Accuracy and Precision of a homemade Ultrasonic Thermometer compared to a Infrared and Liquid-in-Glass Thermometers

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I explore how an Ultrasonic Thermometer works and build a homemade one from readily available parts and see how its accuracy and precision compares to conventional thermometers that are already on the market such as Infrared and Mercury thermometers. The focus of this research was to see if Ultrasonic Thermometer can be used for everyday cases or if this type of technology is only useful in specialized use cases that are outside the needs of the public due to the technology's limits. The primary audience of this research is individuals interested in Ultrasonic Thermometers to focus their research on the problems that ultrasonic thermometry faces or pinpoint what applications ultrasonic thermometry is ideal for. My research found that the accuracy of an inexpensive Ultrasonic Thermometer can get readings very similar to conventional thermometers but it lacks the ability to give consistent precise thermal readings when dealing with real-world variables such as air density, air flow or dust that can interfere with the sensor's reading. The ideal application for ultrasonic thermometry is in specialized cases where outside factors are eliminated.

I. INTRODUCTION

There are many methods to measure temperature such as thermocouples, radiation thermometers (infrared thermometers) and liquid-in-glass thermometers but each of them have their own limitations that can be overcome with ultrasonic thermometry.[2] Thermocouples are quite accurate thermometers but it's extremely difficult to get accurate measurements safely under very high or low temperature environments and dangerous situations due to the durability of the thermocouple and its need to be in direct contact with the object of interest. Liquid-in-glass thermometers such as mercury or alcohol thermometers suffer from the same problem because the chemicals used in these thermometers are only able to cover a certain range of temperatures and usually fail at very low and high temperatures either due to the chemical's physical properties or the container of the chemical's durability at hostile environments. The container of most liquid-in-glass thermometers are glass and under very low temperature, it can freeze and break while at high temperatures, it can melt. Liquid-in-glass thermometer have poor accuracy compared to the other thermometer types because it is very hard to get the same degree of precision that other thermometer can easily get due to having to eye-ball the measurements. A liquid-in-glass thermometer's temperature detection time is much longer compared to its opposition and dependent on what chemical is being used. Radiation thermometers such as infrared thermometers are excellent at measuring temperature on moving objects, objects in dangerous environments or at unreachable positions but they can suffer from outside interference such as the detection of infrared radiation from a much hotter object than the intended object leading to inaccurate measurements. It is also very susceptible to error due to fume, mist and dust which can easily affect temperature measurements by reflecting, absorbing or emitting radiation. Certain objects that are very reflective like metal will make it difficult for an infrared thermometer to obtain an accurate temperature measurement since it gets its temperature reading based on blackbody radiation which reflective surfaces barely emit as they mainly reflect.

Utilizing the concept that sound waves travel at different speed depending on the medium's composition and temperature, it's possible to determine the temperature of a medium knowing the composition and distance between the ultrasonic wave sender and receiver and vice versa. The speed of sound within a medium is dependent on the medium's composition and temperature. Under the condition of an ideal gas, the velocity of the sound in a medium is directly proportional to the square root of the absolute temperature. The state of matter that the medium is changes the dependency between the speed of the sound and the temperature. Which for liquids, the relationship between speed and temperature is usually linear while solids have the speed of sound greatly decreased as the temperature is increased.[3]

This research intends to find how accurate and precise a homemade ultrasonic based thermometer is compared to other commercially available thermometers. The motivation for this research is to see if this proof of concept is valid with only the most precise sensor or is it possible to get both accurate and precise data from an inexpensively made ultrasonic thermometer compared to other commercially available thermometers. The research will be conducted with an ultrasonic transmitter and receiver connected to an arduino microcontroller that utilizes ultrasonic sound waves to determine the time that it takes for the sound wave to transverse back and forth a fixed distance within a medium. From that time, I can infer the temperature which will be compared to other conventional commercially available thermometers at different

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environments. Comparing the temperature readings with other thermometer would allow me to determine how accurate and precise the Ultrasonic Thermometer is compared to an Liquid-in-glass and Infrared thermometer.

II. METHODOLOGY

Research with ultrasonic waves have resulted in the development of many technique that utilize ultrasonic waves to get the average temperature between two points in a medium such as the time-of-flight method, phase-shift analysis of single-frequency continuous wave method, and the multiple-frequency continuous wave method.[3] The time-of-flight method of obtaining the temperature of a medium suffers from measurement errors when used in an air medium due to uncertainty in environment humidity and air pressure. The errors that rise from the time-of-flight method result in the development of the single-frequency continuous wave phase shift method which is based on the phase difference of the repeating ultrasonic signal sampled for a statistically significant number of wave periods which caused the random variation in phase shift to cancel itself out when averaged. Essentially instead of solely using the time it takes from the sound wave to traverse a medium, they used a continuous wave of numerous wave periods or numerous burst of the same wave that would average out the time. The phase shift of this single frequency could determine the distance which is inversely proportional to the measured temperature but only if the distance didn't exceed one wavelength. This solved the environmental variables that the time-of-flight method suffered from but was only valid very short distances. This prompted the multi-frequency continuous wave method which resulted in the ability to measure the temperature in larger distances by utilizing more frequencies for the air temperature measurement. The increasing of the number of frequencies used for phrase comparison would increase the maximum distance possible with the trade-off of more computation time.

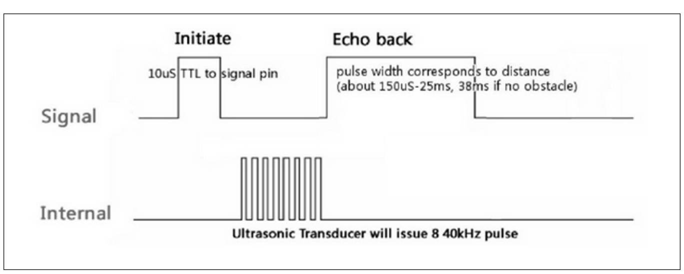

FIG. 1. Ultrasonic Sensor operations.

This multi-frequency continuous wave method would be the ideal way of obtaining the duration of time that has traversed between the sensor sending the ultrasonic wave and receiving it but this type of sensor is not readily available on the market cheaply. The sensor that is used in this experiment is a HC-SR04 Ultrasonic sensor that is capable of sending ultrasonic sound waves and receiving ultrasonic sound waves due to it's ultrasonic transmitter and receiver module. The sensor is capable of sending and receiving sound waves that range from 2cm up to 400cm in length from the sensor. The sensor works by transmitting out a burst of eight cycles 40k Hz ultrasonic sound waves right after an initial signal from the pin then waiting for the reflected ultrasonic sound waves to reflect and be detected by the receiver module. After the ultrasonic sound waves have bounced and returned to the sensor module, it will echoback a pulse to the microcontroller that corresponds to the time the wave has taken to traverse the medium shown by Figure 1. Having this sensor connected to a micro controller such as an arduino, I was able to take the time or ping time which are the same that the sensor records and converts it into temperature through this code:

I tested the precision of the sensor by testing what the ping time obtained was at different distances, this was done multiple times at different distances to see which separation distance between the sensor and the reflecting object was ideal to get rid of any inconsistencies.

I put a small plastic box that was 10cm directly in front of the sensor and keeping it always at that distance by gluing both the sensor and the plastic box on a wooden block then attaching a battery to the microcontroller alongside a LCD Module to show the temperature reading without having to be connected with the computer at all times. This kept the distance between the sensor and the object that's suppose to reflect the sound wave consistent, and it allowed to move the sensor from location to location. After doing this, I changed the code in the arduino to convert the time given by the sensor which was in microseconds into temperature. The duration that it takes for the sound wave to propagate the medium within the set distance was dependent on the composition and the temperature. My experimental setup kept everything constant and consistent except for the temperature. From the time given by the sensor, I converted it to temperature based on this formula:

$$Temperature = \frac{\frac{d*20{,}000}{t_{ping}} - 331.4}{0.6} + 273.15 \qquad (1)$$

Where the d is the separation distance from the sensor and the reflecting object and t_{ping} is the time returned by the sensor. It is multiplied by $20,000$ to converts $\frac{cm}{microseconds}$ into $\frac{m}{second}$ and the final temperature calculated is given in Kelvins. This is the speed of sound formula at different temperatures in air, where I converted the units into meters per second.

Utilizing the equation above which is the speed of sound in air based on temperature, I was able to calculated the temperature using this code, where I get the reading from my Ultrasonic Sensor at every 1000 millisecond intervals:

```
SR04::SR04(int echoPin, int triggerPin) {
```

```
    _echoPin = echoPin;
    _triggerPin = triggerPin;
    pinMode(_echoPin, INPUT);
    pinMode(_triggerPin, OUTPUT);
    _autoMode = false;
    _distance = 999;

long SR04::Time() {
        _duration = 0;
    digitalWrite(_triggerPin, LOW);
    delayMicroseconds(2);
    digitalWrite(_triggerPin, HIGH);
    delayMicroseconds(10);
    digitalWrite(_triggerPin, LOW);
    delayMicroseconds(2);
    _duration = pulseIn(_echoPin,
    HIGH, PULSE_TIMEOUT);
        delay(25);
        return _duration;
}

#include "SR04.h"
#define TRIG_PIN 12
#define ECHO_PIN 11
SR04 sr04 = SR04(ECHO_PIN,TRIG_PIN);
float a;
float speedOfSound;
float dist = .1; //m
float temp; //Kelvins

void setup() {
   Serial.begin(9600);
   delay(1000);
}


void loop() {
   a=sr04.Time();

   speedOfSound=(((dist*.01)*2*1000000)/a);
   temp=((speedOfSound - 331.4)/0.6)
   + (273.15);

   Serial.print(temp);
   Serial.println(" Kelvins");


   delay(1000);
```

After getting the microcontroller and the sensor setup, the thermometer is tested in two different environments along with an Liquid-in-glass thermometer and an infrared thermometer. The two environments are at room temperature and within a freezer. I tested the thermometer along with the other thermometers 5 times in each environment and compared them to each other to determine if the results from the ultrasonic thermometer is as accurate or as precise as the conventionally available thermometers.

Ping Timing Trials (μs)			
5cm	10cm	20cm	30cm
328	586	1175	1780
324	586	1176	1779
322	587	1169	1811
331	586	1175	1780
324	587	1174	1755
327	586	1175	1785
330	586	1174	1756
325	587	1175	1779
326	586	1169	1779
325	587	1174	1806

TABLE I. Ping Times of the sensor at different distances

Room Temperature Trials			
Trial	Ultrasonic Thermometer (K)	Infrared Thermometer (K)	Wall Thermometer (K)
1	282.67	287.09	288.15
2	287.09	287.15	288.15
3	279.88	287.09	288.15
4	287.80	287.09	287.15
5	287.51	287.15	288.15

TABLE II. Temperature obtained from each type of Thermometer at Room Temperature

III. DATA

A. Sensor Consistency

The first test conducted was to see how the sensor's precision differed at different distances. Table 1 reveals that as I start increasing the distance of the reflective object from the sensor, the sensor's reading became more and more inconsistent except for the first trial which was at 5cm. Having the reflective object at 5cm seemed to causes some problems with the sensor resulting in the ping time to all vary. This pattern didn't consist after 5cm since the variation wasn't as chaotic to the 5cm trials, which I suspected was due to having the reflective object too close the sensor which causes some problems.

B. Room Temperature

Table 2 shows the data obtained from testing the 3 types of thermometers at Room Temperature 5 times. All the Thermometer's reading weren't too far off from each other with the Infrared and Wall Thermometer's reading very close to each other and without much variation through multiple trials. The exception was the Ultrasonic Thermometer, it was able to give temperatures that were close to the one's given off by the other two thermometers but it seems to have occasional imprecise readings that were up to almost 8 Kelvins difference from the other two.

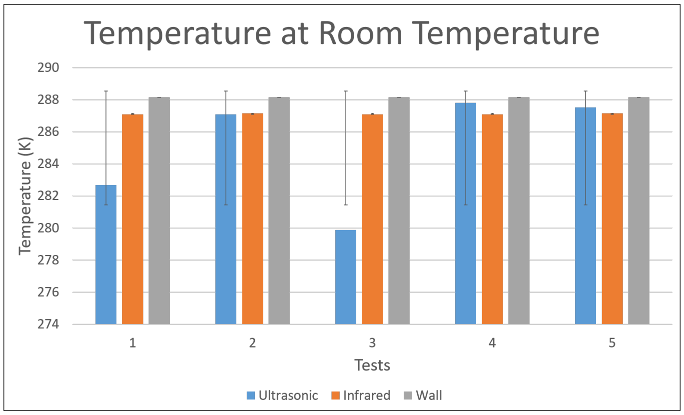

FIG. 2. Comparing all the Thermometer by Trials at Room Temperature.

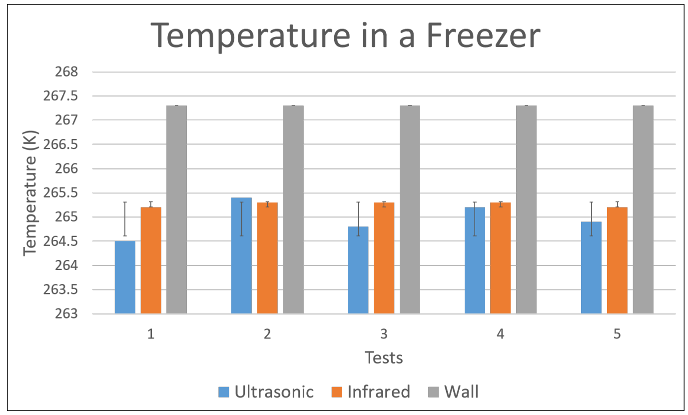

FIG. 3. Comparing all the Thermometer by Trials at Freezer Temperature.

Freezer Temperature Trials			
Trial	Ultrasonic Thermometer (K)	Infrared Thermometer (K)	Wall Thermometer (K)
1	264.59	265.26	267.59
2	264.32	265.26	267.59
3	264.59	265.26	267.59
4	265.48	265.31	267.59
5	264.59	265.31	267.59

TABLE III. Temperature obtained from each type of Thermometer at Freezer Temperature

C. Freezer

Table 3 shows the data obtained from testing the 3 types of thermometers at Freezer Temperature 5 times. The Infrared and Wall Thermometer were able to maintain their consistency while the Ultrasonic Thermometer's consistency improved compared to the Room Temperature trials. The big difference in this trial is that the infrared sensor's readings were much closer the Ultrasonic Thermometer rather than the Wall Thermometer at Room Temperature. The gap between all the 3 types of thermometers also tightened as the temperatures were much closer to each other than at Room Temperature where I saw a maximum difference of 8 Kelvin while there was only a maximum of 3 Kelvin within the freezer.

IV. DATA ANALYSIS

The first test I took was to determine how consistent was the sensor at certain distances. Testing of the sensor at different distance revealed that the sensors ability to give consistent results diminished as the distance increased and that having the sensor being too close to the reflective object gave chaotic results that weren't seen at longer separation distances. This made it much more favorable to test at smaller distance but not too small to be prevent any inconsistencies that might come up such as very sudden movement of the sensor or the reflecting object, or dust and particles interfering with the measurements. The data obtained by testing the Ultrasonic thermometer alongside the other conventional thermometer at room temperature and inside a freezer showed that the Ultrasonic thermometer generated data that had much more greater variability and volatility compared to the other thermometer. This resulted in it having a much higher standard derivation error bar compared to the other two in both room temperature and inside a freezer, especially at room temperature.

Having all the data for the thermometers being within 8 Kelvins maximum of each other in Table 2 shows that the concept of an Ultrasonic Thermometer works and the difference in temperature readings of an Ultrasonic thermometer wouldnt cause a lot of problems for normal day to day activities. The data inside the Freezer is even better at 2 Kelvins difference but the infrared readings are much lower than expected, Im suspecting this is due to the ice within the freezers emissivity affecting the infrared sensor ability to accurately measure a temperature since it is giving off less radiation than it should. It could also be that the sensor is just measuring the temperature of the ice rather than the air itself which is much colder. For the ultrasonic sensor, I am suspecting that constant air flow that is happening in the freezer is making the data generated by the Ultrasonic thermometer to also be much lower than suspected because it's affecting the the sound waves' path. The main downfall of an Ultrasonic thermometer is that it is incredibly way too inconsistent as shown by the standard deviation error bars which are enormous compared to the ones generated by the infrared thermometer and wall thermometer. Meaning that an Ultrasonic Thermometer's accuracy is not very different from a infrared thermometer and wall thermometer but the inconsistency in the air makes it very hard to get accurate readings. Meaning that a homemade Ultrasonic Thermometer's accuracy isn't far off from conventional thermometers but it's precision is. Also, an Ultrasonic thermometer is not a point thermometer like the other because it gets the average temperature between itself and the reflector unlike the other twos which take a temperature at a certain point.

V. CONCLUSION

In summary, an Ultrasonic Thermometer can perform on par with its competitors but due to sensitivity to error from numerous factors such as air density and air flow that cant be controlled in day to day situation makes it not a really good point thermometer that would be used in every day situations. This technology really shines in situation where other thermometers fail such as when chemical based thermometers cant perform accurately at very high or low temperatures or when direct physical contact is impossible, or when radiation based thermometer fail due to surfaces having very low emissivity making it very reflective or when it reads a temperature of a much stronger nearby heat source than the intended target. Ideally, an Ultrasonic Thermometer works best within a laboratory where experiments arent effected by outside or uncontrolled variables, or when you want to find the average temperature within a known medium because both wall thermometers and infrared thermometers are point thermometers and cant accurately measure the average temperature of an object unless the object is able to proportionally diffuse its temperature to be the same at every surface point.

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[1] Huang, K. N., et al., *"High precision, fast ultrasonic thermometer based on measurement of the speed of sound in air."*, Review of scientific Instruments 73.11: 4022-4027., 2002.

[2] Tsai, Wen-Yuan, Hsin-Chieh Chen, and Teh-Lu Liao., *"An ultrasonic air temperature measurement system with self-correction function for humidity."*, Measurement science and technology 16.2: 548., 2005.

[3] Tsai, Wen-Yuan, Hsin-Chieh Chen, and Teh-Lu Liao., *"High accuracy ultrasonic air temperature measurement using multi-frequency continuous wave."*, Sensors and Actuators A: Physical 132.2 (2006): 526-532., 2006.

[4] Huang, Y. P., et al., *"Envelope pulsed ultrasonic distance measurement system based upon amplitude modulation and phase modulation."* , Review of scientific instruments 78.6: 065103., 2007.

[5] Tsai, Wen-Yuan, Chih-Feng Huang, and Teh-Lu Liao.., *"New implementation of high-precision and instant-response air thermometer by ultrasonic sensors."* , Sensors and Actuators A: Physical 117.1: 88-94. , 2005.