, a trend on par with the behaviour of the matched filter approach. The cause of this is twofold; the pMUTs are inherently more sensitive to low temperatures (e.g., below 45^{o}C), an effect further intensified by the over-testing of the devices under high/low temperature conditions.

It can be observed that at higher temperature readings (meas. no. 5-7 in Fig. 4), the difference between the estimated temperatures for the two methods increases. This poor performance by the matched filter approach would be attributed to multiple peaks of similar magnitude being present in the cross-correlation curve, particularly at higher temperatures, leading to the selection of an incorrect ToF value.

It is worth noting that the presence of air flow would impact the accuracy of the estimated dry-buld temperature given that the flow of air would influence the speed of sound of the ultrasonic wave. On the contrary, vibrations in the environment will not impact the accuracy of the estimated temperature, given the fixed spacing between the pMUTs.

V. Conclusion

In this paper, a novel signal processing algorithm for monitoring the temperature in moist air (i.e., dry-bulb temperature) was presented considering a pair of PSON ScAlN pMUTs. This work reports, for the first time, the use of time-frequency analysis for environmental temperature sensing using pMUTs. The proposed signal processing algorithm was validated experimentally giving dry-bulb temperature estimates with a mean accuracy of 95% considering a 5^oC resolution for a temperature sensing range of 30 to 60^oC. These promising results could pave the way for the use of the proposed temperature sensing scheme towards various applications requiring knowledge of the temperature in a moist environment (e.g., artwork preservation and smart gardening).

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