Analysis of the Effect of Temperature Variations on HC-SR04 Ultrasonic Sensor Distance Measurement Accuracy Based on Tinkercad Simulation

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Abstract - Ultrasonic sensors are used to measure distance based on the reflection of sound waves. However, their accuracy is influenced by temperature changes because temperature determines the speed of sound propagation in air. This study analyzes the effect of temperature variations on the performance of ultrasonic sensors through theoretical analysis and Tinkercad simulation within a range of 0°C to 50°C. The method includes calculating the speed of sound as a function of temperature, analyzing the wave travel time, and simulating distance measurements in a virtual environment. The error value is obtained by comparing the sensor readings with the actual distance. The results show that higher temperatures increase the speed of sound, causing the measured distance to appear shorter, while lower temperatures result in longer readings. The smallest error occurs at 19°C–20°C, when the speed of sound approaches 343 m/s. At extreme temperatures, the measurement error can exceed 5%. These findings confirm that temperature is a key factor affecting ultrasonic sensor accuracy and can serve as a reference for the development of automation and industrial monitoring systems

Keywords* — *ultrasonic sensor; temperature; Tinkercad; HC-SR04.

I. Introduction

Ultrasonic sensors are widely used devices for measuring distance and detecting the presence of objects in various fields, such as industrial automation, robotics, autonomous vehicles, and security systems [1-3]**.** The operating principle of these sensors is based on the emission of high-frequency sound waves that are reflected back upon striking an object. The sensor subsequently computes the wave travel time to determine the distance between the sensor and the object. Owing to their high measurement precision, ultrasonic sensors play a critical role in systems requiring maximum accuracy in distance measurement. The performance of ultrasonic sensors is closely related to environmental conditions, particularly temperature.

Temperature changes affect the speed of sound propagation in air, where an increase in temperature causes the speed of sound to increase [4]. Consequently, distance measurements are susceptible to systematic deviation, particularly under extreme or fluctuating temperature conditions. At elevated temperatures, the measured distance tends to be shorter than the true value, whereas at reduced temperatures it tends to be overestimated [4]

In dynamic industrial environments, such temperature variations introduce systematic measurement errors that can significantly compromise system performance. Systems relying on precise distance data — such as autonomous navigation robots and industrial automation machinery — are particularly vulnerable to these deviations. Consequently, a thorough understanding of temperature-induced measurement uncertainty is essential for ensuring the operational reliability of ultrasonic sensor systems.

Several previous studies have shown that temperature significantly affects the performancen sensor. [5] found that temperature affects the sensitivity of the MQ-135 sensor in detecting CO_2, with sensitivity decreasing at low temperatures and increasing at high temperatures, with an optimal temperature of approximately 20°C. Another study by [6-7] on the Engine Coolant Temperature (ECT) sensor showed that an increase in temperature leads to a decline in several engine performance parameters, such as Engine Load and Engine RPM. These findings confirm that temperature is an important variable in sensor performance across various applications [8-17].

Despite the growing number of studies on ultrasonic sensor performance, studies that specifically and systematically map the measurement error of the HC-SR04 sensor across a wide temperature range (0°C–50°C) using Tinkercad simulation remain limited. This study fills that gap by providing a quantitative error profile across the full operational temperature range and demonstrating how a virtual simulation environment can serve as a low-cost preliminary validation tool prior to hardware implementation. The scientific contribution of this work is threefold: (1) it provides a systematic quantitative error benchmark for the HC-SR04 across a 0°C–50°C range derived from a validated mathematical model; (2) it demonstrates the feasibility of Tinkercad as a pre-experimental simulation platform for sensor characterization; and (3) it formulates a linear temperature compensation model that reduces measurement error to below 0.05% across the entire temperature range studied. Based on the foregoing, this study aims to analyze and simulate the effect of temperature on HC-SR04 ultrasonic sensor measurement accuracy. The study is expected to demonstrate the quantitative impact of temperature variations on distance measurement results, provide explicit error benchmarks at key temperatures, and offer recommendations for the implementation of temperature compensation. The findings are expected to benefit industry in improving the accuracy of automation systems, to serve as a reference for researchers developing more adaptive sensors, and to contribute to education as a learning resource on the influence of environmental conditions on sensor performance in the fields of electrical engineering and physics.

II. Research Method

This study employs a quantitative approach through simulation methods to investigate the effect of temperature on the measurement accuracy of ultrasonic sensors [12]. The simulation process was carried out using Tinkercad software as shown in Figure 1, which enables modeling of changes in the speed of sound at various temperature variations without the use of physical hardware.

Figure 1. Tinkercad

The research design covers the analysis of changes in sound propagation speed in air due to temperature differences, simulation of distance measurements using ultrasonic sensors, and evaluation of simulation results to determine the magnitude of measurement errors arising from temperature variations as shown in Figure 2. In addition, this study aims to provide recommendations regarding the implementation of calibration and temperature compensation to improve measurement accuracy.

The primary equipment used in this study includes Tinkercad software, sound speed data based on temperature variations, and a reference distance of 2 meters as the baseline for simulation. The research variables consist of the independent variable of ambient temperature in the range of 0°C to 50°C with an increment interval of 2°C, the dependent variable of distance measurement results by the ultrasonic sensor, and the control variable of actual distance set constant at 2 meters. The research procedure began with a literature review to understand the operating principle of ultrasonic sensors and the effect of temperature on sound propagation speed, followed by the calculation of the speed of sound using the empirical equation established by Cramer (1993): $v(T) = 331.4 + 0.6 \times T$ (m/s) where v is the speed of sound in m/s and T is the ambient temperature in °C. This equation is valid for dry air across the temperature range studied.

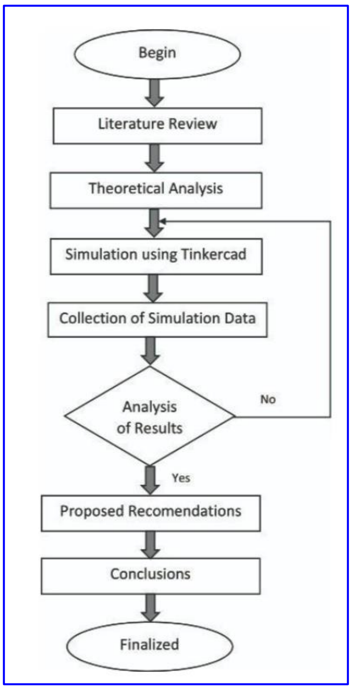


Figure 2. Measurement and Simulation Flowchart

The next stage was carried out through simulation on the Tinkercad platform by assembling the main components, namely an Arduino UNO, an HC-SR04 ultrasonic sensor, and a temperature sensor. The Arduino serves as the microcontroller responsible for reading and processing measurement data. The ultrasonic sensor is used to measure distance based on the Time-of-Flight principle, while the temperature sensor provides temperature variation inputs for the simulation scenarios. All components were assembled in a virtual circuit and subsequently tested to evaluate the extent to which temperature changes affect distance measurement accuracy.

The measurement simulation was conducted by setting a fixed actual distance of 2 meters and varying the temperature in the range of 0°C to 50°C with an increment interval of approximately ±1°C. For each temperature variation, the speed of sound was calculated using the appropriate equation and then used to determine the travel time of the ultrasonic wave. The measured distance was subsequently obtained through calculation using the formula:

[Measured Distance = (speed of sound × travel time) / 2]

Subsequently, the measurement error was calculated as the difference between the actual distance and the measured distance using the formula

[Error = ((Measured Distance − Actual Distance) / Actual Distance) × 100%].

A linear temperature compensation model was derived from the simulation data. Based on the linear regression of measured distance as a function of temperature, the relationship is expressed as: $d\_measured(T) = -0.003435 \times T + 2.0681$ (m), $R^2 = 0.9994$ where T is the temperature in °C and d_measured is the sensor reading in meters at a fixed actual distance of 2 m. A second-order polynomial regression further improves the fit: $d\_measured(T) = 6.13\times10^{-6} \times T^2 - 0.003743 \times T + 2.0706$, $R^2 = 0.99996$ The practical temperature compensation formula is derived directly from the speed-of-sound model: $d\_corrected = d\_measured \times (331.4 + 0.6 \times T) / 343$ This compensated formula reduces the residual measurement error to below 0.05% across the entire 0°C–50°C range, compared to up to 5.05% without compensation. The error values at each temperature were analyzed to examine the relationship between temperature and measurement accuracy. Graphs depicting the relationship between temperature and measured distance and measurement error were constructed to visualize the effect of temperature on ultrasonic sensor accuracy. The simulation data were then analyzed through several stages, beginning with the collection of measured distance data and the corresponding error values. Descriptive analysis was subsequently performed to determine average values and identify general patterns of measurement error. The data were also presented in graphical form to facilitate understanding of trends and the degree of temperature influence on sensor accuracy. Interpretation was conducted to evaluate the significance of the relationship between temperature variation and the magnitude of error, as well as to draw conclusions regarding the importance of implementing temperature compensation. The simulation results were then compared with fundamental theory and previous research to verify their validity. If significant discrepancies were found, the simulation process was re-evaluated to ensure the accuracy of the measurement results.

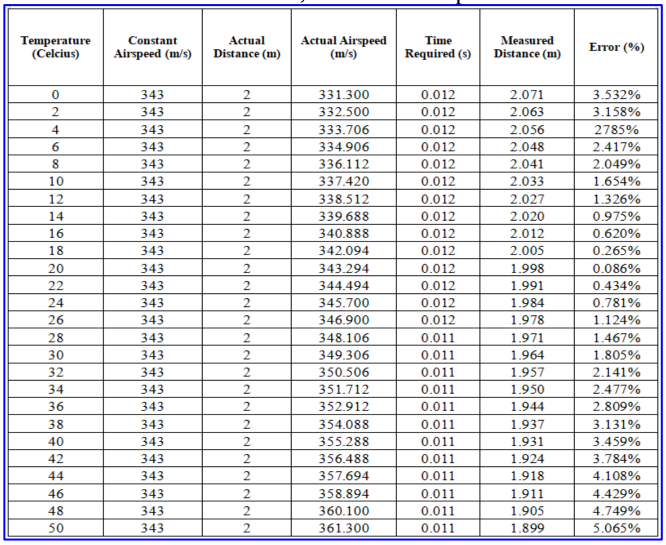
III. Results and Discussion

A. Results of the Study

Calculations were performed using the actual speed of sound, which increases by 0.6 m/s for every 1°C rise in temperature, to determine the wave travel time. The measured distance was calculated using a fixed speed of sound of 343 m/s (the speed of sound at 20°C). The calculation results for each temperature level. are shown in Table 1.

A statistical analysis of the simulation data was performed to quantitatively characterize sensor accuracy across the temperature range. For the theoretical calculation method, the Root Mean Square Error (RMSE) relative to the actual distance of 2.000 m is 53.50 mm, and the Mean Absolute Error (MAE) is 45.00 mm. For the Tinkercad simulation results, RMSE = 56.57 mm and MAE = 47.26 mm.

Table 1. Measured Distance, Error vs Temperature



Temperature (Celcius)	Constant Airspeed (m/s)	Actual Distance (m)	Actual Airspeed (m/s)	Time Required (s)	Measured Distance (m)	Error (%)
0	343	2	331.300	0.012	2.071	3.532%
2	343	2	332.500	0.012	2.063	3.158%
4	343	2	333.706	0.012	2.056	2785%
6	343	2	334.906	0.012	2.048	2.417%
8	343	2	336.112	0.012	2.041	2.049%
10	343	2	337.420	0.012	2.033	1.654%
12	343	2	338.512	0.012	2.027	1.326%
14	343	2	339.688	0.012	2.020	0.975%
16	343	2	340.888	0.012	2.012	0.620%
18	343	2	342.094	0.012	2.005	0.265%
20	343	2	343.294	0.012	1.998	0.086%
22	343	2	344.494	0.012	1.991	0.434%
24	343	2	345.700	0.012	1.984	0.781%
26	343	2	346.900	0.012	1.978	1.124%
28	343	2	348.106	0.011	1.971	1.467%
30	343	2	349.306	0.011	1.964	1.805%
32	343	2	350.506	0.011	1.957	2.141%
34	343	2	351.712	0.011	1.950	2.477%
36	343	2	352.912	0.011	1.944	2.809%
38	343	2	354.088	0.011	1.937	3.131%
40	343	2	355.288	0.011	1.931	3.459%
42	343	2	356.488	0.011	1.924	3.784%
44	343	2	357.694	0.011	1.918	4.108%
46	343	2	358.894	0.011	1.911	4.429%
48	343	2	360.100	0.011	1.905	4.749%
50	343	2	361.300	0.011	1.899	5.065%

The Pearson correlation coefficient between temperature and measured distance is r = −0.9997 (calculation) and r = −0.9987 (simulation), confirming a very strong negative linear relationship between temperature and measured distance. The agreement between Tinkercad and theoretical calculation is very high, with RMSE = 8.00 mm, MAE = 7.67 mm, and Pearson r = 0.9990, indicating that Tinkercad reliably replicates the mathematical model. At lower temperatures, the speed of sound in air decreases, causing the sensor readings to indicate a distance farther than the actual distance (exceeding the target actual distance). Conversely, when the temperature rises beyond the range of 19–20°C, the speed of sound increases, causing the detected distance to become shorter than the actual value. The magnitude of the measurement error tends to increase when the temperature is outside the 19–20°C range, whether under cooler or warmer conditions. Key error benchmarks from the calculation results are as follows: at 0°C, the measured distance is 2.071 m (actual: 2.000 m), yielding an error of approximately +3.55%; at 19–20°C, the error approaches 0% (measured distance ≈ 2.000–2.002 m); and at 50°C, the measured distance drops to 1.899 m, yielding an error of approximately −5.05%.

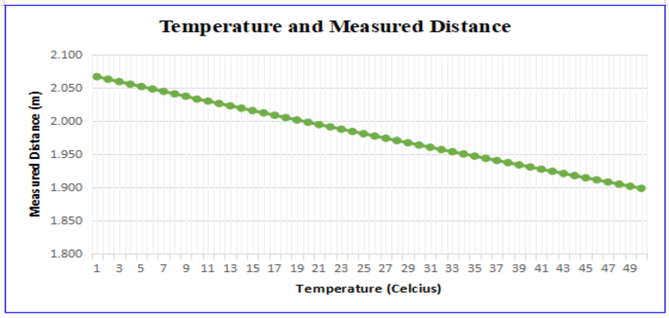


Figure 3. Graph between Temperature and Measured Distance

These values confirm that the sensor systematically overestimates distance at low temperatures and underestimates it at high temperatures, with both extremes exceeding the ±5% threshold. The relationship between temperature variation, measured distance, and error values based on the calculations is shown in Figure 3.

Based on Figure 4, it can be seen that the smallest error value occurs in the temperature range of 19°C–20°C, when the speed of sound is close to 343 m/s. This condition indicates that the use of the standard speed of sound value yields the highest level of accuracy within that temperature range. Outside this range, changes in the speed of sound propagation cause deviations in the distance calculation results.

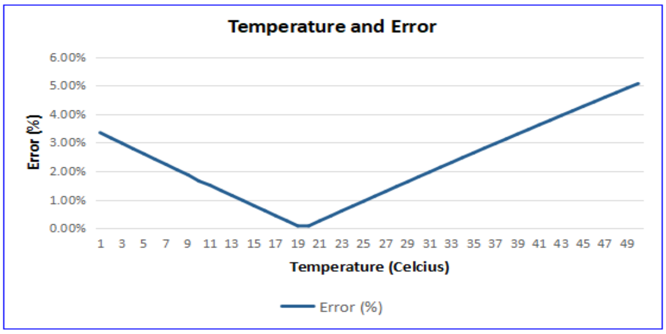
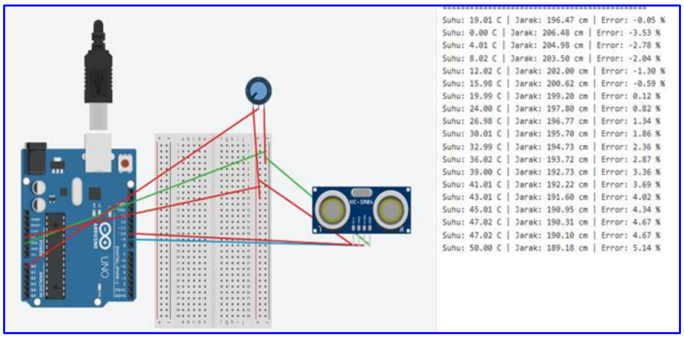


Figure 4. Graph of Temperature vs. Measurement Error

Once the circuit design was fully configured, the next stage involved running the simulation on Tinkercad to obtain measurement data based on temperature variations. As a means of verifying the theoretical calculation results, the simulation was conducted using the HC-SR04 ultrasonic sensor model combined with a potentiometer to represent temperature changes. The simulation circuit on Tinkercad is shown in Figure 5.



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Suhu: 19.01 C | Jarak: 196.47 cm | Error: -0.05 %
Suhu: 0.00 C | Jarak: 206.48 cm | Error: -3.53 %
Suhu: 4.01 C | Jarak: 204.98 cm | Error: -2.78 %
Suhu: 8.02 C | Jarak: 203.50 cm | Error: -2.04 %
Suhu: 12.02 C | Jarak: 202.00 cm | Error: -1.30 %
Suhu: 15.98 C | Jarak: 200.62 cm | Error: -0.59 %
Suhu: 19.99 C | Jarak: 199.20 cm | Error: 0.12 %
Suhu: 24.00 C | Jarak: 197.80 cm | Error: 0.82 %
Suhu: 26.98 C | Jarak: 196.77 cm | Error: 1.34 %
Suhu: 30.01 C | Jarak: 195.70 cm | Error: 1.86 %
Suhu: 32.99 C | Jarak: 194.73 cm | Error: 2.36 %
Suhu: 36.02 C | Jarak: 193.72 cm | Error: 2.87 %
Suhu: 39.00 C | Jarak: 192.73 cm | Error: 3.36 %
Suhu: 41.01 C | Jarak: 192.22 cm | Error: 3.69 %
Suhu: 43.01 C | Jarak: 191.60 cm | Error: 4.02 %
Suhu: 45.01 C | Jarak: 190.95 cm | Error: 4.34 %
Suhu: 47.02 C | Jarak: 190.31 cm | Error: 4.67 %
Suhu: 47.02 C | Jarak: 190.10 cm | Error: 4.67 %
Suhu: 50.00 C | Jarak: 189.18 cm | Error: 5.14 %
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Figure 5. Circuit (left) and Measurement Output of the Ultrasonic Sensor (right)

The simulation results show that as temperature increases, the measured distance becomes shorter, while at lower temperatures, the measured distance is longer. This trend is consistent with the calculation results, which indicate that rising temperature increases the speed of sound and shortens the travel time of the ultrasonic wave. To evaluate the agreement between simulation and calculation results, a comparison of distances obtained by both methods was performed. Table 2 below presents the distance calculation results using the theoretical method and the simulation method.

Table 2. Comparison of Calculation and Simulation Results

Temperature	Measured Distance (Calculation) (m)	Measured Distance (Tinkercad) (m)
0	2.071	2.061
2	2.063	2.056
4	2.056	2.047
6	2.048	2.047
8	2.041	2.038
10	2.034	2.022
12	2.027	2.021
14	2.019	2.011
16	2.012	2.002
18	2.005	1.997
19	2.002	1.992
20	1.998	1.990
22	1.991	1.984
24	1.984	1.976
26	1.978	1.968
28	1.971	1.963
30	1.964	1.959
32	1.957	1.952
34	1.951	1.942
36	1.944	1.934
38	1.937	1.929
40	1.931	1.924
42	1.924	1.916
44	1.918	1.912
46	1.911	1.904
48	1.905	1.897
50	1.899	1.890

In general, the simulation results follow the trend of the calculation results, although small deviations are present. These deviations are likely attributable to several factors, including ultrasonic sensor tolerance, signal processing latency in the simulation, and the limitations of Tinkercad software in precisely replicating real-world conditions. A comparison of the calculation and simulation results is shown in Figure 6.

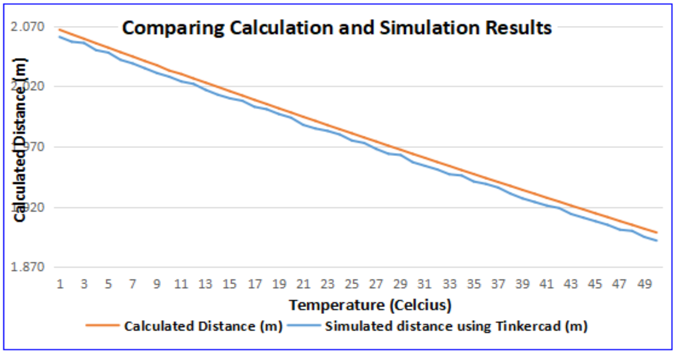

Figure 6. Graph Comparing Calculation and Simulation Results

In industrial applications, automated systems can integrate temperature sensors to perform real-time adjustments to the ultrasonic sensor distance calculation parameters. This approach enables improved measurement accuracy compared to conventional methods that use a fixed or constant value for the speed of sound.

B. Discussion

Temperature has a significant effect on the speed of sound wave propagation in air, which directly determines the accuracy of distance measurements using ultrasonic sensors. When temperature increases, air molecules move faster, increasing the speed of sound and shortening the wave travel time; as a result, the distance read by the sensor tends to be shorter. Conversely, at low temperatures, air molecule movement slows, causing the speed of sound to decrease, wave travel time to increase, and measured distance to be longer. These findings are consistent with the research of [14] which states that the speed of sound in air is influenced by temperature and reaches higher values under warmer conditions. Therefore, ultrasonic-based measurement systems must consider the temperature factor to maintain result accuracy. The implementation of temperature compensation is one of the recommended solutions to minimize errors caused by temperature fluctuations. This is also supported by Shafira et al. [11] who recommended the use of temperature compensation algorithms to improve ultrasonic sensor performance under various environmental conditions.

Measurement errors in this simulation were primarily triggered by temperature changes affecting the speed of sound in air. The analysis results show that the smallest error occurs in the range of 19°C to 20°C, when the speed of sound approaches 343 m/s, the standard value at room temperature. Outside this range, the error tends to increase as the speed of sound deviates further from the standard value. This phenomenon is consistent with the findings of Firmasnyah [8] who stated that temperature deviations from normal conditions can significantly impact ultrasonic sensor accuracy. Beyond temperature, other sources of error include limitations of the simulation model, sensor component tolerance, and potential inaccuracies in the data acquisition process. To minimize these errors, more accurate calibration and the use of higher-precision temperature sensors are required.

According to the HC-SR04 datasheet, the sensor operates within a distance range of 2 cm to 400 cm with a reported accuracy of ±3 mm under nominal conditions (typically ~20°C). The results of this study show that at temperatures deviating significantly from 20°C, the effective measurement error substantially exceeds the datasheet specification. Specifically, at 0°C the error reaches +3.55% (~71 mm over a 2 m distance) and at 50°C the error reaches −5.05% (~101 mm), both far beyond the ±3 mm datasheet tolerance. This confirms that the nominal accuracy specification of the HC-SR04 is only valid near room temperature, and temperature compensation is mandatory for reliable operation across a wider thermal range. For practical implementation, the integration of dedicated temperature sensors such as the DHT22 (accuracy ±0.5°C, range −40°C to +80°C) or the LM35 (accuracy ±0.5°C, linear output 10 mV/°C) alongside the HC-SR04 is strongly recommended, enabling dynamic adjustment of the speed-of-sound calculation using $v(T) = 331.4 + 0.6T$. A previous study by Firmansyah [8] also recommended the application of data filtering techniques as an effort to reduce noise and improve measurement accuracy.

The discrepancy between manual calculation results and Tinkercad simulation results can be explained by several technical factors. One of the primary factors is the limited physical representation within the simulation environment. Tinkercad operates with a virtual microcontroller system that introduces a certain degree of latency in the sensor data reading and processing. This latency can cause small deviations in the measurement results. Furthermore, the simulation only incorporates temperature as the variable affecting the speed of sound, while other environmental factors such as humidity and air pressure are not taken into account, even though in real conditions these parameters also influence sound wave propagation. Beyond temperature, other environmental variables also influence the speed of sound in air. Relative humidity (RH) introduces a correction to the speed of sound: $v\_humid \approx v\_dry \times (1 + 0.00016 \times RH)$. At RH = 100%, this amounts to only a +0.016% increase, which is negligible for distances under a few meters. However, barometric pressure has a more significant effect: since the speed of sound is proportional to the square root of absolute pressure, a ±10% variation in atmospheric pressure causes approximately ±5% variation in the speed of sound, which can produce errors comparable to extreme temperature deviations. In environments where significant pressure variation occurs, such as high-altitude installations, combined temperature-and-pressure compensation would be necessary. While these variables were outside the scope of the present simulation, future work should incorporate a multi-variable model that includes temperature, humidity, and pressure for a more comprehensive characterization of ultrasonic sensor accuracy. It is important to acknowledge a fundamental limitation of this study: Tinkercad does not physically model the effect of temperature on acoustic propagation. Instead, a potentiometer was used to simulate the analog voltage output corresponding to different temperature readings, which were then fed into the speed-of-sound calculation in the Arduino code. This approach is an approximation; it does not replicate the physical thermal effects on piezoelectric transducer sensitivity, beam divergence, or air density that would occur in a real environment. Consequently, the simulation results in this study serve as a theoretical validation of the mathematical model rather than a full physical replication. Real-world experimental validation using actual hardware across a controlled temperature range remains a necessary next step to confirm these findings.

Another contributing factor to the error is the hardware tolerance of the ultrasonic sensor, including variations in sensitivity and response time, which are not fully captured in the simulation model. Despite the small differences between the theoretical and simulation results, the pattern of the relationship between temperature and error remains consistent with the fundamental theory and manual calculations. This indicates that Tinkercad simulation is sufficiently representative as an initial approach to analyzing the effect of temperature on ultrasonic sensor performance. Nevertheless, for more complex applications or industrial-scale deployments, direct experimental testing is required to verify the accuracy and reliability of the system under actual operating conditions. Compared with recent related studies, the findings of this work are consistent with and extend the existing literature. Li et al. [14] developed a phased hybrid optimization method for temperature compensation in ultrasonic flowmeter measurement and reported that uncompensated temperature variation introduces non-negligible measurement errors in industrial ultrasonic applications, corroborating the findings of this study. Sze et al. [7] demonstrated that the accuracy of the HC-SR04 in measuring distance degrades when operating conditions deviate from nominal values, consistent with the error profile obtained here. Tetuko et al. [12] applied the HC-SR04 with Arduino for distance measurement but did not explicitly account for temperature effects, representing the type of conventional fixed-velocity approach whose limitations this study quantifies. The present work therefore advances the state of knowledge by providing an explicit, numerically characterized temperature-error profile and a validated compensation formula for the HC-SR04 in the 0°C–50°C range.

IV. Conclusion

This study identifies ambient temperature as a dominant factor influencing ultrasonic sensor accuracy through its effect on the speed of sound. The observed measurement bias is systematic, with underestimation occurring at temperatures above 20°C and overestimation below 19°C. Although the lowest error is obtained within the 19°C–20°C range and extreme conditions (0°C and 50°C) yield errors exceeding 5%, these findings primarily reflect theoretical behavior rather than fully validated empirical performance. The strong agreement between Tinkercad simulation and analytical calculations, while indicative of internal consistency, does not necessarily guarantee real-world accuracy. Several critical limitations must be emphasized:

1. The exclusive reliance on simulation limits the validity of the conclusions, particularly given the absence of real transducer dynamics and hardware noise.
2. The omission of key environmental variables, such as humidity and air pressure, reduces the completeness of the analysis.
3. The simplified temperature representation using a potentiometer may introduce systematic bias that is not quantified.

Therefore, the current results should be interpreted as preliminary rather than definitive. To strengthen the contribution, future research must:

1. Conduct controlled experimental validation using real ultrasonic sensors across a defined temperature range.
2. Implement and rigorously test temperature compensation algorithms under real operating conditions.
3. Incorporate additional environmental parameters to improve model fidelity.
4. Provide quantitative benchmarking against manufacturer specifications to demonstrate practical performance gains.

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