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Assessment of Accuracy in Measuring Distance with Ultrasound †

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Abstract

Many measurements are performed using ultrasound in technology. The main advantage of this measurement method is the lack of contact between the measuring element and the object being measured. An application based on the Arduino platform is presented, created for measuring distances with ultrasound. The assessment of the measurement accuracy and the sensitivity of the measuring elements to different types of surfaces will be presented. The compilation of measurement systems and the mathematical processing of the results obtained from repeated measurements will assist students in the learning process in various engineering disciplines related to the measurement of non-electrical quantities and the creation of various systems for automatic control of measurement systems.

Keywords: monitoring; distance; ultrasound; measurement system; multiple measurements; accuracy assessment

1. Introduction

The Arduino platform has gained popularity due to its open source nature, many free libraries, and intuitive operation. Arduino is aimed more at the mass consumer than at the specialized user, but it still provides enough power and flexibility to build diverse applications. The affordable price and freely available libraries are also not to be ignored.

Measurements using ultrasound in technology are extremely numerous. They represent sound waves with a very high frequency (above 20 kHz), which the human ear does not perceive. Usually in technology and medicine, frequencies exceeding 20 MHz are used. The specific operating range depends on the specific application. One of the advantages of this type of state measurement is that the reflected wave is obtained regardless of the material properties of the detected object, and the measurements themselves are contactless.

Ultrasonic time-of-flight (ToF) rangefinders are widely used for low-cost, non-contact distance measurement in robotics, automotive parking aids, assistive devices, and general instrumentation. Arduino-based prototypes using commodity 40 kHz modules such as the HC SR04 (and close variants like HC SR04P) are now routine in educational, hobbyist, and applied research contexts, including vehicle "safe distance" indicators [1], generic distance meters [2–4], motion detectors and level gauges [5], and navigation aids for blind users [6]. Across these applications, the HC SR04 is attractive because it offers a nominal operating band of approximately 2–400 cm with millimeter-scale resolution in a simple, 5 V compatible module that interfaces directly to Arduino class microcontrollers [2,3,5,7,8].

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Despite its popularity, the true absolute accuracy of HC SR04-based systems depends on far more than the datasheet specification. Manufacturer data and secondary summaries typically claim a resolution or accuracy on the order of 0.3 cm over 2–4 m [2,3,7,8], yet multiple experimental studies report larger and distance-dependent errors when measurements are compared against ground truth distances. Hunter systematically analyzed a low cost HC SR04 module and found that empirical errors can exceed datasheet claims and tend to increase with distance [9]. Kaur and Pal observed non-negligible deviations between measured and actual distances over a 2–4 m span using an HC SR04 with an 89S52 microcontroller, particularly at shorter ranges [2]. Mudda et al. reported a distance error of approximately 1% up to about 2.5 m in their "Distance Analysis Using HC SR04" study [7] and recent accuracy tests across several HC SR04 units in IJCONSIST showed near ideal behavior from 2 to 20 cm but highlighted unit to unit variability and occasional outliers [8]. Collectively, these results suggest that HC SR04 modules behave as inexpensive but imperfect analog front ends whose absolute errors must be characterized empirically for each system.

A substantial body of work therefore focuses on error characterization and calibration rather than on raw sensor specifications. In Arduino-based distance meters and parking prototypes, errors are often summarized as aggregate percentages over a few test distances. Prehartini et al. report an average percentage error of only 0.011% for an Arduino Uno + HC SR04 parking distance system evaluated at 70–250 cm [1], while Arum et al. state an error range of 0–0.067% for their Arduino-based ultrasonic distance meter [4]; both studies, however, test only sparse mid-range distances and do not disentangle environmental or surface dependent effects. Mutava and Kuria tabulate actual versus displayed distances for a carton target in an Arduino Uno + HC SR04 motion detector, finding "small deviations" up to nearly 2 m [5]. Gandha and coworkers treat HC SR04 non-linearity more systematically: they acquire dense measurements, fit Newton polynomial models, and show that mean squared error (MSE) can be reduced by 50–95% through embedded calibration algorithms [10,11]. Khaleel et al. similarly use a Pelican Optimization Algorithm with a MATLAB–Arduino interface and report that calibrated readings become "approximately equal" to desired distances over 2–400 cm [12]. More recently, speed radar prototypes using HC SR04 and Arduino have combined calibration and statistical analysis to relate distance and speed errors to environmental conditions such as temperature and humidity [3]. Together, these calibration centered studies indicate that HC SR04 errors are largely systematic and can be substantially reduced by appropriate modeling, but they generally treat the target surface as generic and do not address material dependence.

Material and boundary conditions have begun to receive attention in a smaller set of studies. In [3], HC SR04 distances were compared against manual measurements for ceramic, Styrofoam, and fish targets; ceramic and Styrofoam surfaces yielded statistically indistinguishable mean distances, whereas fish produced a large, systematic bias in the test analysis [3]. Astarani et al. focused on metal objects, combining Arduino control, MATLAB 2023 processing, and oscilloscope measurements to estimate reflection coefficients around 0.81–0.93 at 40 kHz and observing that HC SR04 readings tended to underestimate true metal target distances by roughly 2 cm, corresponding to <95% accuracy in their configuration [6]. In many Arduino application papers, the target is implicitly a cardboard box, plastic container, or vehicle body, as in [5] or waste segregation bins using paper and plastic objects [1,3], yet the surface material is not treated as an explicit factor. Systematic, per material accuracy studies for engineering surfaces (e.g., metals, glass, rigid plastics, sound absorbing panels) remain rare.

Environmental influences further complicate absolute accuracy. The authors of [13] reported that an Arduino-based HC SR04P module in an ultrasonic cane exhibited an absolute error of 2.64% at −7 °C, improving to 0.96% at 24 °C, clearly implicating temperature-driven sound speed variation [13]. Speed radar experiments likewise identify temperature and humidity as key contributors to HC SR04 ranging error [8]. Studies such as JARTMS's "Distance Measurement Using Ultrasonic Sensor and Arduino" reiterate that, in principle, HC SR04 can achieve ≈3 mm accuracy over 2–400 cm, but they assume standard room temperature conditions and emphasize practical guidelines such as requiring a smooth target area of at least 0.5 m^2 to avoid degraded measurements [3]. These findings are consistent with theoretical expectations that, within typical indoor ranges, temperature and (to a lesser extent) humidity produce percent level shifts in sound speed comparable to or larger than many reported "instrument errors".

When these strands are viewed together, an important gap emerges. Many works demonstrate that Arduino controlled HC SR04 systems can achieve seemingly excellent accuracy in mid-range scenarios for generic targets [1–5,7,8]; others model and correct systematic distance dependent error via polynomial or metaheuristic calibration [7,8,10–12]; and a few explore how specific materials and environmental conditions affect measurements [2,6,7,9,13,14]. However, no study to date simultaneously uses an Arduino-controlled HC SR04, characterizes absolute distance error over a dense set of distances spanning roughly 150–3000 mm, employs flat, perpendicular targets drawn from a controlled panel of engineering surface types (metal, optically transparent, textured, sound absorbing, cardboard, and rigid plastic), and documents typical indoor environmental conditions with sufficient precision to separate environmental, material, and timing path contributions to error. Previous analyses either restrict the distance range, collapse over material and environmental variations, or measure HC SR04 error in microcontroller agnostic test beds.

The present work is designed to address this gap. We systematically quantify the absolute distance error of an Arduino-based HC SR04 ranging system across 150–3000 mm for flat, perpendicular targets representing common reflective, transparent, textured, absorbing, cardboard, and plastic surfaces under well characterized indoor conditions. Building on prior calibration and material specific studies [1–3,5,6,8,10–14], we establish a calibrated baseline using a high reflectivity reference surface, evaluate residual bias and variance as functions of distance and surface type, and relate observed trends to known ultrasonic beam patterns, surface acoustic properties, and Arduino timing behavior. By doing so, we aim to provide an application-ready error map for HC SR04-based Arduino systems and a clearer physical understanding of how target surface and environment jointly shape their metrological performance. References [2,3,8] below were identified via a conventional web search rather than the Undermind literature search and are therefore less systematically curated.

One of the factors that can negatively affect the measurement process is air turbulence. It can "defocus" the propagation of ultrasound and deflect it away from the receiver. Materials whose surfaces absorb or deflect sound also negatively affect accuracy. The size of the object has a significant impact on accuracy. The smaller the object, the smaller the detection range at which it can be reliably detected.

To ensure the accuracy of the sensor measurements, the reflecting surface of the object must be perpendicular to the direction of the signal emission. The ambient temperature also affects the readings of ultrasonic sensors. This is why it is necessary to introduce models with automatic temperature compensation, operating, for example, in the range from −40 to +100°. This is because heated objects change the configuration of the reflected wave, which leads to an error in the measured distance.

Determining the suitability of a sensor for a particular application is based on the Response Curves. These curves are shown in Figure 1 and are usually part of the meter specification.

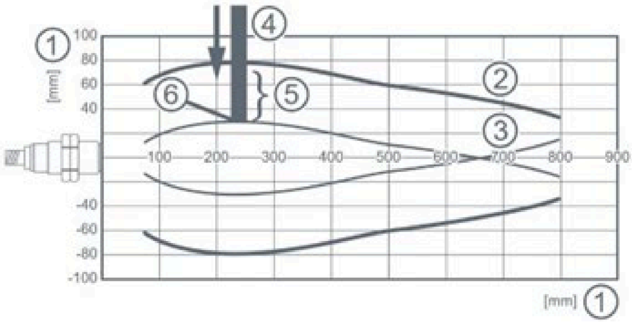

Figure 1. Response curves.

The x- and y-axes represent the detection distance and the width of the sound beam, respectively. For reliable detection, at least half of the object must be within the range of the emitted ultrasonic wave.

For targets that approach the sensor axially, the sensor will detect the target as soon as it reaches the switch-on curve.

For applications where the sound curve is too large, additional devices are used to properly direct and focus the sound. These devices are also called “sound pipes”.

Ultrasonic sensors typically have an unusable area near the front of the sensor, also called a “blind zone.” If the beam completes a detection cycle before the sensor has finished transmitting, the sensor cannot accurately receive the reflected signal and an error occurs again in determining the distance. The so-called “blind zone” determines the minimum distance an object must be from the ultrasonic sensor for the device to give an accurate measurement.

Various configurations are available on the market and usually use one or more sensing elements, depending on the application. In the case of an ultrasonic meter with multiple sensing elements, the distance between them is an essential characteristic to consider. If sensing elements are placed too close to each other, mutual interference can occur.

The design of the ultrasonic emitter is presented in Figure 2 and is made up of the following elements.

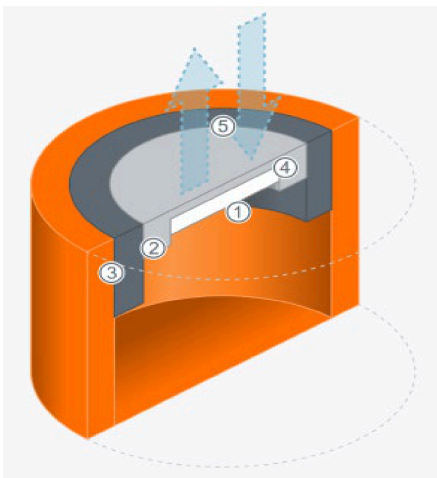

Figure 2. Ultrasonic transducer design.

It consists of piezo element 1, which sends and receives ultrasonic waves. The resonator 2 (membrane), housing 3, matching layer matches the sound impedance between the air and piezo element 4, 5 sound wave.

Typically, there are two operating states: as an emitter or receiver.

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When operating in emitter mode, a voltage with the desired frequency is applied to the acoustic transducer. It is recommended that the piezoelectric effect of the transducer is activated (it starts to oscillate) and increases the pulses in the ultrasonic range.

When operating in receiver mode, the ultrasonic acoustic transducer is "attacked" by an ultrasonic wave. This "activates" the piezoelectric transducer, which generates a voltage with a frequency corresponding to the frequency of the "attacking" wave.

Figure 3 presents the propagation of ultrasound.

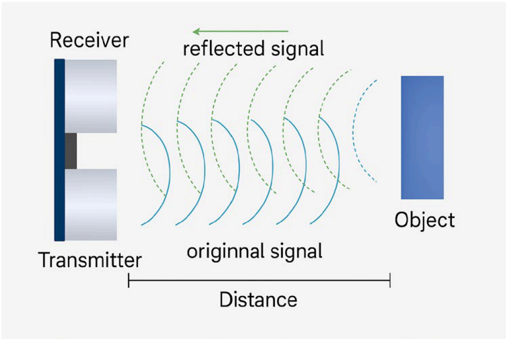

Figure 3. Propagation of ultrasound.

The idea is to present an application based on the Arduino platform, designed for measuring distances with ultrasound. The sensitivity of the measuring elements to different types of surfaces will be investigated and the accuracy of the measurements will be assessed.

2. Materials and Methods

Arduino is a microcontroller that provides digital and analog input–output interfaces for connecting sensors, actuators, and communication modules. It enables rapid development and testing of systems, making it suitable for both prototyping and small-scale applications. Programming is done in a language similar to C/C++. The software runs in a deterministic infinite loop after initialization. The platform abstracts the low-level hardware, but retains the ability to directly control timers, interrupts, and registers.

The ultrasonic transmitter–receiver used in the study is of the HC-SR04 type. It is presented in Figure 4. The measurement range is within 2–400 cm, and the accuracy can reach 3 mm. The module includes a transmitter, a receiver and a control module. Some of the characteristics that it possesses are presented below:

Figure 4. Ultrasonic module.

Ultrasonic operating range at a frequency of 40 kHz; operating temperature range: 0 °C to 60 °C (±10%); sensor angle: no more than 15 degrees; detection distance: 2–400 cm; high precision: up to 0.3 cm.

A standard display is provided to present the results.

The measurement procedure was created in a specialized IDE environment. It is presented in the block diagram in Figure 5. The blocks marked on it are as follows: 1. Converter. 2. Oscillator (excites the converter). 3 and 4. Amplifier. 5. Comparator (digitizes the signal). 6. Clock pulse generator.

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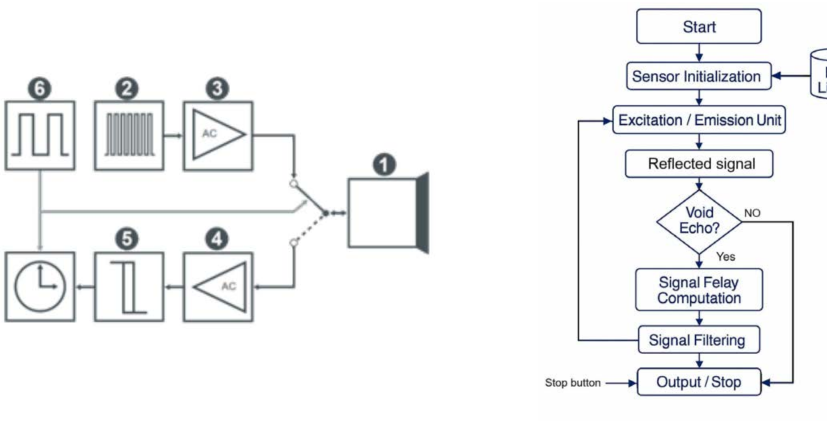

(**a**) Functional diagram (**b**) Block diagram

Figure 5. Diagram of an ultrasonic sensor.

The Arduino code for the program is presented below.

```
#include <LCD5110_Graph.h>

#define echoPin 6 // Echo Pin
#define trigPin 7 // Trigger Pin

LCD5110 lcd(8,9,10,12,11);

extern unsigned char BigNumbers[];
extern uint8_t ui[];

int maximumRange = 400; // Maximum range needed
int minimumRange = 1; // Minimum range needed
long duration, distance; // Duration used to calculate distance

String distanceString = "0";

void setup() {
 pinMode(trigPin, OUTPUT);
 pinMode(echoPin, INPUT);
 lcd.InitLCD();
 lcd.setFont(BigNumbers);
}

void loop() {
 int stringLength = 0;

 lcd.clrScr();
 lcd.drawBitmap(0, 0, ui, 84, 48);
 distanceString = readSensor();

 stringLength = distanceString.length();
 printDistance(stringLength);
 lcd.update();
 delay(50);
}
```

```
void printDistance(int length)
{
  switch(length)
  {
    case 1: lcd.print(distanceString,38,19); break;
    case 2: lcd.print(distanceString,24,19); break;
    case 3: lcd.print(distanceString,10,19); break;
    default: lcd.print(distanceString,0,19); break;
  }
}

String readSensor()
{
  String distanceS = "0";
 digitalWrite(trigPin, LOW);
 delayMicroseconds(2);
 digitalWrite(trigPin, HIGH);
 delayMicroseconds(10);
 digitalWrite(trigPin, LOW);
 duration = pulseIn(echoPin, HIGH);

 distance = duration/58.2;
 distanceS = String(distance);
 if(distance>maximumRange || distance<minimumRange)
 {
    distanceS = "---";
 }
 delay(50);
 return distanceS;
}
```

In working condition, the voltage is applied to the acoustic transducer with the required frequency. Due to the piezoelectric effect, the transducer starts generating a signal. At this moment, the clock pulse generator switches the sensor to the receiving mode and the time measurement begins. When the series of generated pulses hits an object, a reflected wave occurs, which returns back to the sensor. This reflected wave causes the transducer to vibrate and due to the piezoelectric effect, a voltage is created and the time measurement stops. Based on the measured time from the moment of sending to the moment of receiving the reflected signal and the speed of sound, the distance to the object is determined by (1).

$$\mathrm{L} = \frac{\mathrm{c}t}{2} \tag{1}$$

where

c is the speed of sound;

t is the time from sending the pulse to its return.

When calculating the relevant times, it should be borne in mind that ultrasound is a high-frequency wave whose frequency exceeds the audible range of human hearing and propagates in the air at a speed of about 340 m/s.

One of the prerequisites for a correct measurement is to ensure sufficient time for the reception of the reflected signals. If such time is not provided, the reflected signal will arrive after the second one is sent and the distance will be incorrectly measured. This time between two consecutive probing pulses must be greater than the interruption of the transmitted signal and the reflected signal.

The time required between two consecutive pulses is calculated from the speed of light and is called the maximum range. It is determined by Equation (2).

$$R_{max} = \frac{c_0.(T - \tau)}{2} \quad (2)$$

where

R_{max} is the maximum unambiguous range;

c_0 is the light speed.

When processing the results of repeated measurements, the following sequence is followed: checking for gross errors; checking for systematic errors; checking the hypothesis of normal distribution; constructing the interval estimate.

Measurement results generally contain random and systematic components.

Statistical processing of the results does not eliminate or reduce the systematic error; therefore, it must be either corrected—by introducing a correction—or removed. However, statistical processing allows for averaging the result, thus reducing the width of the uncertainty band where the true value of the measured quantity is located [15].

It is most often assumed that the measurement results have a normal distribution and point and interval estimates are constructed on this basis. The arithmetic mean value of the quantity X is determined with (3), which represents one point estimate:

$$X = \frac{1}{n} \sum_{1}^{n} X_i \quad (3)$$

The interval estimate is given by (4):

$$J\{X\} = \overline{X} \pm t \frac{S(X)}{\sqrt{n}} \quad (4)$$

The standard deviation of Xi is determined by (5):

$$S(X) = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2} \quad (5)$$

The coefficient t is Student's coefficient at n < 30 and is actually a normalized quantile of the distribution. The quantile is the size of a random variable with a given probability.

$$u_A = \frac{S(x)}{\sqrt{n}} \quad (6)$$

The absolute error is given by (7):

$$\Delta_p = \left| X_{referanse} - X_{measured} \right| \quad (7)$$

The relative error is determined by (8):

$$\delta = \frac{\Delta p}{\overline{\overline{X}}}, \% \quad (8)$$

3. Results and Discussion

The results for the absolute error from repeated measurements on different types of surfaces are presented in Table 1.

The graph reflects the results of the tabular representation of the relationship of absolute error depending on the distance to objects with different types of surfaces (Figure 6).

The observed local peaks in absolute error are due to interference effects, the geometry of the sound beam, and partial absorption or scattering of the signal by various surfaces. At longer distances, the attenuation of the reflected signal leads to unstable detection and a significant increase in error.

Table 1. Absolute error at different object surfaces in percent [%].

Distance	Metal Surface	Optically Transparent Surface	Textured Surface	Sound-Absorbing Surface	Cardboard Surface	Plastic Surface
mm	Abs. error [%]	Abs. error [%]	Abs. error [%]	Abs. error [%]	Abs. error [%]	Abs. error [%]
150	0	0	0	0	0	0
200	0	0	0	0	0	0
250	0	0	0	0	0	0
300	1	0	0	0	0	0
400	1	0	0	0	0	0
500	1	0	0	0	0	0
600	1	0	0	0	0	1
700	1	0	0	0	0	0
800	1	0	0	0	1	1
900	3	0	0	1	1	1
1000	0	1	0	0	0	1
1500	1	1	1	1	1	1
2000	1	1	1	1	1	1
3000	11	11	12	3	2	12

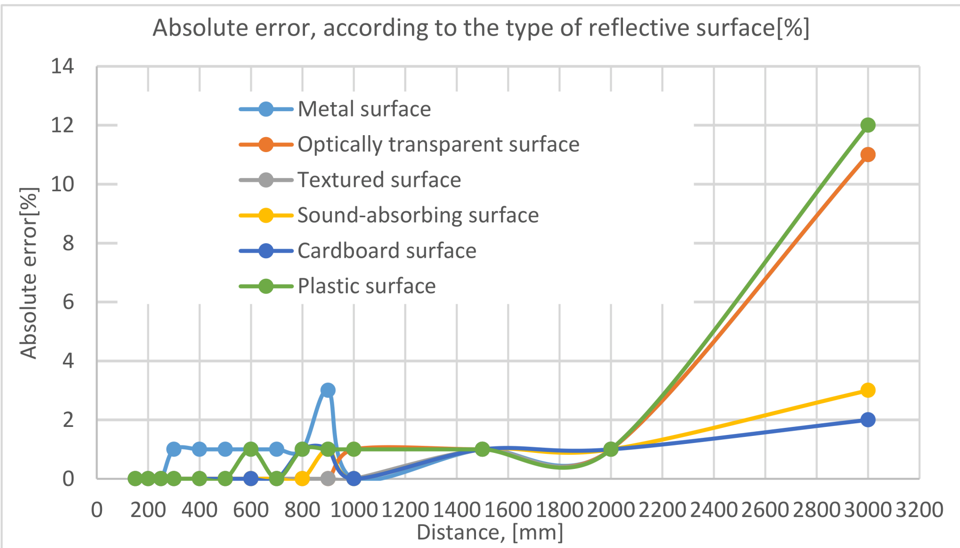

Figure 6. Assessment of measurement accuracy on different surfaces.

4. Conclusions

One of the advantages of this type of distance measurement is that the measurement result is not affected by the material properties of the object. Shiny, colored or textured surfaces, even optically transparent objects, are reliably and guaranteed to be registered.

An error occurs when measuring the distance to moving objects. By including a microcontroller in the processing module, further improvements in measurement accuracy are realized. Typical linearity values are below 1%. Repeatability is a few tenths of a percent and the response time is about 0.1 s.

The created system will be useful for training students in the creation of measurement systems using various types of sensors.

By using known measuring instruments and applying standard methodologies for assessing their accuracy, the created system will be useful for training students from various specialties.

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