Mtemp: An Ambient Temperature Estimation Method Using Acoustic Signal on Mobile Devices

Hao Guo
University of Massachusetts Amherst

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MTEMP: AN AMBIENT TEMPERATURE ESTIMATION METHOD USING ACOUSTIC SIGNAL ON MOBILE DEVICES

A Thesis Presented
by
HAO GUO

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
IN ELECTRICAL AND COMPUTER ENGINEERING

May 2021

Electrical and Computer Engineering
MTEMP: AN AMBIENT TEMPERATURE ESTIMATION METHOD USING ACOUSTIC SIGNAL ON MOBILE DEVICES

A Thesis Presented

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HAO GUO

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ACKNOWLEDGMENTS

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ABSTRACT

MTEMP: AN AMBIENT TEMPERATURE ESTIMATION METHOD USING ACOUSTIC SIGNAL ON MOBILE DEVICES

MAY 2021

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M.S.E.C.E. UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Jie Xiong

Ambient temperature sensing plays an important role in a number of applications in agriculture, industry, daily health care. In this thesis project, we propose a new acoustic-based ambient temperature sensing method called Mtemp. Mtemp empowers acoustic-enabled IoT devices, smartphones to perform ambient air temperature sensing without additional hardware. Basically, Mtemp utilizes on-board speaker and microphone to calculate the propagation speed of acoustic signal by measuring the phrase of the target signal, thereby estimate the ambient temperature according to a roughly linear relationship between temperature and sound speed. Mtemp is portable and economical, making it competitive compared with traditional thermometers for ubiquitous sensing.
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CHAPTER 1

INTRODUCTION

1.1 Background

Ambient temperature sensing plays an important role in a number of applications such as precision agriculture [1][2], animal husbandry [3], HVAC (Heating, Ventilation and Air Conditioning) system management [4] and room temperature monitor [5] in our daily life. Though measuring ambient temperature is often deemed as an easy job, conventional temperature sensors have lots of limitations [6][7][8]. They normally cannot achieve real-time sensing and are not connected to the internet. In addition, they are not ubiquitously available right now. Therefore, alternative ambient temperature sensing approaches are called for.

Nowadays, mobile devices including smartphones enjoy an explosive growth. In 2020, worldwide mobile users are projected to reach 4.78 billion, among which 3.5 billion are smartphones [9]. With rich built-in sensors and powerful processors, mobile devices show big advantages in mobile networking, ubiquitous computing and sensing [10][11]. In this case, can we turn these widely-used mobile devices into a ubiquitous thermometer without adding additional hardware?
1.2 Challenge

However, implementing Mtemp on a commodity smart device is very challenging. First of all, it is difficult to obtain ground truth of ambient temperature. As we all know, ambient temperature distribution is uneven and constantly changing. The different thermometers show different results of the temperature in the same area at the same time. Second, using a single smart device to achieve temperature sensing is challenging. In previous research, they used to use two smartphones in their system [12], one used as sender and the other used as receiver, which is not convenient for users since each smartphone has both speaker and microphone. However, using a single smartphone to achieve temperature sensing will be easily influenced by self-generated heat of smartphone, unless heat isolation or proper device layout are adopted.

![Figure 1.1: Signal propagation model](image)
In addition, the multipath problem can affect the accuracy, if not handled properly, could severely affect the sensing results. The Figure 1.2 shows the signal propagation model of a commodity smartphone. The received signal is a combination of the signals traveling through many paths which includes Line-Of-Sight (LOS) path as well as those reflected by static objects.

1.3 Overview

In this thesis project, we propose a new acoustic-based ambient temperature sensing method called Mtemp. Mtemp empowers acoustic-enabled IoT devices, smartphones to perform ambient air temperature sensing without additional hardware. Basically, Mtemp utilizes on-board speaker and microphone to analyze the target acoustic signal and calculate the propagation speed of acoustic signal, thereby estimate the ambient temperature according to a roughly linear relationship between temperature and sound speed.

Figure 1.2: Mtemp overview
Mtemp is portable and economical, making it competitive compared with traditional thermometers for ubiquitous sensing. As we mentioned before Mtemp can be described as a software acoustic thermometer which means what we try to propose is a general method for ambient temperature sensing on smart devices. So Mtemp has the potential to achieve temperature sensing on different smart devices. These smart devices are not only include smartphone pad and laptop, but also smart watch robot drones. Further more, to be considered as a common package or a platform, Mtemp allow developers to design multiple interesting application on distributed real-time temperature sensing on different smart devices.
CHAPTER 2

RELATED WORK AND THEORETICAL FOUNDATION

2.1 Related work

For general temperature sensing, there are two main categories: contact sensing method and non-contact sensing method [12]. Contact sensing method which requires a physical contact between a sensor and a test subject, is difficult to implement on mobile devices. For non-contact sensing method, there are lots of researches by using different wireless signals to estimate temperature without any physical contact. By the comparison with other non-contact sensing method [13][14][15], Acoustic-based temperature sensing method shows big advantages for example, enough detection range and no extra cost for additional heat isolation hardware.

In 1991, Kaimal and Gaynor [16] proposed a research about sonic thermometry and in their research, acoustic signals have been used to measure air temperature and speed in meteorology. According to the paper, they exploited the relationship between sound speed and temperature. Therefore, temperature can be estimated easily by the propagation speed of acoustic signals. But the methods they use require either high sampling rates or ultrasonic signals, which is unfeasible on commodity mobile devices [17].
Nowadays, great progress has been made in research about acoustic signals on mobile devices. But most of them focus on localization, tracking, and gesture recognition by acoustic sensing on mobile devices [18][19][20]. Wang [21][22] exploits the phase of acoustic reflections to perform high-precision gesture tracking and recognition. Mao [23] borrows chirp mixing approach from the RF radar technologies and utilize its acoustic implementation to achieve sub-centimeter level tracking. However there are few researches about ambient temperature sensing by using acoustic signal on mobile devices which inspires us to design a software based ambient temperature sensing method: Mtemp.

2.2 Theoretical foundation

In 1990s, acoustic signals have been used to measure air temperature and speed in meteorology. According to the Kaimal’s research, they exploited the relationship between sound speed and air temperature [16], which is known as:

\[ c^2 = \alpha T_{\text{emp}} (1 + \beta h) \]  

(2.1)

where Temp denotes the temperature in Kelvin, c represents the sound speed (m/s) in air, h is the ratio between vapor pressure of water in air and absolute atmospheric pressure, which is affected by humidity, \( \alpha \) and \( \beta \) are two constants.
After neglecting the influence by humidity, we can simplify equation (2.1) via Taylor expansion but omit high order terms to obtain a widely used relationship between temperature and sound speed, which is known as:

\[ c = c_0 + KT_{emp} \]  

(2.2)

where \( c_0 = 331 \) and \( K = 0.606 \) are two constants.
CHAPTER 3

SYSTEM DESIGN

As we mentioned before, we want to achieve an accurate convenient real-time temperature sensing. So we proposed an acoustic signal reflection based method by using single smart device. There are several advantages in this system. Firstly we just use one device, our system is more convenient comparing with the previous system. Secondly, our system focus on the acoustic signal reflection, which avoid the influence by self-generated heat. And there is no need for heat isolation or other additional hardware. Finally, this system allow us detect a specific range of temperature even the distribution of it.

3.1 System structure

Bastically Mtemp utilize the on board speaker to send Continuous Wave (CW) signal of \( \cos 2\pi ft \), where \( f \) is the frequency of the sound. We use the microphones on the same device to record the sound wave. As the received sound waves are transmitted by the same device, there is no Carrier Frequency Offset (CFO) between the sender and receiver. Therefore, we can down convert the received sound signal to a baseband signal. The received signal is firstly split into two identical copies, we then use a Cascaded Integrator
Comb (CIC) filter to remove high frequency components and decimate the signal to get the corresponding In-phase and Quadrature signal.

As the received signal is a combination of the signals traveling through many paths, we need to first extract the baseband signal component that corresponds to the one reflected by the target reflector. so that we can calculate the propagation speed of Acoustic signal by the phase of that component and a given propagation distance. Then finally we can estimate the temperature result by a roughly liner relationship between sound speed and temperature.

![System structure](image)

**Figure 3.1: System structure**

### 3.2 Multipath effect mitigation

As we showed before, the received signal is complex, containing the signals traveling through multiple paths. And it can be identified as a combination of two vectors: a static vector and a dynamic vector. The static vector corresponds to the sound wave traveling through the direct path (Line of Sight path) between speaker and microphone or reflected by static objects, such as walls and tables. This vector remains static during this short time period. The dynamic vector corresponds to the reflection caused by the moving reflector.
Figure 3.2: (a) Multipath refection effect  (b) I/Q trace of sound wave baseband signal under mutipath
We borrowed an idea from a research about finger tracking and used Local Extreme Value Detection (LEVD) algorithm to estimate the static vector. This algorithm operates on the I/Q component separately to estimate the real and imaginary parts of the static vector. We first find alternate local maximum and minimum points that are different more than an empirical threshold, which is set as three times of the standard deviation of the baseband signal in a static environment. These large variations in the waveform indicate the movements of surrounding objects. We then use the average of two nearby local maximum and minimum as the estimated value of the static vector. When we finished static vector estimation we can subtract it from the baseband signal to get the dynamic vector. we then use the phase of the dynamic vector to estimate the temperature.

3.3 Temperature estimation

The temperature is estimated by its relationship with sound speed, which is known as Equation 2.1. According to the phase-based distance measurement method in LLAP [21], we can unwrap the phase $\phi(t)$ and the path length $d(t)$ during the time period $0 \sim t$ is given by:

$$d(t) - d(0) = -\frac{\phi_d(t) - \phi_d(0)}{2\pi} \times \lambda \quad (3.1)$$
where \( d \) is the propagation distance from the speaker reflected through the movable reflector to the microphone, and \( \lambda \) is the sound wavelength. As we all known, sound wavelength \( \lambda \) can be calculated by sound speed \( c \) and the frequency \( f \):

\[
\lambda = \frac{c}{f}
\]  

(3.2)

Based on the equation (3.1) (3.2), we can calculate the sound speed by using the phase of the received signal when the path length and frequency are given. Therefore, we can estimate the temperature by the relationship between temperature and sound speed mentioned before.
CHAPTER 4

PERFORMANCE EVALUATION

We have implemented a system prototype on popular Android platform and evaluated the performance in representative environments. The smartphone we used is Samsung Galaxy S9+. The implementation of our method on android is showed in Figure 4.1.

![Figure 4.1: Mtemp Implementation on Android](image)

4.1 Initial experiment

First of all we conducted an initial experiment. The experiments are conducted in an indoor room and the setup is shown in Figure 4.2.
In this experiment we focus on the reflection signal send by the phone, and we use movable reflector in this experiment. To measure ground truth temperature, we use a dedicated digital thermometer with an accuracy of 1.5°C in measuring temperature and an accuracy of 5% in relative humidity. The electric heater in the figure 4.2 is used to warm up air and we move the distance between a smartphone to the heater so as to equivalently
adjusting ambient air temperature. The detailed experiment setup are shown in Table 1 of APPENDIX B.

Table 4.1 shows the Initial Experiment result. The result showed below roughly reflects the relationship between temperature and phase: with the increase of temperature, the phase of the signal decreases. Since we just use electric heater to change the ambient temperature, so we can not get a stable temperature actually and combined with the accuracy and response time problem, digital thermometer can not provide accurate ground truth of ambient temperature.

<table>
<thead>
<tr>
<th>Ambient Condition</th>
<th>Acoustic Signal Phase (rad)</th>
<th>Estimated Sound Speed (m/s)</th>
<th>Estimated Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot (around 35°C)</td>
<td>128.33</td>
<td>353.86</td>
<td>37.72</td>
</tr>
<tr>
<td>Warm (around 30°C)</td>
<td>134.24</td>
<td>348.24</td>
<td>28.10</td>
</tr>
<tr>
<td>Ordinary (around 25°C)</td>
<td>136.79</td>
<td>346.02</td>
<td>24.79</td>
</tr>
<tr>
<td>Cool (around 20°C)</td>
<td>143.75</td>
<td>342.44</td>
<td>18.63</td>
</tr>
</tbody>
</table>
4.2 Improved experiment

Based on the initial experiment, we update our system design and experiment equipment showed in Figure 4.3 and Table 2 of APPENDIX c to validate our method in experiment.

Figure 4.3: Improved experiment setup
Specifically, we use Quincy Lab Incubator. It can provide stable temperature and an ideal environment for our experiment. The temperature range is 15-60 centigrade. And we replaced the movable reflector with a Cozmo Robot with a reflector on it to achieve accurate moving in a fixed speed. The movement accuracy is around 2mm. In addition we use alcohol thermometer with an accuracy around 0.8 centigrade to get a more accurate ground truth of ambient temperature.

![Figure 4.4: Phrase of the target reflection signal under different temperature](image)

The Figure 4.4 and Figure 4.5 show the experiment results. It is observable that the phrase of target reflection signal changes at different temperature points as shown in Figure 4.4. And Figure 4.5 reveals that the phrase-temperature relationship indicated by measured data are highly consistent with theoretical basis, demonstrating the effectiveness of our proposed model.
Figure 4.5: Temperature-Phrase relationship: measurements vs. theoretical line

Figure 4.4 also showcases that the measured phrase is quite stable, showcasing the robustness of our system. This experiment demonstrates our method can achieve real-time temperature sensing with good performance. Extensive measurements have revealed that Mtemp can achieve a median accuracy of 1.2 °C.
CHAPTER 5

IMPACT ANALYSIS

5.1 Signal strength

Here we conducted research about the factors affecting temperature sensing. Firstly we analysis the impact of signal strength on our method. As we all know, sound volume, determining the signal intensity of transmitted signals, can affect the multipath profiles of the two microphone channels, thus resulting in different reflection signal. Specifically, large volume can lead to more severe multipath reverberations.

Figure 5.1: CDF of measurement errors under different volumes(signal strength)
To explore how signal strength affects the sensing results, we have conducted experiments under different sound volumes. Extensive measurements (shown in Figure 5.1) have revealed that reducing the volume from 80% to 40% on the transmission side would slightly decrease the system performance. And when the volume is around 20%, the performance become worse with an average accuracy over 4°C.

### 5.2 Smart phone diversity

We have conducted evaluations using different smartphones. Specifically, we choose smartphones with different acoustic sensor layouts for experimentation to analysis the impact of smartphone diversity.

![Figure 5.2: CDF of measurement errors by different smartphone diversity](image)
Among the surveyed smartphones, Over 95% smartphones adopt similar layouts, where two microphones are placed at top and bottom, and the speaker is close to the bottom microphone (usually >2cm apart).

In our experiment, we select two typical Android smart phones: Galaxy S9+ and Huawei Mate 10. Experiment result showed in Figure 5.2 here has revealed that our method can be used in different smart phone brands and it shows similar result of temperature. And Samsung Galaxy S9+ exhibit slightly better performance than Huawei Mate 10.
CHAPTER 6

LIMITATION AND FUTURE WORK

Mtemp demonstrates that commercial mobile devices can use acoustic phase information to estimate ambient temperature with around 1.2°C accuracy. However, our current implementation of Mtemp has the following limitations. Mtemp requires to obtain the propagation distance for accurate sound speed estimation. Although this only needs to be done once for all, it can still be a difficult task for common users. Therefore, we recommend that application designers to accomplish this task and make it accessible for users. In addition, as Mtemp utilizes refection signal to estimate the sound speed and ambient temperature, it can be influenced by the environment factor. So our future work will focus on analyzing the impact of other environment factor (e.g. humidity, wind speed etc.) on Mtemp and improving the accuracy of temperature measurement method in our system.
In this thesis, we make following key contributions. First, we proposed an acoustic signal reflection based ambient temperature sensing method using single smart device. Second, we implemented our system Mtemp on android commercial mobile phones and conducted extensive experiment studies to validate our method. In addition, we tested robustness of Mtemp under different conditions and analyzed the impact of other factors. We envision that Mtemp will enable a plethora of novel acoustic signal reflection based ambient temperature sensing mobile applications.
APPENDIX A

LEVD ALGORITHM

LEVD (Local Extreme Value Detection) Algorithm

**Input:** One baseband signal component $X(t) = I(t)$ or $Q(t)$, $t = 0 \ldots T$

**Output:** Real or imaginary part of the estimated static vector $S(t)$, $t = 0 \ldots T$

1. Initialize $n$: number of extrema, $S(0)$: initial estimation, $E(n)$: extrema list

3. **for** $t = 1$ to $T$ **do**

4. /*Find extreme points that meet our requirements*/

5. **if** $X(t)$ is a local maxima or minima **then**

6. Compare $X(t)$ with the last extreme point $E(n)$ in the list;

7. **if** Both $X(t)$ and $E(n)$ are local maxima/minima, and the value of $X(t)$ is larger/smaller than $E(n)$ **then**

8. $E(n) \leftarrow X(t)$;

9. **end**

10. **if** One of $X(t)$ and $E(n)$ is maxima and the other is minima, and $|X(t) - E(n)| > \text{Thr}$ **then**

11. $n \leftarrow n + 1$;

12. $E(n) \leftarrow X(t)$;

13. **end**

14. **end**

15. /*Update the static component estimation using exponential moving average*/

16. $S(t) \leftarrow 0.9 \times S(t - 1) + 0.1 \times (E(n - 1) + E(n))/2$;
17  end

18  return S(t)
## APPENDIX B

### TABLE 1: INITIAL EXPERIMENT EQUIPMENT

Table 1: Initial experiment equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart phone</td>
<td>Brand: Samsung Galaxy S9+</td>
</tr>
<tr>
<td>Movable reflector</td>
<td>Size: 173×92×58 mm</td>
</tr>
<tr>
<td>Digital thermometer</td>
<td>Accuracy: 1.5(^\circ)C</td>
</tr>
<tr>
<td></td>
<td>Response time: 3s</td>
</tr>
<tr>
<td>Electric Heater</td>
<td>Power: 1875W</td>
</tr>
<tr>
<td>Tape measure</td>
<td>Measurement range: 0-2 m</td>
</tr>
</tbody>
</table>
### APPENDIX C

#### TABLE 2: IMPROVED EXPERIMENT EQUIPMENT

Table 2: Improved experiment equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart phone</td>
<td>Brand: Samsung Galaxy S9+</td>
</tr>
<tr>
<td>Quincy Lab Incubator</td>
<td>Brand: Model 12-140E</td>
</tr>
<tr>
<td></td>
<td>Temperature range: 15-60°C</td>
</tr>
<tr>
<td>Cozmo Robot</td>
<td>Movement accuracy: 2 mm</td>
</tr>
<tr>
<td>Alcohol thermometer</td>
<td>Accuracy: 0.8 °C</td>
</tr>
<tr>
<td>Reflector</td>
<td>Size: 173×92×58 mm</td>
</tr>
</tbody>
</table>


