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Innovative Approach to Physics Experiments: Low-Cost Apparatus for Measuring the Speed of Sound and its Dependency on Temperature

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Abstract: ***This research paper introduces an innovative paradigm for cost-effective and high-resolution physics experimentation, tackling the constraints associated with traditional methods that often rely on bespoke and expensive lab equipment, predominantly found in well-funded private schools. Our study delves into the application of commercially available off-the-shelf (COTS) materials for physics experiments, specifically emphasizing the measurement of the speed of sound and its correlation with temperature.***

Keywords: Physics Experiments, COTS, Sensors, Microcontrollers

1. Introduction

Physics experimentation has long been synonymous with bespoke and expensive lab apparatus, with traditional approaches often confined to the environs of well-funded private schools. These institutions have historically enjoyed the privilege of well-equipped laboratories and the necessary resources to engage students in hands-on learning experiences. However, such advantages are not universal, as state-funded schools frequently grapple with limited access to sophisticated equipment and face challenges in providing students with the practical aspects of physics education.

The conventional model of physics experiments not only relies on specialized apparatus but also demands extensive support from educators and lab staff. This traditional approach, while effective in certain settings, poses significant barriers to accessibility. Students in state-funded schools often find themselves at a disadvantage, lacking the requisite resources to engage in meaningful hands-on experimentation. Even when equipment is available, the intricate nature of its operation necessitates substantial assistance, placing a strain on both educators and students.

Recognizing these challenges, our research endeavors to revolutionize physics education by proposing a departure from traditional methodologies. We advocate for a paradigm shift toward the use of commercially available off-the-shelf (COTS) materials, offering a cost-effective and accessible alternative to traditional lab setups. The goal is to devise physics experiments tailored for high-school levels using COTS, aligning with our philosophy to bring hands-on experiments to every school and every home. By doing so, we aim to ignite more curiosity towards STEM topics at the high-school level and beyond. By leveraging commonly available components, such as open-source microcontrollers and sensors, we aim to democratize physics experimentation, making it feasible for a broader spectrum of educational institutions, including those with limited financial resources. Through these efforts, we strive to contribute to a more inclusive and engaging approach to physics education.

In the landscape of making physics experiments more affordable through commercially available materials, existing studies have primarily centered on temperature sensors, light sensors, and electricity-related experiments involving resistors and capacitors [1] [2]. However, these studies often fall short in addressing the methodical and systematic approach that scientific experiments demand. In our novel approach, we recognize this gap and specifically target a completely new area of physics, focusing on sound waves. Our emphasis is on bringing a scientific approach to this domain, offering a methodological framework that not only makes experiments more accessible but also ensures a rigorous exploration of fundamental principles in physics. This unique perspective allows us to contribute valuable insights to the broader conversation on democratizing physics education.

In the subsequent sections of this paper, we delve into a specific experiment conducted as part of our innovative approach – measuring the speed of sound in the air and exploring its dynamic relationship with temperature. Implementing a systematic methodology inherent in scientific experiments, we meticulously collect, log, and analyze data. Notably, what distinguishes our approach is not only its scientific rigor and precision but also its unparalleled affordability. The total cost of conducting this experiment, inclusive of all components, stands at an impressive under 10 USD (INR 800). This cost-effectiveness underscores the accessibility of our methodology, affirming that sophisticated experiments of this nature can be conducted with remarkable accuracy and scientific precision in any school or home environment.

2. Components Used in Speed of Sound Measurement Experiment

Microcontroller

In alignment with our commitment to simplicity and affordability, aimed at bringing physics experiments to students' homes from sophisticated and rarely accessible labs, we undertook a thorough investigation into various microcontrollers. The goal was to identify a hub for our experimentation that could efficiently collect data from diverse sensors and record it for subsequent analysis. Through a comprehensive performance versus cost analysis and considering the easy availability of components, we evaluated microcontrollers such as Arduino UNO, Raspberry Pi, and ESP32 [3]. Arduino UNO (Figure 1) emerged as the optimal choice due to its popularity as an open-source platform, affordability, and compatibility with our experimental needs. Arduino Uno is a microcontroller board based on the ATmega328P. Featuring 14 digital input/output pins, 6 analog inputs, USB connection, power jack, ICSP header, and a reset button, Arduino UNO offered a versatile and accessible foundation for our physics experiments [4].

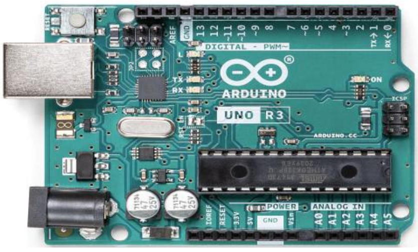

Figure 1: Arduino Uno

Ultrasonic Sensor (HC-SR04)

To execute the measurement of the speed of sound, a pivotal step in our scientific experiment, we required a microcontroller to collect data from peripherals, i.e., sensors, and store it for further analysis. Arduino UNO, with its robust capabilities and user-friendly interface, stood out as an ideal choice. The HC-SR04 ultrasonic sensor (Figure 2) was selected for speed measurement, featuring ultrasonic sound wave transmitter and receiver modules and an on-board timer to precisely track the time between transmitted and reflected, time-of-flight, of ultrasonic sound waves [5]. This sensor's suitability for our experiment laid the groundwork for accurate and reliable speed of sound measurements.

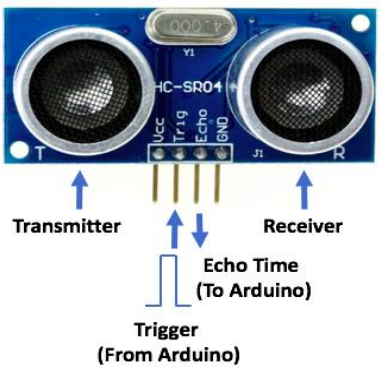

Figure 2: HS-02 Ultrasonic Sensor

Temperature & Humidity Sensor (DHT-11)

In our experiment, monitoring ambient temperature and humidity was crucial. For this purpose, we opted for the DHT-11 sensor (Figure 3), aligning with our philosophy of affordability and common availability. Comprising a capacitive humidity sensor and a thermistor, the DHT-11 sensor [6], while basic and slow, effectively serves the purpose of our experiment. Its straightforward digital signal output can be easily read using the Arduino UNO microcontroller, providing essential data for our analysis.

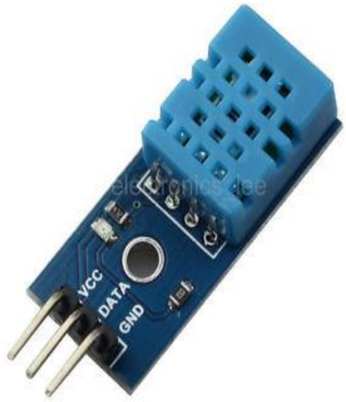

Figure 3: DHT-11 Sensor

Data Logger (Micro SD Card)

With Arduino UNO serving as the heart of our experiment, collecting data from HC-SR04 and DHT-11 sensors, we incorporated a micro SD card module (Figure 4) to store the recorded data. The module communicates with Arduino UNO via the SPI bus (SPI library), and with the built-in SD library in the Arduino IDE, it functions as a reliable data logger [7]. Data is stored in a .txt format on the micro SD card, allowing for seamless transfer to a PC for in-depth analysis. This integrated system ensures both efficiency and accessibility in our physics experimentation process.

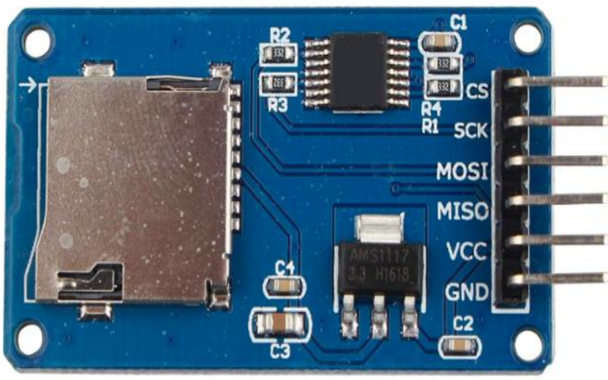

Figure 4: Micro SD Card Data Logger Module

3. Formulas

Formula to Measure Speed of Sound

To determine the speed of sound, we utilize the following formula in conjunction with an ultrasonic sensor.

$$speed = \frac{distance}{time} \quad (1)$$

The procedure involves using the trig and echo pins, of the ultrasonic sensor (see Figure 2). Upon powering the sensor and applying a pulse to the trig pin through a microcontroller (Arduino UNO in this case), the transmitter initiates the emission of ultrasonic sound waves into the air. If an obstruction is encountered, the waves strike the obstacle and rebound. The receiver captures the reflected waves, and the timer on the ultrasonic module records the total flight time (Figure 5). The recorded time is then outputted on the echo pin and read by the microcontroller. To calculate the speed of sound, an obstruction is strategically placed at a known distance in the path of the ultrasonic waves. Utilizing this known distance and the time-of-flight from the echo pin, the speed of sound is determined using equation (2).

$$speed\ of sound = \frac{distance}{(time\ of flight/2)} \quad (2)$$

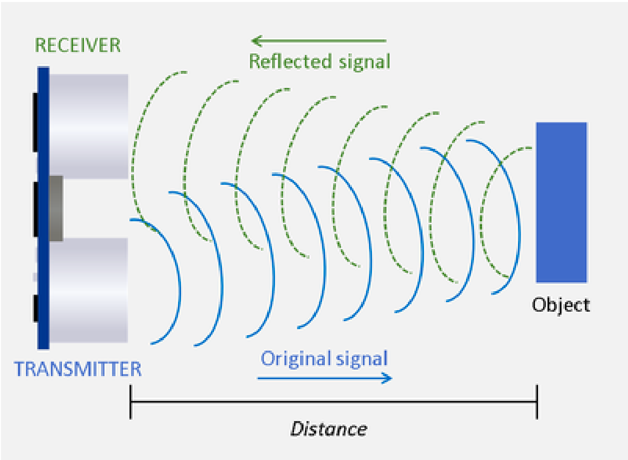

Figure 5: Ultrasonic Sensor with Transmitted and Reflected Waves with Obstacle

Relationship between Speed of Sound and Temperature

The primary determinant influencing the speed of sound in air is temperature, with the speed of a sound wave contingent upon air properties, especially temperature and to a lesser extent, humidity. Temperature impacts the strength of particle interactions, exhibiting an elastic property. Under normal atmospheric pressure, the temperature dependence of wave speed in dry air is approximated by a proportional relationship to the square root of the absolute temperature, resulting in an increase of approximately 0.6 m/s per degree Celsius [8]. Additionally, heat, akin to sound, represents kinetic energy, leading to faster molecular vibrations at higher temperatures and consequently, quicker sound wave travel. The speed of sound in room temperature air is 346 meters per second, exceeding the 333 meters per second at freezing temperatures.

The theoretical approach to derive the speed of sound as a function of temperature is as follows. Velocity of sound is given by formula (3) [9] [10].

$$V_{Sound} = \sqrt{\frac{\gamma P}{\rho}} \quad (3)$$

Where P pressure, ρ is the density of the surrounding medium, γ is a constant. Substituting density (4) and ideal gas equations (5) in (3) leads to (6).

$$\rho = \frac{m}{v} \quad (4)$$

$$pv = RT \quad (5)$$

$$V_{Sound} = \sqrt{\frac{\gamma RT}{m}} \quad (6)$$

Where R, γ and m are constant for a given surrounding air. Equation (6) can be re-written as follows.

$$V_{Sound} = constant * \sqrt{T} \quad (7)$$

This equation can be written as (8) for two different temperatures t_1 (0 ^{0}C) and t_2 (t ^{0}C).

$$\frac{V_{t_2}}{V_{t_1}} = \sqrt{\frac{T_2}{T_1}} \quad (8)$$

Where T_1 and T_2 are absolute temperatures of t_1 (0 ^{0}C) and t_2 (t ^{0}C) respectively.

$$T_1 = 0C = 273K$$
$$T_2 = tC = t + 273K$$

$$\frac{V_{t_2}}{V_{t_1}} = \sqrt{\frac{t+273}{t}} = \sqrt{1+\frac{t}{546}} \quad (9)$$

Applying binomial approximation, the following equation can be derived.

$$\frac{V_{t_2}}{V_{t_1}} = \left(1+\frac{t}{2*273}\right) = \left(1+\frac{t}{546}\right) \quad (10)$$

By substituting V_{t_1} as 333m/s (speed of sound at 0C) we can derive the speed of sound as a function of temperature as in equation (11).

$$V_{t_2} = V_{t_1} + \frac{V_{t_1}}{546} * t$$

$$V_{t_2} = 333 + \frac{333}{546} * t$$

$$V_{t_2} = 333 + (0.61 * t)$$

$$V_t = V_0 + 0.61 * t \quad (11)$$

Where V_0 is the speed of sound and 0C and t is the ambient temperature in centigrade (C). V_t formula provides a means

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to calculate the average speed of sound for any given temperature.

4. Experimental Setup

In our experimental configuration, all sensors, including the HC-SR04 ultrasonic sensor and the DHT-11 temperature and humidity sensor, as well as the micro SD card module, are interconnected with the Arduino Uno as in circuit diagram (Figure 6). The Arduino Uno is programmable using Embedded C and C++ through the Arduino IDE, offering a versatile platform for software development and execution.

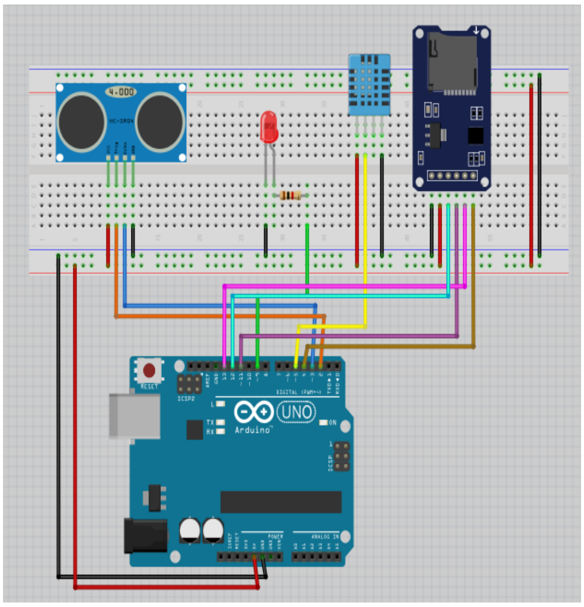

Figure 6: Schematic Diagram for Sound of Speed Measurements and Logging

Figure 7: Picture of Experimental Setup

5. Results

Speed of Sound in air at Room Temperature

The software code is specifically designed to initiate ultrasonic waves from the HC-SR04's transmitter. An obstruction is strategically positioned at a fixed distance, placed at right angles to the sensor. As the emitted waves encounter the obstruction, they reflect back to the sensor's receiver. The on-board timer on the HC-SR04 sensor accurately records the time-of-flight.

The time-of-flight is recorded for varying distances—5cm, 10cm, 15cm, 20cm, and 25cm. The speed of sound is calculated using equation (2) for each distance. The average speed of sound is calculated and by taking the average of all these values as shown in Table 1. From this experiment, overall average speed of sound is determined to be approximately 340m/s at a temperature of 28°C, as recorded by the DHT-11 sensor. This comprehensiveapproach ensures the accuracy and reliability of our speed of sound measurements under varying experimental conditions.

Table 1: Speed of Sound in Air at Room Temperature (28 C)

	Room Temperature: 28C		
S.No.	**Distance (cm)**	**Time (μs)**	**Speed of Sound (m/s)**
1	5	288	347.22
2	10	581	344.23
3	15	896.9	334.49
4	20	1159.59	344.95
5	25	1445	346.02
	Average Speed		**343.38**

Speed of Sound in air at Various Temperatures

We extend this experiment further to analyse the temperature dependence of sound of speed. In our experiment, measurements of the speed of sound were meticulously recorded at various temperatures to provide a comprehensive understanding of the relationship between these variables. To capture different room temperatures, readings were taken at various times of the day and night, ensuring a diverse dataset. The DHT-11 sensor was employed to measure temperature. Speed measurements were obtained at temperatures of 2°C, 5°C, 17°C, 26.1°C, 27.1°C, and 41°C, and the results were tabulated in Table 2. To derive a more comprehensive view, the average speed of sound was calculated for each temperature and tabulated in Table 3.

Table 2: Speed of Sound in Air at Various Temperatures

S.No	Distance (cm)	Time (μs)	Speed of Sound (m/s)	S.No	Distance (cm)	Time (μs)	Speed of Sound (m/s)
Temp	2 C			Temp	26.1 C		
1	10	602.92	331.72	1	10	528	378
2	15	909.92	329.7	2	15	887	338
3	20	1203.5	332.37	3	20	1097	364
4	25	1525.13	327.84	4	25	1381	362
5	30	1797.38	333.82	5	30	1650	363
		Ave. Speed	331.09			Ave. Speed	361
Temp	5 C			Temp	27.1 C		
1	10	604.74	330.72	1	5	288	347.22
2	15	909.92	329.7	2	10	581	344.23
3	20	1203.47	332.37	3	15	896.9	334.45
4	25	1484.38	336.84	4	20	1159.59	344.95
5	30	1792	334.82	5	25	1445	346.02
		Ave. Speed	332.89			Ave. Speed	343.374
Temp	17 C			Temp	41 C		
1	10	528	378	1	5	289.73	345.15
2	15	887	338	2	10	577.67	346.22
3	20	1097	364	3	15	851.06	352.5
4	25	1381	362	4	20	1129.34	354.19
5	30	1650	363	5	25	1407.94	355.13
		Ave. Speed	361			Ave. Speed	350.638

Table 3: Speed of Sound at Various Temperatures

Temperature (C)	Speed of Sound (m/s)
2	331.09
5	332.89
17	333.89
26.1	361.75
27.1	345.4275

A graphical representation, depicted in Figure 8, showcases the relationship between air temperature and the speed of sound. A best-fit straight line was plotted, and the equation of the line was extracted. Notably, this equation aligns with our theoretical equation 11, affirming the validity of our experimental approach. This successful alignment encourages further exploration and validation of the speed of sound as a function of temperature, opening avenues for deeper analysis in future experiments.

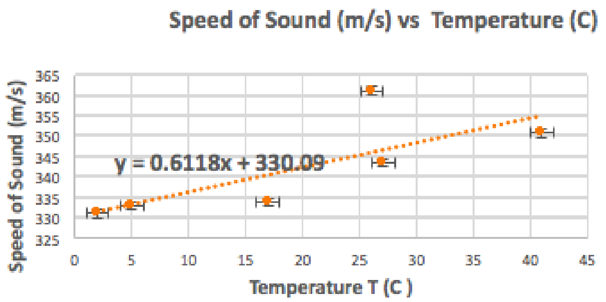

Figure 8: Graph of Temperature © Vs Speed of Sound (m/s)

6. Conclusions

In conclusion, we have presented a groundbreaking methodology for experimental physics, leveraging commercially available components and sensors to democratize physics experiments at the high-school level. Our primary objective is to revolutionize physics education by employing off-the-shelf materials. Taking the first step towards this goal, we not only calculated the speed of sound but also introduced a systematic approach to data collection, logging, and analysis, exploring the intricate relationship between the speed of sound and temperature. This methodology extends beyond mere calculations; it demonstrates a means of verifying and validating scientific formulas. In addition, the total cost of conducting this experiment, inclusive of all components, stands at an impressive under 10 USD (INR 800). Our work showcases that experiments of this caliber can be conducted at affordable prices, with high scientific precision, making them accessible to everyone, regardless of sophisticated lab access. The overarching aim is to expand the repertoire of accessible physics experiments, enabling a broader audience to engage in hands-on scientific exploration from the comfort of their homes.

7. Future Scope

Building upon our foundational work, the overarching goal is to devise a comprehensive array of physics experiments suitable for high-school education, utilizing COTS materials and components. Our philosophy revolves around democratizing hands-on experiments, extending accessibility to every school and home. By fostering a culture of experimentation, we aspire to kindle greater curiosity and interest in STEM topics at the high-school level. Looking ahead, our next endeavour involves the development of kinematics experiments, encompassing the measurement of velocity, acceleration, force, friction coefficients, as well as investigations into velocity due to gravity, and potential and kinetic energy measurements. The ongoing effort aims to introduce affordable and easily accessible components, ensuring that kinematic experiments become an integral part of our broader initiative to make physics education inclusive and engaging for all. Through these advancements, we anticipate further enriching the learning experience, encouraging a wider demographic of students to actively participate in the exploration of fundamental scientific principles.

References

[1] Petry, C.A., Pacheco, F.S., Lohmann, D., Correa, G.A & Moura, P. (2016). Project teaching beyond Physics: Integrating Arduino to the laboratory. In Proceedings of IEEE Technologies Applied to Electronics Teaching (TAEE).

[2] Bouquet, F., Bobroff, J., Fuchs-Gallezot, M., Maurines, L. Project-based physics labs using low-cost open-source hardware, American Journal of Physics, Vol. 85, Issue 3, 216-222, 2017.

[3] Qamarina, N., Jamaludin, A.A., Azizan, A., Abas, H. Arduino vs Raspberry Pi vs Microbit: Platforms for FastIoT Systems Prototyping. Research Gate. November 2018

[4] www.arduino.cc [last accessed 22nd January 2024]

[5] Handson Technologies, Ultrasonic Sensor Datasheet, www.handsontec.com [last accessed 23rd January 2024]

[6] Adafruit Industries, DHT-11 Datasheet, www.adafruit.com [last accessed 23rd January 2024].

[7] dafruit Industries, Data Logger Module Datasheet, www.adafruit.com [last accessed 23rd January 2024]

[8] Bello, A., Garcia, S.C., Measurements of Speed of Sound As a Function of Temperature Via Resonance and Normal Modes Method. Proceedings of 12th SPVM National Physics Conference, 2010.

[9] Sound Waves and Music, The Physics Classroom, www.physicsclassroom.com [last accessed 23rd January 2024].

[10] Feynman, R.P., Leighton, R.B., Sands, M.L., The Feynan Lectures on Physics, Volume 1, Addison-Wesley, 1989.

Author Profile

Disha Boorela is a student at Greenwood High International School in Bangalore. Her interest in physics has led her to research into topics like sound waves and galaxy scaling relations. Apart from her research in physics, she likes studying chemistry and learning new languages. In her free time, she enjoys reading fictional books and practising music.

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